Biotechnological Strategies for Microplastics and Nanopollutants

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Abstract

The swift spread of microplastics and nanopollutants in both terrestrial and aquatic environments has become a serious environmental issue, endangering human health, food security, and biodiversity. Because of their high costs, secondary contamination, and limited effectiveness at the nanoscale, traditional physicochemical cleanup procedures frequently prove insufficient. By using the natural ability of microbes, enzymes, plants, and bioengineered systems to break down, change, or immobilize these persistent pollutants, biotechnological approaches offer a creative and sustainable substitute. The creation of specialized microbial strains with improved breakdown routes for polyethylene, polystyrene, and polyethylene terephthalate (PET) has been made possible by developments in genetic and metabolic engineering. Improved selectivity and efficiency in pollutant removal are provided by novel techniques such as biofilm-mediated degradation, nanobiocatalysts, and synthetic biology interventions. Furthermore, scalable, environmentally friendly methods for environmental restoration can be supported by combining biotechnological tactics with engineering technologies. This chapter offers a thorough analysis of the biotechnological technologies and their advancements for removal and mitigation of microplastics and nanopollutants to expedite the translation of laboratory research results into practical applications and promote sustainable pollution management within the context of a circular bioeconomy.

Keywords: Nanopollutants, Microplastics, Bioremediation, Genetic engineering, Synthetic biology, Environmental biotechnology

5.1 Introduction

The rapid industrialization and exponential growth in the use of synthetic polymers have led to an alarming accumulation of plastic waste in terrestrial and aquatic ecosystems. Among these, microplastics (MPs), plastic particles smaller than 5 mm, and nanoplastics (NPs), those below 100 nm, represent a new class of environmental contaminants posing significant ecological, physiological, and biochemical challenges (Cherian et al. 2023). Their persistence, potential for bioaccumulation, and toxicity have made them one of the most pressing environmental issues of the 21st century (Hwang et al., 2020; Hou et al., 2022).

Similarly, nanopollutants, encompassing engineered nanoparticles (ENPs) such as metal oxides, carbon nanotubes, and other nanocomposites, are increasingly being released through industrial, agricultural, and consumer product applications. Due to their minute size, large surface area, and high reactivity, these particles interact with biological systems in unpredictable ways, raising concerns about their long-term environmental and health impacts (Gao et al., 2023). Recent studies have shown that both microplastics and nanopollutants can cross biological barriers, interfere with cellular metabolism, and induce oxidative stress, inflammation, and genotoxicity in a wide range of organisms from microorganisms to higher vertebrates (Babele et al., 2020). Their ubiquitous presence in soil, water, air, and even the food chain underscores the urgent need for effective mitigation and remediation strategies (Sonwani et al., 2021). Conventional physical and chemical treatment methods, including filtration, coagulation, oxidation, and incineration, have proven inefficient or economically unfeasible for complete removal, particularly for nanoscale particles. Moreover, these approaches often generate secondary pollutants or require high energy input, undermining their sustainability (Singh et al., 2021; Girish et al., 2023).

In this context, biotechnological approaches have emerged as a promising, eco-friendly, and cost-effective alternative for the management and degradation of nanopollutants and microplastics. These approaches harness the natural metabolic capabilities of microorganisms, enzymes, and plants to transform, immobilize, or mineralize pollutants into less toxic or inert forms. Biotechnological strategies not only provide avenues for degradation and detoxification but also align with the principles of circular bioeconomy and sustainable waste management (Sun et al., 2022; Tian et al., 2023). One of the most promising frontiers in this area is microbial biodegradation. Several bacteria, fungi, and algae have demonstrated the capacity to colonize plastic surfaces and initiate depolymerization through enzymatic action (Chia et al., 2020). Enzymes such as laccases, lipases, cutinases, and PETases can catalyze the hydrolysis of polymer chains into smaller monomers, which can then be metabolized by microbial consortia (Wei et al., 2017). Algae, on the other hand, not only adsorb microplastics but also contribute to biofilm-mediated degradation in aquatic environments (Chai et al., 2021).

Biotechnological strategies for nanopollutant remediation have also gained traction. Microbial biofilms and biosorbents offer efficient mechanisms for trapping and immobilizing nanoparticles through surface binding and extracellular polymeric substances (EPS) (Maurya & Raj 2019). Similarly, phytoremediation, involving plants and their associated rhizomicrobiota, plays a vital role in the uptake, accumulation, and transformation of nanopollutants, especially in soil ecosystems (Munir et al., 2023). Advances in synthetic biology and metagenomics are revolutionizing this field by enabling the discovery and engineering of novel biodegradation pathways. Genome editing tools such as CRISPR-Cas systems allow the optimization of enzyme efficiency and microbial resilience under harsh environmental conditions (Palit et al., 2025).

Another emerging area involves enzyme immobilization and nanobiocatalysts, where enzymes are conjugated onto nanomaterials to enhance their stability and activity. This hybrid approach bridges nanotechnology and biotechnology to create sustainable treatment platforms capable of addressing pollutants at both macro- and nanoscales (Chandran et al., 2023; Saravanan et al., 2023). Biochar-based systems, derived from agricultural residues, are being developed as bioactive matrices that support microbial colonization and simultaneous adsorption of microplastics and nanoparticles (Tan et al., 2015; Singh et al., 2021). However, the large-scale implementation of these strategies is still in its nascent stage. Challenges include the optimization of environmental conditions for effective biodegradation, the slow rate of polymer depolymerization, and limited understanding of long-term ecological impacts of engineered microbes or enzymes. Integrating biotechnology with material science and environmental engineering will be crucial to overcome these limitations (Alam and Rahman 2024).

The intersection of biotechnology and environmental nanoscience offers transformative potential for tackling the growing menace of nanopollutants and microplastics. By leveraging the catalytic power of nature through microorganisms, enzymes, and plants, and enhancing it with modern biotechnological tools, it is possible to design sustainable, scalable, and adaptive strategies for detoxifying our ecosystems. This chapter sets the stage for an in-depth exploration of these biotechnological innovations, their mechanisms, applications, and future prospects in creating a cleaner, safer, and more resilient environment.

5.2. Classification and Characterization of Nanopollutants and Microplastics

In recent years, small-sized plastic waste (<5 mm) and nanomaterials (NMs, 1–100 nm) have been recognized as emerging pollutants, commonly referred to as "nanopollutants." These tiny particles fall into the subcategory of nanoparticles, also known as ultrafine particles, those are typically in the nanometer size range (Yu et al., 2023). Nanopollutants are specifically used to describe hazardous or inadvertent nanoparticles discharged into the environment as a result of various human activities. Additionally, they possess unique chemical and physical properties that can lead to environmental concerns (He et al., 2021). Sometimes, fibers and tubes that are less than 100 nm in only two directions, or larger particles up to 500 nm, are referred to by this term. Nanoparticles differ from microplastics (1-1000 µm) and fine particles (100-2500 nm) (Paul et al., 2020; Alshammari et al., 2023). Based on the chemical composition, microplastics can be classified into polystyrene, PVC (polyvinyl chloride), polyethylene terephthalate, polyurethane, and polypropylene, as shown in Figure 5.1.

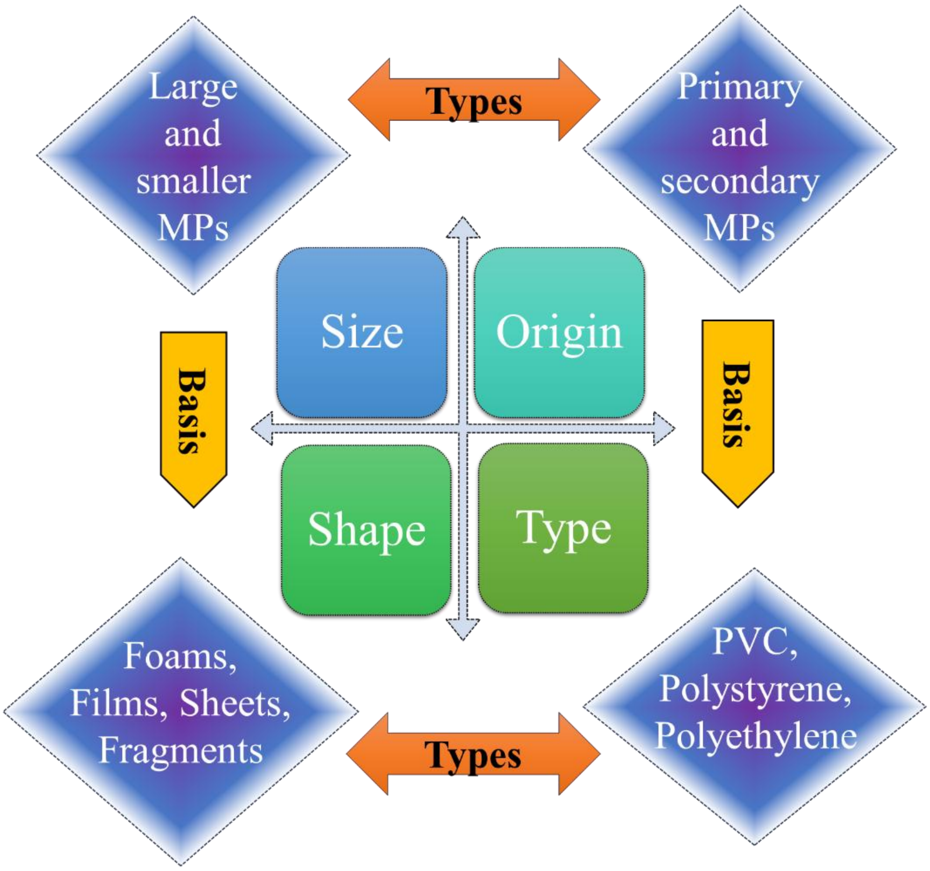

Figure 5.1: Basic classification of microplastics based on different parameters

The size of polystyrene in the environment can range from 0.5 to 500 µm. Because of their small size, they are easily ingested by a variety of organisms, which eventually affects humans through the food chain (Siddiqui et al., 2023). Ethylene undergoes addition polymerization to create polyethylene, a thermoplastic. It is the most extensively used plastic polymer, which is odourless and non-toxic in nature, and because of its unique chemical structure, it has excellent ductility, chemical stability, and low-temperature resistance. (Su et al., 2025). Polyvinyl Chloride (PVC) is widely used in automobile parts, medical equipment, and flexible wrapping films. It is susceptible to severe photodegradation even if it resists natural degradation. Additionally, a large amount of microplastics and nanoparticles may develop during the production of various PVC products (Nosova & Uspenskaya, 2023; Su et al., 2025).

Similarly, the pollutants generated by nanoparticles are categorized according to their morphology, aggregation, 0-dimensionality, and chemical composition. These display a range of morphological traits, including aspect ratio, flatness, and sphericity (Khan et al., 2022). They can be further classified as either inorganic or organic (Alshammari et al., 2023). Additionally, their size, which varies from 1 to 100 nm in at least one dimension, determines this classification. Considering the materials' overall form and dimensionality (Saleh, 2020). It is possible to classify a wide range of nanoparticles with different origins and properties as nanopollutants, as shown in Figure 5.2. A few typical categories of nanopollutants, based upon their chemical composition, may be metal, carbon, engineered, and polymeric nanoparticles. Carbon nanotubes (CNTs), which are allotropes of carbon, fall into the category of carbon-based nanomaterials. These are composed of rolled graphene sheets, which are cylindrical in structure with a diameter of several nanometers. Their symmetry, number of layers, diameter, and length can all differ; either a half fullerene molecule or a hollow end can be found on CNTs (Kumari & Sarkar, 2021).

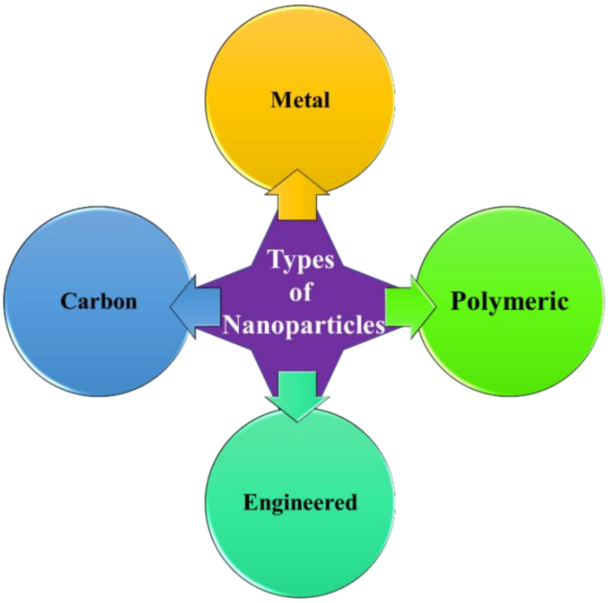

Figure 5.2: Types of nanoparticles based on chemical composition

Nanometals represent another category of nanomaterials, specifically metals or metal oxides at the nanoscale. Depending on their size and production process, they can take the form of nanoparticles, nanorods, nanowires, or nanofilms. Among nanomaterials, nanometals are a particular kind or subset of nanomaterials. Nanosilver, nanogold, and nano-iron are a few examples (Mekuye & Abera, 2023). Engineered or anthropogenic nanopollutants are intentionally synthesized nanomaterials designed for specific industrial, medical, agricultural, or consumer applications. These include metal and metal oxide nanoparticles (Ag, TiO_2, ZnO, Fe_3O_4), carbon-based nanomaterials (fullerenes, carbon nanotubes, graphene), quantum dots, and polymeric nanoparticles (Khalid et al., 2020). Despite their technological benefits, their uncontrolled release during manufacturing, usage, or disposal poses environmental and health risks.

These nanoparticles can persist in air, water, and soil, interact with biological systems, and generate reactive oxygen species (ROS), leading to potential toxicity in living organisms (Babele et al., 2020; Gao et al., 2023). Hence, responsible production and disposal strategies are vital for minimizing their ecological impact. Polymeric nanoparticle pollutants are nanoscale plastic particles derived from the degradation, fragmentation, or manufacturing of synthetic polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) (Taniguchi et al., 2019; Yong et al., 2020). Commonly referred to as nanoplastics, these pollutants originate from plastic waste, packaging materials, textile fibers, cosmetics, and industrial processes. Due to their extremely small size (<100 nm), they can easily disperse through air, water, and soil, entering food chains and biological systems (Sieg & Böhmert 2020). Polymeric nanoparticles can adsorb toxic chemicals or heavy metals on their surface and induce oxidative stress, inflammation, and cellular damage in living organisms, posing significant ecological and health concerns.

5.3. Environmental Behaviour of Microplastic and Nanopollutants

The movement of these minuscule particles through soil, water, and air, which affects their distribution, destiny, and impact on the ecosystem, is referred to as the environmental mobility of nanoparticles (Li et al., 2021). According to some studies, plants may be able to absorb nanoparticles from the soil through the fissures created during lateral root development. They may also enter the human body through the food chain, and if they are exposed to plants for an extended period of time, they can hinder their growth (Hwang et al., 2020; Gao et al., 2023). Approximately 70-80 million tons of crop residue are currently burned for disposal, making it a significant source of nanoparticles in the atmosphere and a known irritant of respiratory conditions (Sieg & Böhmert 2020). The transport of nanoparticles based on the respiratory airway’s structure, in the alveolar region, allows nanoparticles to accumulate due to their tiny size and high retention duration. Some of them can also penetrate the capillary endothelial cells and alveolar epithelium to enter the cardiovascular system and other internal organs (Sonwani et al., 2021).

Microplastics have the potential to negatively impact freshwater, marine, and terrestrial ecosystems. An estimated 50% or more of all microplastics are thought to be retained in the terrestrial environment as a result of land-based anthropogenic activity (Bullard et al., 2021). It is observed that rivers and streams carry microplastics mostly to adjacent freshwater systems and the ocean. After entering a body of water, microplastic particles with low densities first float in the water column before being carried by water flows or sinking into sediments because of increased densities brought on by other factors, like biofilm accumulation or interaction with suspended clay particles (He et al., 2021). Recent studies have emphasized the role the atmosphere plays in the long-distance movement of MPs, which are smaller than 5 mm. As a result, microplastics, especially fibrous microplastics with moderate settling velocities and relatively large aspect ratios, can be carried 100-1000 km from their origin before going through dry or wet deposition (Abbasi et al., 2021).

Microplastics bioaccumulate when their absorption from the environment through all potential pathways, including touch, ingestion, and respiration, from any source, including water, sediment, or prey, surpasses the organism's capacity to expel them. Fish, bivalves, crustaceans, marine mammals, and zooplankton have all been shown to undergo this procedure (Parolini et al., 2023). There are several routes that MPs can enter an organism, but the most common one is through an animal's digestive tract, where they accumulate within the body. Additionally, freshwater creatures can consume and collect it. Goldfish have been known to consume MPs when fish food and MPs were packaged together, which may have harmed their digestive system (Li et al., 2023). Additionally, terrestrial animals are also exposed to MPs through inhalation due to the high levels of plastic particles in the air. According to this, MPs disrupt the epithelial cell layer and cause oxidative stress, inflammation, and some cytotoxic effects in human lung epithelial cells (Yong et al., 2020).

5.4. Biotechnological Interventions to Remove Microplastic and Nanopollutants

Biotechnology plays a central role in mitigating microplastic (MP) pollution in aquatic environments, utilizing both biological and physical processes to capture and remove MPs from water streams (Shah et al., 2021). By utilizing biological systems, including bacteria, fungi, microalgae, and genetically modified organisms, biotechnological methods aim to mitigate microplastics and nanoparticles by breaking down or converting these persistent pollutants into harmless byproducts (Liu et al., 2020). Bioremediation of nanopollutants involves the use of biological systems such as microbes, fungi, and algae to detoxify or remove nanoparticles and nanomaterials from the environment. Specialized bacteria and fungi are capable of bioaccumulation, transforming and immobilizing metal-based or organic nanoparticles (Hidangmayum et al., 2022; Yu et al., 2023). Key advances in MP removal include membrane bioreactors (MBRs), algal-based filtration, the impact of anaerobic digestion (AD), and the use of immobilization carriers for continuous treatment of MPs. Each technology offers unique benefits and addresses different aspects of MP mitigation.

5.4.1. Bacterial Degradation of Microplastic

Recent studies have shown that certain bacteria can degrade microplastics. The plastic-degrading enzymes that these microbes produce can break down the chemical bonds that hold microplastics together, causing them to degrade (Zhang et al., 2021). An example of a microbe that may break down plastic is *Idionella sakaienesis*. *Ideonella sakaiensis*'s enzymes can degrade PET into its most basic components, which the bacterium can use as a source of carbon (Yoshida et al., 2021). Enzymes secreted by microbial consortia within biofilms can fragment and degrade plastic polymers, speeding up the breakdown process and decreasing the persistence of microplastics in the environment (Liu et al., 2020).

The macromolecular polymers are broken down into oligomers and monomers by a variety of extracellular oxidases and hydrolases once the microplastics have entered the biofilm. The bacteria then absorb and further metabolize these short-chain polymers (Zhang et al., 2021). There are four main steps in the process by which microplastics break down biofilms. Microorganisms accumulate on the surface of microplastics and alter their surface characteristics during the initial stage. Leaching of additives is attacked by biologically generated enzymes or free radicals, which cause microplastics to be the second step in microbial breakdown. The third stage is when microplastics and their additives are attacked by biologically generated enzymes or free radicals, which causes microplastic embrittlement and a loss of mechanical stability. During the fourth step, microplastics are broken down by microorganisms as a result of water and microbial filaments penetrating the polymer matrix (Sun et al., 2022).

Microbial degradation of plastic mainly involves the process aerobically or anaerobically depending on the microbe and environment; this results in the transformation of plastic into smaller molecules and eventually into biomass, carbon dioxide, and water (Cai et al., 2023). The most important microplastic-degrading bacteria are found in the genera of *Bacillus, Pseudomonas, Stenotrophomonas, and Rhodococcus* (Da Silva et al., 2024). Organisms of *Bacillus* species are capable of degrading polyethylene (PE), polystyrene (PS), and other plastics through biofilm formation and enzymatic attack. Different species identified in plastic degradation involved *B. cereus, B. vallismortis, B. siamensis, B. wiedmanni, B. subtilis, B. niacin, B. brevies, B. paralicheniformis, B. gottheilii, B. pumilus, B. sphericus, and B. amyloliquifaciens.* For the genus Pseudomonas, the identified species include *P. aeruginosa, P. aestusnigiri, P. protegens, P. geniculate,* and *P. citronellolis (Danso* et al., 2019). They are highly efficient in the degradation of PE, polyethylene terephthalate (PET), and polyvinyl chloride (PVC) (Zhai et al., 2023). *Stenotrophomonas,* which genus includes the species *S. rhizophila, S. panacihumi,* and *S. pavanii.* For the genus *Rhodococcus,* the identified species were *R. ruber* and *R. rhodochrous.* Members of this genus are known for their ability to degrade PE and PS and use them as their carbon source and often form dense carbon sources (Zettler et al., 2013).

Several bacteria, such as *Pseudomonas aeruginosa, Staphylococcus aureus, Bacillus selenitrireducens, etc.,* are documented to internalize, accumulate, and interact with nanoparticles as part of their physiology, bioremediation, or even nanoparticle synthesis (Tripathi et al., 2017). It has been demonstrated that some small granular structures either accumulate in the cells or adhere near the cell wall. This may lead to alteration in the integrity of the cell by continuous leaking of the potassium ions from the cell (Ghosh et al., 2021). Once inside, these particles are directed to specific organelles or cytoplasmic regions enclosed as vesicles or granules to minimize cellular disruption. These particles are then transformed by enzymatic reduction or oxidative processes. They then employ efflux systems, biotransformation, or sequestration by binding to proteins or polymers and even precipitation to immobilize nanoparticles and reduce toxicity within the cells (Tripathi et al., 2017; Babele et al., 2020).

14.4.2. Fungal Degradation of Microplastic

Some fungi, such as *Aspergillus, Penicillium, Trichoderma, Alternaria*, etc., are also responsible for the degradation of microplastic. They secrete various enzymes such as cutinase, esterase, lipases, peroxidases, and laccases, which break down complex synthetic polymers into smaller, metabolizable units and increase plastic surface hydrophilicity, which allows further microbial action (Zeghal et al., 2021). *Aspergillus* species such as *A. niger, A. flavus, and A. fumigatus* degrade a variety of microplastic polymers like PE, PP, and PS. *Penicillium chrysogenum* and *Penicillium oxalicum* have been demonstrated to degrade LDPE, HDPE, and PP. Mucor and Rhizopus genera mainly target biodegradable plastic, including PHB, PCL, and even PET copolymers. The marine fungus *Alternaria alternata* efficiently removes PS microplastic from seawater (Ekanayaka et al., 2022). Fungal genera such as *Fusarium, Aspergillus, Penicillium,* and *Verticillium* have the capacity for synthesizing, aggregating, or accumulating silver, gold, selenium, and other metal nanoparticles. They employ both intracellular and extracellular mechanisms and use unique enzymatic and metabolic techniques to transform them.

Intracellular nanoparticles may be sequestered by binding to intracellular proteins or peptides or compartmentalized into vesicles to protect fungal cells from toxicity (Guilger-Casagrande & De Lima, 2019). Fungi such as *Fusarium oxysporum, Aspergillus niger, and Penicillium species* are documented for transforming silver, gold, zinc oxide, and other metal ions intracellularly. Extracellular transformation relies mainly on secreted enzymes, proteins, and other metabolites. Fungi such as *Fusarium oxysporum, Aspergillus niger, Penicillium species*, Trametes, and other white-rot fungi release reductase enzymes such as nitrate reductase, laccase, and other oxidoreductases in the extracellular environment to catalyze reduction of metal ions to elemental nanoparticles. This extracellular transformation immobilizes toxic metal ions outside the fungal cells, reducing intracellular metal stress and enhancing fungal survival in contaminated environments (Michael et al., 2022). Bioaccumulation is a process by which living organisms progressively accumulate substances such as pollutants, metals, or toxins at higher concentrations within their cells or tissues than in the surrounding environment. This occurs mainly when the rate of uptake of substances exceeds its rate of elimination or metabolism (Parolini et al., 2023). It is a two-step process in which the first step is metabolism-independent passive biosorption by processes like adsorption, precipitation, chelation, complexation, and metal ion exchange. Movement of hydrophobic and small molecules mainly occurs by this process. The second step involves metabolism-dependent active bioaccumulation, where metal ion complexes are transported within microbial cells via processes like carrier-mediated ion pumps or even endocytosis (Diep et al., 2018; Li et al., 2023).

5.4.3. Phycoremediation to Remove Microplastic

Key microalgae and cyanobacteria species involved in plastic degradation include *Chamydomonas reinhardtii, Scenedesmus dimorphus, Phormidium kucidum, Anabaena Spiroides,* and diatoms such as *Navicula pupula*. These algae interact with various plastics—most notably polyethylene through mechanisms including enzyme production, surface colonization, and sometimes genetic engineering to express plastic-degrading enzymes (Chai et al., 2020). Enzymatically produce ligninolytic, exopolysaccharide, or polyester depolymerizing enzymes that break plastic polymers into smaller molecules. Algae such as *Scenedesmus dimorphus and Oscillatoria* adhere to plastic surfaces, facilitating physical and enzymatic degradation. Strains like *Chlamydomonas reinharditii and Chlorella vulgaris* have been engineered to express plastic-degrading enzymes such as PETase for PET degradation (Molino et al., 2025). These algae can transform plastic into water, CO_2, and additional biomass, helping mineralize and remove plastic from the environment. Their effectiveness varies with plastic type, environmental conditions, and the presence of pre-existing oxidation or surface modification.

Microalgae exhibit great tolerance against the toxins present in the wastewater, thereby having great significance in treating municipal, industrial, agro-industrial, and livestock waste (Abdelfattah et al.,2022).. They can also minimize the risk of eutrophication. Microalgae species such as *Scenedesmus, Euglena, Oscillatoria, Chlamydomonas,* and *Akistrodesmus* absorb and assimilate nutrients (especially nitrogen and phosphorus), heavy metals, and certain toxic organic compounds from wastewater through their photosynthetic and biosorptive activities (Renuka et al., 2015). Though the processes of bioaccumulation and biosorption are different, it is difficult to quantify them because the two processes are dynamically interchanging. It is quantified using a bioconcentration factor, which is the ratio of the concentration of a contaminant absorbent to the medium (Su et al., 2023). So, for effective bioremediation, the physicochemical environment must be optimized, as the rate and capacity of microalgae depend on the bioaccumulation process (Kundu et al., 2024).

The green algae *C. vulgaris*, which is known for its quick growth and biodegradability, has a high capacity to absorb MPs due to the polysaccharide and protein-rich cell walls. The biochemical makeup and surface properties of *C. vulgaris* make it a great choice for MP removal. Because of the composition of its cell wall, *C. vulgaris* has a high potential for biosorption, which is one of its main advantages (Anbarani et al., 2023). According to recent research, algae species such as *C. vulgaris* have the capacity to eliminate MPs from aquatic habitats. According to a study by Su et al. (2023), different kinds of microalgae had differing degrees of MPs removal efficacy. The most efficient of these was *Scenedesmus obliquus*, which was followed *by C. vulgaris, T. subcordiformis, C. muelleri,* and *S. westermani*. Using *Spirulina platensis*, Gabrabad et al. (2023) demonstrated an astounding 81% clearance rate of polystyrene MPs. These results highlight algae's potential as natural agents to help address the pervasive problem of MP contamination in water bodies.

5.4.4. Role of biofilm and Extracellular Polymeric Substances in Bioremediation

A biofilm is a community of microorganisms that adhere to each other and to the surface, embedded within a self-producing matrix of extracellular polymeric substances, which allow them to survive harsh environmental conditions. Extracellular polymeric substances are mainly composed of a complex matrix of polysaccharides, proteins, lipids, nucleic acids, and other biopolymers as shown in Figure 5.3.

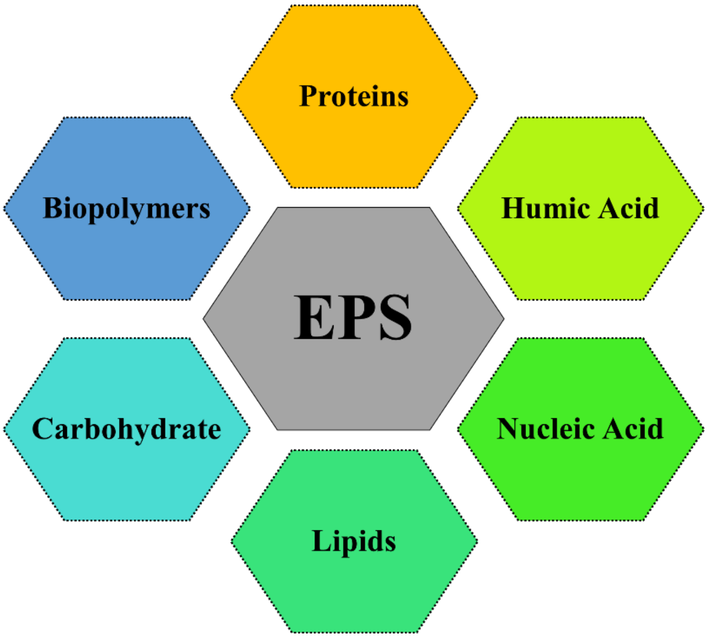

Figure 5.3: EPS composition in biofilm (changes from microorganism to microorganism and is influenced by their surroundings)

Biofilm-mediated remediation is acknowledged as an affordable and ecofriendly alternative to remove contaminants from the environment. This is mainly because of their flexibility, functionality, genetic diversity, and cellular simplicity (Biswal & Malik, 2022). They play a crucial role in bioremediation by providing microbial communities with a stable environment where microbes can thrive despite the presence of toxic pollutants (Wang et al., 2024). They also hold the capability to enhance absorption, degradation, and immobilization of environmental pollutants. They increase microbial tolerance to toxic chemicals, facilitating efficient pollutant degradation through enzymatic activity and enabling complex interactions such as quorum sensing, which regulates gene expression among biofilm cells, improving degradation kinetics and microbial communication stability (Mishra et al., 2022). The dense microbial biomass in biofilms protects microbial cells from environmental stressors, toxins, and antimicrobials, allowing them to persist and function in contaminated environments where free-floating cells may not survive (Sun et al., 2022). It also facilitates horizontal gene transfer, which increases the adaptability and biodegradation capacity of the microbial community. EPS helps to bind pollutants to biofilms, thereby enhancing bioavailability and supporting enzyme activity for biotransformation (Maurya & Raj 2019).

Some EPS also act as biosurfactants, thereby increasing bioavailability by emulsifying hydrophobic compounds. It also facilitates the concentration of enzymes near pollutants and acts as a medium for substrate diffusion, thereby boosting the enzymatic breakdown of contaminants. The polysaccharides in the EPS matrix have the ability to chelate heavy metals. Many bacterial biofilms, such as *Pseudochrobactrum mendocina* NR802, *Pseudochrobactrum saccharolyticum* LY10 sp., and *Arthrobacter* sp., have been used to eliminate heavy metal ions and xenobiotic chemicals (Bhattacharya et al., 2025). Environmental parameters such as nutrition levels, temperature, and pH influence biofilm production. Bacteria adjust the synthesis and activity of proteins, which is linked with cellular function. pH also influences microbial adherence to the surface. The ideal temperature for bacterial growth correlates with the increase in food combustion. When the temperature is raised above optimum, growth is hampered due to a decrease in response rate and thereby the biofilm formation (Parellada et al., 2017).

5.4.5 Membrane Bioreactors (MBRs) for Microplastic Removal

MBRs mix membrane filtration (usually microfiltration or ultrafiltration) with biological wastewater treatment to provide improved MP removal by combining biological and physical retention techniques. In full-scale tests, MBRs have been shown to remove up to 99.69% of MP from municipal wastewater treatment plants, demonstrating continuously high removal efficiencies that frequently surpass 95% (Egea-Corbacho et al., 2023). MPs as tiny as 0.1-0.4 μm are retained by the membrane barrier, whereas particles are entrapped by sludge flocs via bioaggregation. A pilot MBR outperformed traditional activated sludge systems by 1.1%, reducing MPs 250 μm by 99.4% (Lares et al., 2018).

Environmental hazards are greatly decreased when wastewater MP concentrations in MBRs are normally lowered to 1-2 particles/L (Egea-Corbacho et al., 2023). Membrane bioreactors (MBRs) effectively remove microplastics through three key mechanisms: physical sieving by the membrane, biodegradation of organic additives or biodegradable plastics by microbial communities such as *Bacillus* and *Hydrogenophaga*, and incorporation of microplastics into biomass that is subsequently removed via sludge wasting. While membranes retain most polymers, removal efficiency is higher for fragments (95.5–98.8%) than for fibers (57.7–75.5%) (Bayo et al., 2020). However, because MPs can serve as carriers for antibiotic resistance genes (ARGs) like β-lactams, they provide a risk of secondary contamination, especially when sludge is land-applied (Wang et al., 2024). MP-exacerbated membrane fouling is one of the operational problems. Because of pore blockage and biofilm formation, polyethylene (PE) and polypropylene (PP) MPs cause transmembrane pressure

(TMP) to rise two to three times faster, especially at particle sizes close to membrane pore dimensions. Larger particles (300-600 μm) create denser cake layers, but smaller MPs (e.g., <125 μm) penetrate membrane pores and cause irreversible fouling (Liu et al., 2025). By using periodic low-current scouring, electrochemically improved MBRs prevent fouling and sustain >95% MP removal while lowering biofouling rates (Corpuz et al., 2024). According to pilot-scale research, MP-induced fouling in hybrid systems can be successfully reduced by sustaining high aeration velocities, frequent backwash cycles, and moderate transmembrane pressures. A comparative analysis of various strategies used for microplastic removal summarised in Table 5.1.

Table 5.1: Comparative analysis of various treatment technologies for microplastic removal

Technology	**Main mechanism**	**Typical MP removal efficiency**	**Effective MP size ranges**	**Key microbial/ functional agents**	**References**
Membrane Bioreactors (MBRs)	Physical sieving by micro/ultrafiltration; biofloc entrapment	95-99%	0.1-600 μm	*Bacillus* and *Hydrogenophaga*	Egea-Corbacho et al., 2023,Bayo et al., 2020
Algal-based filtration system	Bioadsorption and bioaccumulation via EPS; electrostatic and hydrophobic interaction	70-85% (81% for PS MPs)	<500μm	*Scenedesmus obliquus, C.vulgaris, Spirulina platensis*	Su et al., 2023, Gabrabad et al., 2024
Anaerobic Digestion (AD)	Partial biodegradation of biodegradable MPs (PHB,PLA); microbial conversion to CH_4	Limited, polymer dependent (5-20%)	<1mm	Methanogens and acidogenic consortia	Hou et al., 2020, Zhang et al., 2020
Immobilization on Carriers (Biochar, Zeolites)	Adsorption via surface complexation, electrostatic interactions; physical trapping in pores	75-100% (upto 100% with Fe-modified biochar)	Nano to micro-scale	Iron- modified biochar; activated zeolites	Singh et al., 2021

5.4.6. Role of Anaerobic Digestion in Microplastic Breakdown

The wastewater treatment plant, which includes both effluent discharge and waste activated sludge (WAS) disposal, has been found to be a major source of MPs to the environment. MPs accumulate in WAS as a result of their transition from the liquid to the solid phase, which is the main technique for eliminating MPs from wastewater (Wei et al., 2019). Anaerobic digestion is one of the most promising methods for efficiently lowering MPs among the different sludge treatment techniques, including thermal drying, lime stabilization, and anaerobic digestion. Interestingly, anaerobic digestion can degrade some polymers, such as polyhydroxy butyrate (PHB) and polylactic acid (PLA) (Hou et al., 2020). Anaerobic digestion is effective only against certain types of MPs, and MPs in general present difficulties for biodegradation during sludge treatment (Zhang et al., 2020). Key metabolic processes like hydrolysis, acidogenesis, acetogenesis, and methanogenesis can all be adversely affected by the presence of the MPs and their leached additives, which can have a substantial impact on AD performance (Ezugworie et al., 2022).

The concentration, composition, and dispersion of MPs in the sludge matrix all have a significant influence on these effects. According to a number of studies, MPs may improve sludge mixing or increase microbial activity to initially increase CH_4 generation at low concentrations. Adding roughly 10 MPs particles per gram of total solids (gTS) increased CH_4 generation by 5.9%, presumably as a result of better organic matter solubilisation (Wei et al., 2019). At larger concentrations, though, this stimulatory impact is reversed. CH_4 production decreased when the MP load surpassed 20 particles/gTS, most likely as a result of the leaching of hazardous chemicals like bisphenol-A (BPA), a common molecule used in plastic manufacturing that is known to impede microbial activities. Similarly, AD performance was not significantly inhibited by short-term exposure to low levels of polyethylene MPs (60 particles/gTS) in wastewater sludge, indicating a threshold behavior in MP toxicity (Wei et al., 2019). However, CH_4 yields, enzyme activity, and microbial balance can all be upset by prolonged exposure or increased concentrations. Controlling the input of MPs and related chemicals into anaerobic digesters is essential to reducing these negative effects (Luo et al., 2019). Preventive measures could involve pretreatment of sludge, source control policies to restrict harmful plastic inputs, or pre-removal of MPs by flotation or screening.

5.4.7. Immobilization on Carriers (Biochar, Zeolites) for Continuous Treatment of Microplastic and Nanopollutants

For water filtration to be effective, bio-based adsorbents need to have low surface area, porosity, and chemical makeup. To make a bio-adsorbent cost-effective, the source material and the treatment process must be inexpensive. Zeolites are monolithic aluminosilicate materials that have a well-defined structure, persistent porosity, finely organized crystals, and comparatively stable properties in humid environments (Fu et al., 2022). They have interconnecting chambers that can be utilized to trap target molecules of interest because of their well-defined structure. They have a notable attraction for hydrophobic molecules (polar chemicals) and a low affinity for hydrophilic compounds (non-polar compounds) due to their high percentage of environmentally friendly silicate/aluminate (SiO_2/Al_2O_3). These characteristics are what give zeolites their enhanced internal and exterior adsorption capabilities and thus attracted interest in purification studies (Munir et al., 2023).

A type of charcoal with a distinctive and stable structure, biochar is extremely porous and rich in carbon. Pyrolysis, which involves heating feedstock (such as biomass waste, agricultural residues, or animal litter) in an oxygen-depleted environment, is one of the most popular thermochemical methods for producing biochar (Singh et al., 2021). Volatile components are released after heating, leaving behind biochar made entirely of carbon. The type of raw feedstock, pyrolysis technique, and conditions all affect the properties of the generated biochar, such as adsorption capabilities and the elemental makeup of the adsorbent (Tan et al., 2015). Because of its distinct physical and chemical properties, including its porous structure, high specific surface area, and adaptability in functionalizing its surface, biochar has thus attracted a great deal of interest in adsorption and purification studies, as shown in Figure 5.4.

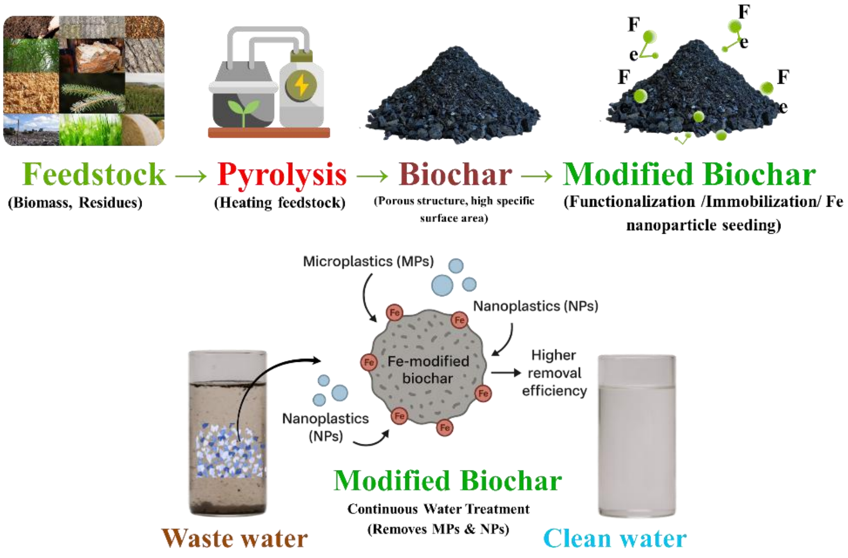

Figure 5.4: Modified biochar production for wastewater purification and microplastic removal

The growing interest in applying biochar to the removal of MPs has been brought to light by recent research initiatives. In a study, Singh et al. 2021seeded iron nanoparticles onto the surface of biochar to alter it. The environmentally friendly biochar adsorbent with iron modification showed improved surface and magnetic properties. After testing the novel adsorbent on the removal of nanoplastics (NPs) under various pH conditions, the researchers came to the conclusion that the pH of the solution has no discernible impact on the removal efficiency. Furthermore, utilizing iron-modified biochar resulted in a removal effectiveness of almost 100%, as opposed to 75% with raw biochar. According to the study, surface complexation and electrostatic interactions between the NPs and nanoparticles governed the adsorption processes. It was successful to regenerate the adsorbent by separating the iron-modified biochar particles from the NPs (Saravanan et al., 2023). The new adsorbent's adsorption capacity was maintained during regeneration and reuse, making it recyclable. The trial also produced the removal with little power consumption and operating costs, making it a potential removal strategy for the industry.

5.4.8 Genetically Engineered Microbes for Remediation of Microplastics and Nanopollutants

Various types of microbes and algae are used in the removal of microplastics. One major obstacle to scaling enzymatic bioremediation is enzyme stability in natural settings. Because enzymes are extremely sensitive to environmental factors like pH, temperature, and salinity, their effectiveness in field applications may be further diminished by inhibitors such as heavy metals or organic contaminants (Parnian et al., 2023). Cutinases and laccases exhibit decreased activity at high temperatures or at pH values that are not ideal, while proteinase K denatures at pH values below 5. Techniques like enzyme immobilization on silica nanomaterials or magnetic nanoparticles have been developed to improve stability and reusability in order to overcome these problems (Saravanan et al. 2023). Additionally, directed evolution and genetic engineering are used to increase substrate specificity, pH tolerance, and thermostability. Furthermore, under severe environmental circumstances, enzyme activity is prolonged by encapsulating in protective matrices like biochar or cross-linked enzyme aggregates (Fan et al., 2023; Lee et al., 2024).

In biotechnology, genome editing has become a potent method that holds promise for reducing plastic waste by creating bacteria that can degrade microplastics into non-toxic components (Palit et al., 2025). By introducing genes that produce enzymes like polyethylene terephthalate hydrolase, dehalogenase, esterase, depolymerase, and laccase, all of which are essential for breaking down microplastics, scientists are using genetic engineering to increase the capacity of microbes to degrade plastic (Yadav et al., 2025). A strain of *Pseudomonas aeruginosa* that has undergone genetic modification, the bacteria are better able to absorb and gather microplastics from their environment (Romero et al., 2022).

Biotechnological methods emphasize both affordability and environmental friendliness in environmental solutions and are becoming more and more important for reducing microplastics and nanoparticles. Bioengineered microbes and nano-enabled filtration systems are two examples of hybrid technologies that offer synergistic removal and degradation capabilities for even nanoscale plastic particles, providing scalable and environmentally sustainable management of microplastic pollution (Zhang et al., 2023). Even at low concentrations, nanomaterials such as magnetic nanoparticles, chitin-based sponges, and metal-organic frameworks have been produced for highly effective selective adsorption and removal of microplastics and nanoparticles from water (Sanjeev et al., 2025). Eco-friendly biodegradation techniques employing microorganisms and enzymes that transform plastics into non-toxic, natural byproducts without producing hazardous residues or secondary contamination are the foundation of biotechnological mitigation of microplastics and nanoparticles (Yousafzai et al., 2025). In addition to this, another advantage is that employing particular bacteria and enzymes, such as *Ideonella sakaiensis's* PETase, to biodegrade PET and other plastics into innocuous byproducts, hence lowering the amount of microplastics that accumulate in the environment (Anand et al., 2023).

The use of modified microorganisms for the bioremediation of micro- and nanoplastics presents a viable substitute for traditional physicochemical techniques; however, there are still issues with their potential effects on the environment. Enhanced enzymatic systems, like cutinases, laccases, or PET hydrolases, are frequently incorporated into engineered microbial strains to efficiently depolymerize complicated plastic polymers into biodegradable intermediates (Tian et al., 2023). Environmental imbalances could result from the intentional or unintentional introduction of genetically modified organisms (GMOs) into natural ecosystems, notwithstanding these developments. One of the biggest dangers is horizontal gene transfer (HGT), which can occur when synthetic genes that give antibiotic resistance or high metabolic activity spread to native microbial populations, possibly upsetting established microbial networks and biogeochemical cycles (Wang et al., 2022). Additionally, the introduced strains may displace native microbes, lowering biodiversity and changing community structures in aquatic and soil systems (Singh et al., 2021).

Microbial degradation byproducts are a further source of concern because if plastics are not completely broken down, micro-toxic intermediates or oligomers may be produced. These could build up and have cytotoxic or endocrine-disrupting effects on aquatic biota (Auta et al., 2018). Challenges with designed genetic circuits' stability and persistence include the possibility of unpredictable behaviour under changing environmental conditions due to mutations or gene loss, which makes evaluating long-term ecological effects more difficult (Zhang et al., 2023). Furthermore, there are still unresolved issues with the biosafety and containment techniques for field-scale applications, such as the use of auxotrophic mutants, physical containment, or kill-switch mechanisms, which raise ethical and regulatory questions. Thus, even if synthetic biology provides revolutionary instruments to reduce plastic pollution, thorough ecological risk assessment frameworks that incorporate environmental modelling, ecotoxicology, and genomics are necessary prior to widespread use (Baker et al., 2020).

Additionally, MNPs interact with biofilms and dissolved organic matter in complex natural matrices, changing their charge and aggregation behaviour, which affects toxin transport across food webs as well as microbial colonization (Zettler et al., 2013). Therefore, to guarantee the safe, effective, and long-lasting restoration of MNP-contaminated settings, biotechnological interventions such as enzyme engineering, microbial consortia, and synthetic biology must be combined with ecotoxicological evaluations, even though they provide hopeful answers (Tian et al., 2023). Before being widely used in the environment, biotechnological methods for the remediation of micro- and nanoplastics (MNPs), such as genetically engineered microorganisms (GEMs), enzyme systems, and synthetic microbial consortia, present serious safety and regulatory issues that need to be resolved. Potential biosafety hazards include horizontal gene transfer, ecological imbalance, and disturbance of native microbial populations when GEMs are purposefully or inadvertently released into natural ecosystems (Zhang et al., 2023). Assessing the risk of degradation byproducts produced during bioremediation is another significant concern. The creation of hazardous oligomers or additives from incomplete polymer breakdown can have poorly defined ecotoxicological characteristics (Wright & Kelly 2017). Furthermore, unforeseen ecological results may result from the behaviour of modified enzymes or microorganisms in varying field settings, such as changing pH, temperature, and nutrient levels (Singh et al., 2021).

5.5 Conclusion

The rising prevalence of microplastics and nanopollutants represents a critical environmental challenge that threatens ecosystems, biodiversity, and human health.

Biotechnological strategies offer a sustainable and efficient pathway to mitigate these emerging contaminants through innovative, eco-friendly solutions. Microbial degradation, enzymatic biocatalysis, biosorption, and biofilm-mediated remediation have demonstrated considerable potential in breaking down or immobilizing micro- and nanoplastics into less harmful by-products. Advances in genetic engineering and synthetic biology further enhance these natural processes by developing engineered strains with improved plastic-degrading capabilities and resistance to toxic pollutants. Biotechnological interventions not only minimize environmental toxicity but also contribute to circular bioeconomy models through the conversion of waste plastics into valuable bioproducts, such as biofuels and biopolymers. However, translating laboratory findings into field-scale applications requires addressing key challenges such as low degradation rates, environmental variability, and biosafety concerns. A multidisciplinary approach involving environmental biotechnology, materials science, and policy support is essential to ensure scalable, safe, and sustainable implementation. Biotechnology holds immense promise in combating the pervasive threat of microplastics and nanopollutants. By integrating advanced microbial, enzymatic, and molecular strategies with green technologies, it is possible to pave the way toward cleaner environments and sustainable resource recovery, ultimately aligning with global goals for environmental health and ecological restoration.

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