Microplastic Removal and Degradation Techniques

Subjects: Water Resources

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Plastics are a kind of synthetic or semisynthetic polymer that are made up of long chains of carbon atoms, and they may also have oxygen, nitrogen, or sulfur atoms attached to them. The majority of plastics are produced by factories that use fossil fuels. Microplastics are small particles of fragments and microfibers of plastic that have a diameter of less than 5 mm. Because of the widespread usage of microbeads in a variety of goods as well as the fragmentation of plastics with increasing age, the quantity of microplastic released in the aquatic environment is alarming, and so effluent water needs to be treated in wastewater plants to remove the microplastics. Different biotic and abiotic approaches have been studied in different research over the years.

microplastics degradation identification policies

1. Biotic Degradation of Microplastics

Biodegradation is described as the process of fragmenting plastic garbage into smaller and smaller particles with the assistance of the digestive processes of microorganisms. There are a few stages that are involved in the biodegradation process, and they are as follows: (1) the creation of a conditional film; (2) colonization; (3) bio-fragmentation; (4) assimilation; and (5) mineralization (**Figure 1**). When a conditioning film is generated over a microplastic fragment, it marks the beginning of the process that leads to the creation of biofilm. This takes place whenever the surface of a microplastic is brought into contact with water [1]. Rummel et al. [2] found that the organisms that sorb into the conditioning film are primarily dictated by the physiochemistry of the film itself. Following that, colonization occurs along the dents and fractures that are present on the surface of the microplastics.

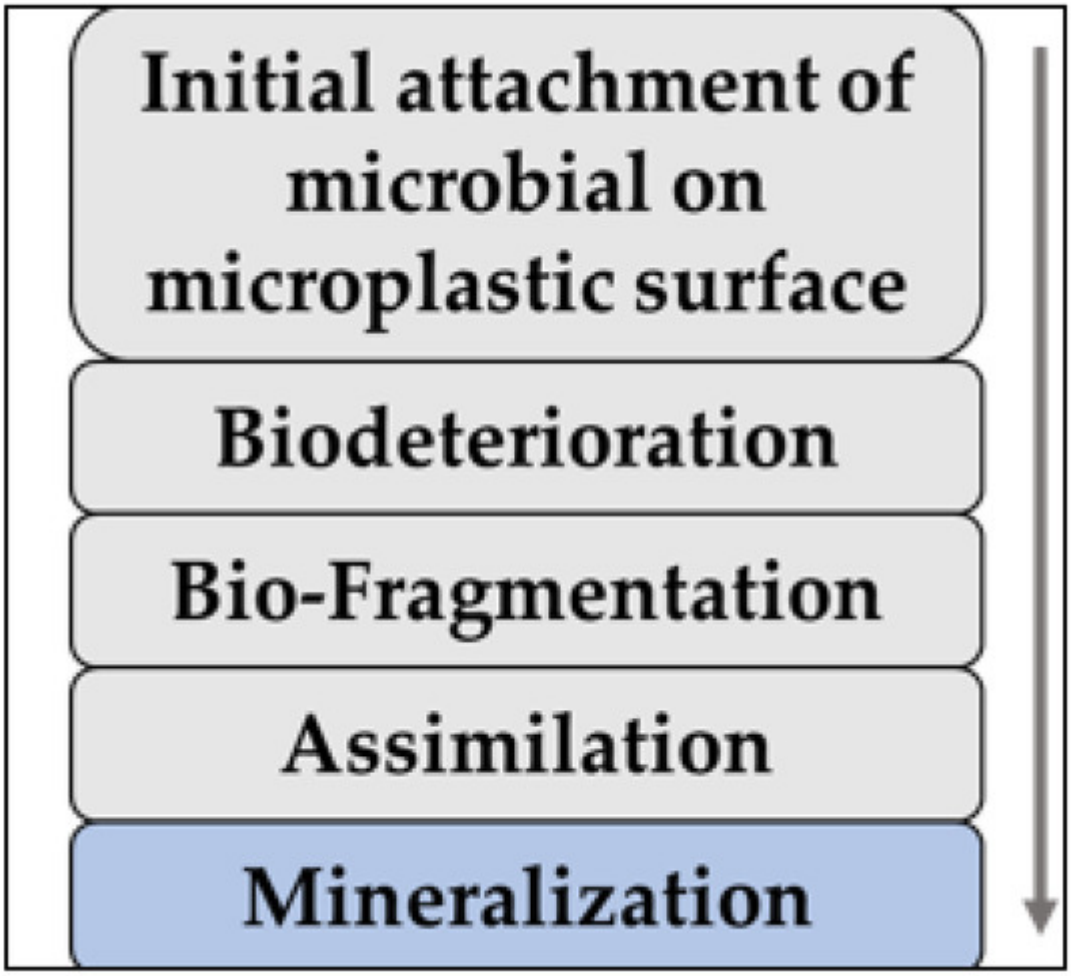

Figure 1. Steps in biotic degradation of microplastics.

Grooves in polyethylene microplastic have shown a tendency to harbor bacterial populations, as described by Zhang et al. [3]. As the Polyethylene (PE) microplastics aged, their rough surfaces and physiochemistry changed, making them a fertile breeding ground for bacteria [3]. Extracellular polymeric substance (EPS) is then secreted by the microorganisms, allowing them to strongly cling to the surface layer and initiate the disintegration of the polymeric matrix through the catalytic properties of the enzymes. To begin the biodegradation process, microplastics must undergo bio-fragmentation, which is regulated by the catalytic activity of microorganisms called enzymes. This activity weakens the carbon backbone of polymers, which in turn promotes fragmentation. Here, the degraded polymer undergoes depolymerization, which ultimately yields oligomers, dimers, and monomers. These enzymes accelerate the hydrolysis of polymers, resulting in the creation of polymer units that are smaller and more easily assimilated by bacteria. For assimilation to take place, microplastics must first be broken down to a size where molecules can easily penetrate the microbial cell wall. Assimilation involves the usage of molecules for both carbon and energy. Carbon dioxide, water, and methane are all byproducts of the mineralization stage of the biogeochemical cycle of carbon. The plastic's molecular weight, crystal structure, functional groups, and additives all have a role in how quickly it biodegrades. Methane is produced in addition to carbon dioxide (CO_2) and water (H_2O) when it occurs anaerobically [4].

2. Bacterial Degradation

In the actual world, the use of bacterial strains has the potential to lessen the impact of microplastic pollution on the surrounding ecosystem. Microplastics provide a range of bacterial communities living in aquatic environments with a place to settle and grow their numbers [5]. It has been found that some strains of bacteria may speed up metabolic processes that are involved in the adsorption, desorption, and destruction of microplastics. Because these microbes can only survive in environments with a limited supply of nutrients, they consume polymer materials as their only source of carbon. As a result, the dry weight, average molecular weight, and molecular dispersion of polymers all decrease, in addition to morphological and chemical structural changes. Auta et al. (2018) investigated microplastic degradation by *Bacillus cereus* and *Bacillus gottheilii* after pretreating the microplastic with UV radiation [5]. Both strains were found to be capable of altering the surface of the microplastics where cracks and grooves emerged, as well as altering structural and functional groups, and other features. Furthermore, it was discovered that the two strains had varied reactions to the various microplastics. *B. cereus* exhibited stronger polystyrene (PS) reaction, resulting in a larger weight loss, while *B. gottheilii* had a superior capacity to degrade a wider range of microplastics and could be regarded as possible multiple degraders [6]. *Bacillus* sp. *YP1* was used in an experiment by Yang et al. (2014) to investigate the breakdown of microplastic. During the biodegradation experiments, *Bacillus* sp. *YP1* caused surface damage such as holes and pits and introduced carbonyl groups, indicating that it has a high capacity for degrading polyethylene. This process took just two months and accounted for about 10.7% of the original weight of the polyethylene. This strain was able to produce a biofilm on polyethylene, which made it possible for the bacteria to make effective use of the non-soluble substrate [7]. Shimpi et al. (2012) achieved a 9.9% biodegradation rate using *Pseudomonas aeruginosa* in only 0.94 months, using 10% of PLA in nanocomposites [8].

By the action of enzymes, the microplastic particles are converted into products with no adverse effects on the environment. However, due to the use of various types of algae, fungi, and microbes for microplastic degradation, ecological balance can be hampered, which can put terrestrial and marine ecosystems at risk. Therefore, this negative aspect of using these biotic means must be taken into consideration before opting for any particular method for the biotic degradation of microplastics.

3. Degradation of Microplastics via Fungi

Fungi are natural candidates for microplastic degradation because of their diverse capabilities of dissolving plastic structures due to their large metabolic capacity, which includes extracellular multienzyme complexes. In contrast to *actinomycetes* and other bacteria, fungi showed better breakdown rates and capability for a variety of polymer types. As shown in **Table 1,** fungi can break down many different types of plastics in an effective manner. *Maritimum*, a marine fungus, was found to have the greatest polyethylene degradative capacity (43%) when it was cultivated on a limited growth medium with it as the only carbon source. The research was conducted by Paco and colleagues in 2017. It caused the polyethylene films to suffer significant damage, which decreased their mass and size while simultaneously increasing their biomass [9]. UV light is an initiator of polyethylene oxidation; it generates carbonyl groups, which are essential for the start of biodegradation by encouraging microorganisms to attack the

shorter segments of polyethylene molecular chains. One such case was studied by Sowmya et al. (2014), where *Trichoderma harzianum* efficiently degraded UV-treated polyethylene, resulting in the formation of cavities and erosion on the plastic surface, as well as the formation of new chemical groups detected by FTIR and NMR. Fungi can biodegrade polyurethane under suboptimal laboratory conditions and in a variety of landfill conditions. Cosgrove et al. (2007) investigated polyurethane degradation by *Aspergillus tubingensis*. It was found that *Aspergillus tubingensis* degraded polyurethane by 90–95%, causing damage to the films such as erosion, surface cracking, pore formation, and tensile strength loss. PVC can also be degraded by fungal strains. Ali et al. (2009) reported that *Phanerochaete chrysosporium* was able to adhere and grow on the surface of PVC films while using this polymer as a carbon source, indicating its ability to degrade this polymer. When the degradation rates of fungi and bacteria are compared, a higher degradation rate was achieved (up to 90%) using different fungal strains than bacterial strains.

Table 1. Plastics degraded by fungi, biodegradation conditions, and degradation rates.

Strain	Biodegradation Condition			Biodegradation Rate (%)	Ref.
	Media	Duration	Temperature (°C)		
Zalerion maritimum	Minimum growth media with 0.130 g of polymer	0.94 months	25	43	[9]
Trichoderma harzianum	Mineral salt medium	3 months	-	40	[10]
Aspergillus tubingensis	Mineral salt medium	0.75 months	37	90	[11]
Phanerochaete chyrosporium	Soil buried (soil mixed with municipal sewage *sludge*)	6 months	-	-	[12]

Algae can establish colonies on plastic surfaces, use the carbon that is contained in plastic polymers as a source of fuel for their development and energy, and secrete enzymes that can break down the plastic polymers. Because algae, and microalgae in particular, are able to break down plastic molecules by utilizing their own toxin systems or enzymes, they are seen as a viable solution for the biodegradation of microplastics [13]. Algae have been shown to colonize artificial substrates in sewage water, such as polyethylene surfaces, and research has shown that these colonizing algae are less hazardous and nontoxic [14]. The process of biodegradation of microplastics starts with the adherence of algae to the surface, and their manufacturing of ligninolytic and exopolysaccharide enzymes is essential to the process [15]. When algal enzymes in the liquid media come into contact with macromolecules on the surface of the plastic, biodegradation is started [16]. Algae exploit the polymer as a source of carbon, due to the fact that the species that grow on the polyethylene surface have greater cellular contents (protein and carbs) and superior specific growth rates. On the surface-populated polyethylene sheets, the transverse section might suffer from surface degradation or disintegration. According to the findings of prior research, the biodegradation of plastics by algae involves five distinct processes. These include fouling, corrosion, hydrolysis and penetration,

4. Removal of Microplastics by Algae and Macrophytes

breakdown of leaching components, and pigment coloring through diffusion into polymers. Research by Kumar et al. (2017) indicated that the blue-green algae (cyanobacterium) *Anabaena spiroides* degraded LDPE at the highest rate (8.18%), followed by the diatom *Navicula pupula* (4.44%), and the green algae *Scenedesmus dimorphus* (3.74%) [17]. According to Sarmah and Rout, freshwater nontoxic cyanobacteria (*Phormidium lucidum* and *Oscillatoria subbrevis*) can colonize the polyethylene surface and biodegrade LDPE effectively without any pretreatment or pro-oxidant chemicals. These bacteria are widely available, grow quickly, and are easy to isolate. *Aeromonas hydrophilia* bacteria and *Chlorella vulgaris* microalgae were utilized by Gulnaz and Dincer to investigate the biodegradation of bisphenol A (BPA). The findings demonstrated that BPA was rapidly broken down by algae, with quantities dropping below detection after 168 h in the absence of estrogenic activity. Similar results were found by Hirooka et al. (2005), using the green algae *Chlorella fusca* var. vacuolate to convert BPA into molecules lacking estrogenic action. Microalgae, as determined by Kim et al., may be genetically modified to become a microbial cell factory that produces and secretes enzymes that degrade plastic. By way of illustration, when the green microalgae *Chlamydomonas reinhardtii* was engineered to produce PETase, and the cell lysate of the transformant was co-incubated with polyethylene terephthalate (PET), dents and holes appeared on the surface of the PET film, and TPA, the completely degraded form of the PET, was produced. Using *P. tricornutum* as a chassis, Kim et al. (2020) were able to effectively produce PETase, an enzyme that exhibited catalytic activity against PET and the copolymer polyethylene terephthalate glycol (PETG) [18]. This means that the door has been opened to a potentially sustainable method of biologically degrading microplastics using microalgae.

Due to their potential use as environmental indicators and pollution bio-accumulators, macrophytes have been widely exploited for environmental biomonitoring. The polluted macrophyte tissues may serve as a significant reservoir for contamination, facilitating the uptake of microplastics by higher trophic levels and lengthening the time the contaminant spends in the water column. In a study by Sfriso et al. (2021), 94% of the macrophyte samples were found to contain microplastics in the range of 0.16 to 330 items g^{-1} fresh weight (fw). The average amount of microplastic in all species and locations was 14 items, with relevant variations between species.

A study by Rozman et al. (2022) focused on the long-term interactions between low-density polyethylene microplastics and the floating macrophyte *Lemna minor*. It involved the development of a phytoremediation strategy, which was concerned with the effects of microplastics on *Lemna minor* and on the attachment of microplastics to plant tissues. According to long-term monitoring of the effects of microplastics on the plant's growth and biochemical parameters, it was found that *Lemna minor* can withstand high concentrations of microplastics. The bio-adhesion of microplastics moved along fairly quickly; after seven days, the microplastics were already attached to *Lemna minor*, and about 25% of all microplastics that were introduced were absorbed by the biomass of the plant.

It can be concluded that the findings from these two studies are in favor of phytoremediation, which is currently one of the most promising methods for the stabilization and removal of microplastics in situ.

5. Degradation of Microplastics by Periphytic Biofilms

The biofilms epiphyton and epixylon provide the basis of one of the most popular biotic approaches for the breakdown of microplastics, known as periphytic biofilm degradation [19]. Carbon fixation and nutrient cycling are two of these biofilms' most important roles in aquatic ecosystems [20]. Biofilms have long been used in ecotoxicological investigations because of their value as a bioindicator for the impacts of pollution on aquatic habitats. Periphytic biofilms in freshwater ecosystems are made up of a wide variety of microorganisms, including cyanobacteria, algae, diatoms, and protozoans, as well as detritus that is attached to submerged surfaces or floats freely in the water column. There are five primary types of periphytic biofilms, based on the substrate they grow on: epiphyton (plants), epilithon (rocks), epipelon (sediments), epixylon (wood), and epipsammon (epiphytes) (sand). Photoautotrophic benthic microbial biofilms are primary producers in aquatic habitats [21][22][23].

The structure and function of microplastics are susceptible to a wide range of modifications caused by periphytic biofilms. Biofilms use microbial enzymes in their ability to change and hydrolyze surface characteristics, degrade additives, and produce metabolic by-products [24]. Enzymes that degrade microplastics use one of two processes, surface modification or degradation. Some enzymes (oxidases, amidases, laccases, hydrolases, and peroxidases) are responsible for the direct breakdown of polymers, while others (hydrolases) are engaged in the surface modification process [25][26]. It is reasonable to believe that microorganisms ingest subunits of big polymers after they have been digested extracellularly by the release of appropriate enzymes. Once within the cells, the breakdown products enter metabolic pathways to acquire growth-promoting energy. The creation of biofilms and the subsequent breakdown of microplastic are both natural processes in aquatic settings, but the degradation rates are modest, and the processes are gradual. Syranidou et al. (2017) conducted a microcosm experiment to examine the ability of native and bio-augmented microbial consortia to degrade polystyrene (PS) sheets in an environment mimicking maritime conditions. Bioaugmented consortia were shown to efficiently lower the mass of PS fragments by 4.7% after 6 months of incubation, whereas indigenous consortia only accomplished a weight loss of 0.19%. Therefore, it may be extremely beneficial to include biotechnology-based therapies in the whole process. Shabbir et al. (2020) developed a unique technique for the biological degradation of three structurally different microplastics using periphytic biofilm in the context of different carbon sources. These microplastics were polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP). After 60 days, the biodegradation of microplastics by periphyton biofilm rose from 9.52% (for PP), 5.95% (for PE), and 13.24% (for PET), when natural biofilm was used, to 18.02% (for PP), 14.02%, and 19.72% (for PE and PET), respectively, when glucose was added as a carbon source. Adding carbon sources also shifted the dominant microbial species in the biofilm, which may explain the improved degradation. To accelerate plastic breakdown, Gao and Sun (2021) used an innovative approach: they reassembled a bacterial population on biofilm. Screening hundreds of plastic wastes, they found an abundance of three bacteria capable of plastic decomposition. They also successfully showed the potential of the reconstituted microbial population to break down polymers such as PET and PE. They also used state-of-the-art methods to study the breakdown byproducts. They showed that it was possible to use marine bacterial populations specifically selected to build biofilms to effectively decompose microplastic debris. Using bio-aggregation processes, Liu et al. (2021) demonstrated that microplastics may be captured and aggregated in the sticky extracellular polysaccharide (EPS) formed by biofilms, demonstrating yet another innovative approach to trapping microplastics. The scientists created a biofilm containing bacteria whose extracellular polysaccharide (EPS) could

first lead microplastics to bio-aggregate for easy isolation, then an inducible biofilm dispersion mechanism would trigger a release of imprisoned microplastics for resource recovery. To validate their “capture-release mechanism”, they performed this experiment. They also showed that artificial biofilm may be used to lessen microplastic contamination in ocean water samples taken near a sewage outfall. Attempts are being made to determine whether biofilms can be used to clean up marine ecosystems and mitigate the expected worsening of microplastic pollution. However, the microbial populations on biofilm-coated microplastics, the factors controlling their colonization, and the subsequent interactions with the plastic substrate are not well understood. To further understand the functions and ecology of epispastic marine microbial communities and how they may be employed to clean up microplastic debris from the aquatic habitats, more study is urgently required [27].

6. Removal of Microplastics through Adsorption

Adsorption is a surface phenomenon that may be used to eliminate both organic and inorganic contaminants via the same process [28][29][30][31][32][33]. Adsorption has gained a lot of attention as a method for the removal of microplastics because of its cheap cost, high efficiency, and uncomplicated operating approach. Biochar’s unique physical and chemical features, such as its porous structure, high specific surface area, and adaptability in functionalizing its surface, have attracted a lot of interest in recent decades, particularly for its usage as an adsorbent for microplastic removal. The fabrication of an adsorbed phase whose composition differs from the bulk fluid phase is the cornerstone of separation by adsorption technology. All the atoms in a substance may form bonds with one another because of the abundance of other atoms in the material. To complete the bonding of the atoms that makes up a material, there are other atoms in the bulk that meet the conditions. However, the adsorbent’s surface atoms may attract adsorbates since they are not completely surrounded by other adsorbent’s surface atoms. Studies suggest that the electrostatic interactions, hydrogen bond interactions, and p–p interactions that take place in this approach contribute significantly to its high removal efficiency. Recent innovative techniques have incorporated the use of biochar to enhance the adsorption process, leading to improved removal efficiency, a potentially inexpensive procedure, and robust immobilization of microplastics. When biochar is mixed with other substances, the microplastics may become so tangled and large that they are unable to move. Biochar’s potential use in applications that filter out microplastics has been the subject of increasing investigation in recent years. Wang et al. conducted an experiment to determine whether biochar made from maize straw or hardwood feedstock was more successful than the control in removing polystyrene microbeads with a diameter of 10 m. The experiment aimed to improve the efficacy of microplastic removal in wastewater treatment facilities by adding biochar to sand filtration systems. Removal effectiveness was shown to be more than 95%, well beyond the 60–80% achieved by unmodified sand filtering systems. Biochar’s surface was modified in a separate work by Singh et al. (2021) by seeding it with iron nanoparticles. Eco-friendly biochar adsorbent with iron modifications showed improved magnetic and surface characteristics. Researchers tested the new absorbent for its ability to remove nano-plastics in solutions of several pH levels and found that the solution’s pH had only a little impact on the adsorbent’s ability to do its job. Finally, the iron-modified biochar outperformed the raw biochar by a wide margin, with a removal efficiency of almost 100%. Activated biochar was created by Siipola et al. (2020) by gradual pyrolysis of pine and spruce bark at 475 °C. Steam activation at 800 °C was then used to prepare the biochar, a very low-cost method,

to induce more pores to modify its form and increase its adsorption capabilities. The effectiveness of removing several kinds of microplastics, including spherical polyethylene (PE), microbeads (10 m), cylindrical PE pieces (2–3 mm), and fleece shirt fibers, was studied. Successful results were achieved in the retention of larger particles. All the cylindrical PE fragments and almost all the fleece shirt fibers were saved by the biochar's activation in steam. Large particles were retained well, which was encouraging, however, smaller particles (spherical PE microbeads) were not efficiently absorbed. Another recent experimental study looked at how well magnesium-/zinc-modified magnetic charcoal adsorbents (Mg/Zn-MBCs) removed microplastics. Removal efficiencies of 98.75%, 99.46%, and 94.80% were achieved when polystyrene microspheres were extracted from an aqueous solution employing Mg-MBC, Zn-MBC, and MBC, respectively. Research summaries on biochar for microplastic removal are provided in **Table 2.**

Table 2. Summary of the studies on microplastic removal using biochar.

Characteristics of Adsorbent	Process Parameters	Removed Microplastics	Efficiency of the Process	Involved Mechanisms	Ref.
Biochar consisting of corn straw and hardwood	pH = 7.56 Filtration column for biochar Hybrid sand	Polystyrene microplastic spheres (diameter = 10 µm)	Greater than 95%	Sticking, entangling, trapping	[34]
Magnetic biochar modified by Mg/Zn	Temperature = 25 °C	Microplastic spheres of polystyrene (diameter = 1 µm)	Mg-MBC-98% Zn-MBC-99.46% MBC-94.80%	Chemical bonding, electrostatic interaction	[35]
Biochar modified by iron and pyrolyzed at 550 °C and 850 °C	pH = 5.5 Temperature = 25 °C	Nano-plastics (diameter = 30 nm and 1000 nm)	Around 100%	Surface complexation, electrostatic attraction	[36]
Pine and spruce bark biochar pyrolyzed at 475 °C and steam-activated at 800 °C	Temperature = 25 °C	Spherical, cylindrical and fleece shirt fibers polyethylene microbeads (diameter = 10 µm)	Around 100% in the case of cylindrical polyethylene pieces and fleece fibers.	Adherence between biochar particles.	[37]

The photocatalytic degradation of organic pollutants is a regular practice [38][39][40][41][42][43][44]. In recent, there has been much study and use of advanced oxidation processes (AOPs) for the destruction of a broad range of resistant environmental pollutants. The sulfate radical ($SO_4^{\bullet 2-}$, E_0 = 3.1 V vs. normal hydrogen electrode (NHE)) and the hydroxyl radical (•OH, E_0 = 2.7 V vs. NHE) are two examples of ROS with high standard reduction potentials that are produced by AOPs during organic pollutant removal. To a lesser extent, the strong oxidizing free radicals produced by AOPs may cause the molecular chain of microplastics to eventually break down into tiny molecule organics such as H_2O and CO_2. Microplastics of differing sizes may be broken down by a wide range of processes, including UV photolysis, UV/H_2O_2, O_3, UV/visible light-induced photocatalysis, heat-activated PS and PMS, and plasma (**Figure 2**). Degradation of microplastics by advanced oxidation can be accomplished in two ways:

7. Degradation of Microplastics by Advanced Oxidation Process

homogeneous and heterogeneous. While electromagnetic, thermal, ozonation, electrical, and H_2O_2/O_3 processes are all homogeneous processes, photocatalytic oxidation and catalytic oxidation are both heterogeneous processes. Degradation in photocatalytic advanced oxidation processes can be accomplished using either UV/catalyst or visible light/catalyst methods. Thermal/catalyst/PMS methods are involved in microplastic degradation via catalytic oxidation.

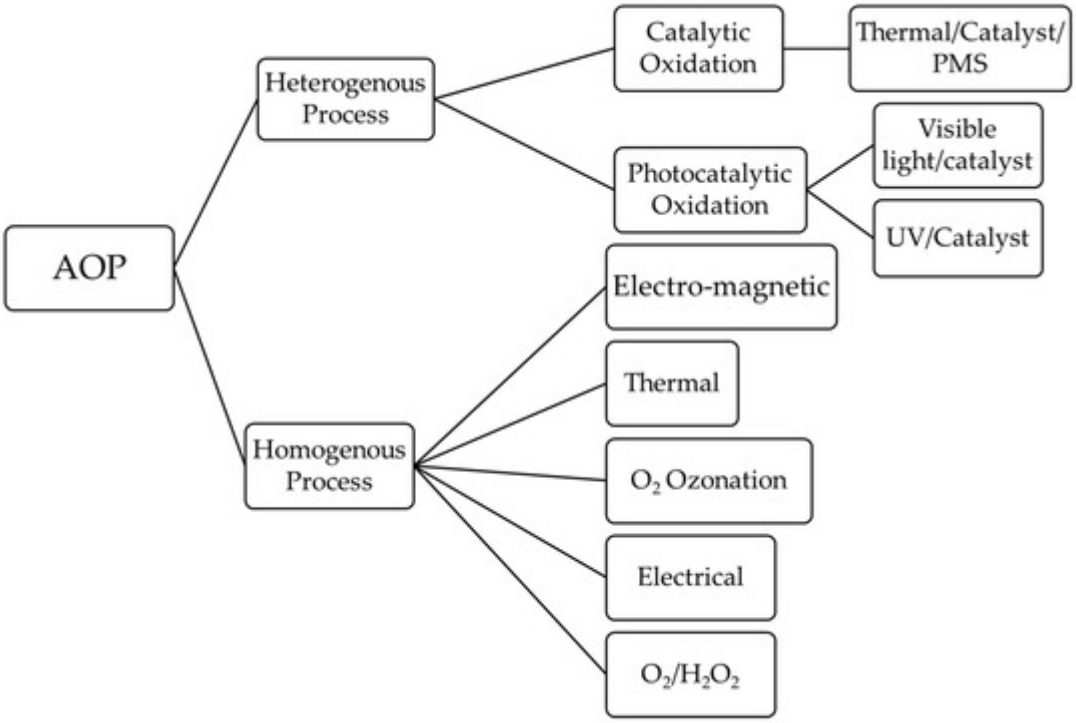

Figure 2. A diagram of the currently available advanced oxidation processes for the removal of microplastics.

8. Microplastic Treatment by Coagulation and Flocculation

For wastewater treatment of microplastics, one of the most feasible techniques could be coagulation and flocculation (**Figure 3**).

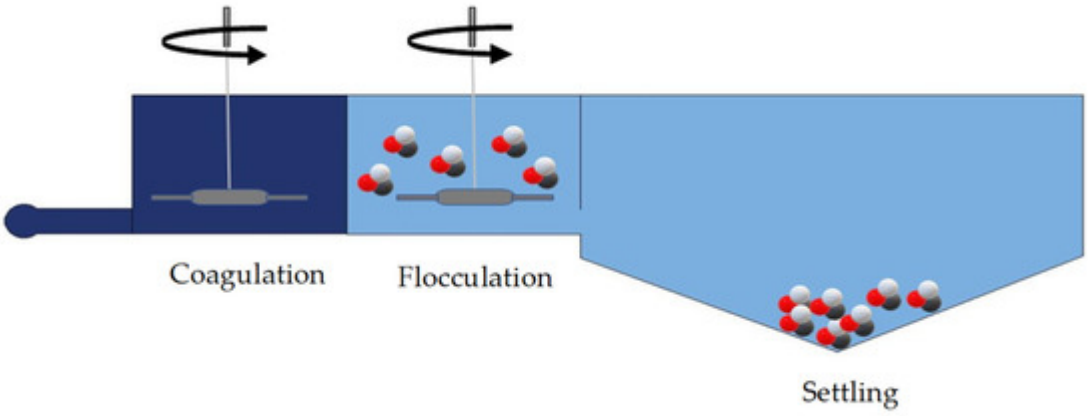

Figure 3. Coagulation, flocculation, and settling of microplastic.

9. Electrocoagulation

Electrocoagulation is an effective method for getting rid of pollutants, in which a metal is used as an anode to create a coagulant with electricity. The function of electrocoagulation is carried out by producing metal ions at the anode and producing hydroxide ions by the cathodic reaction of water. They both combine to form the metal hydroxide, which acts as a coagulant. The coagulants destabilize the surface charge of microplastics and help them form flocs (**Figure 4**). The following reactions occur in the electrocoagulation method [45]:

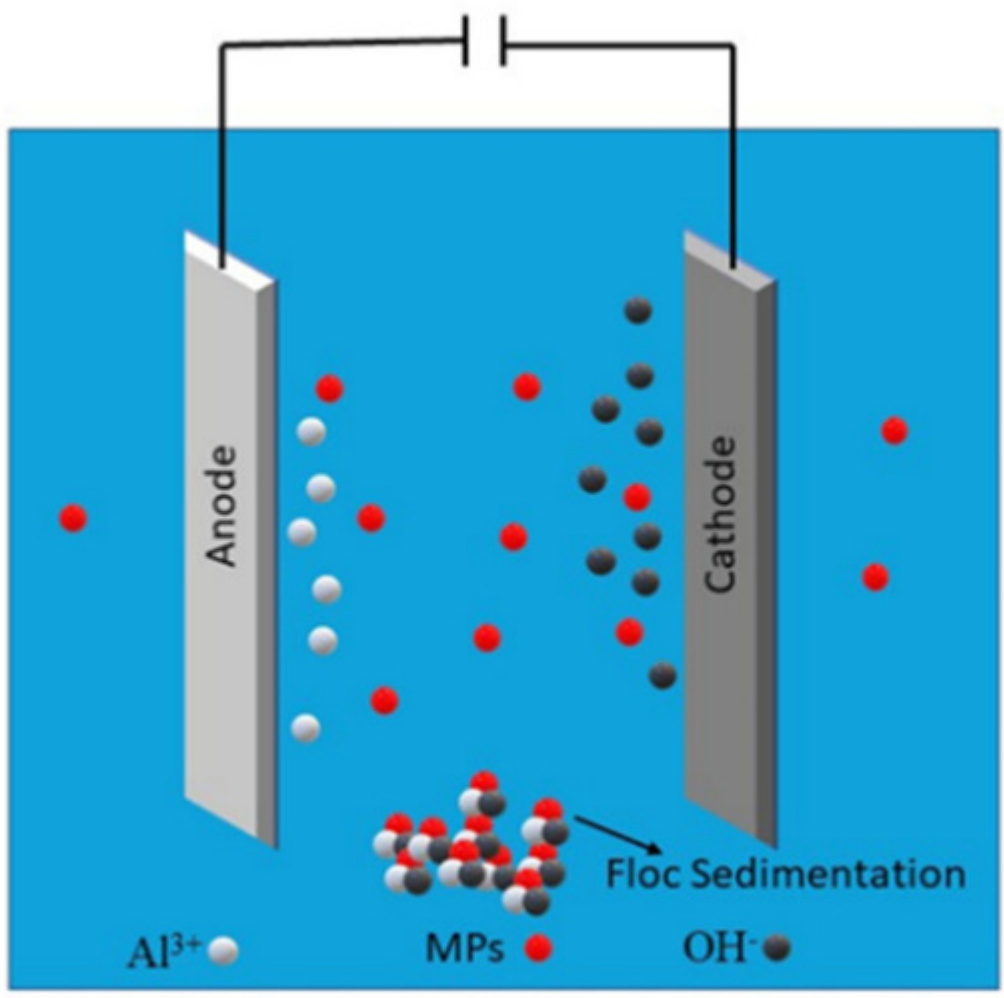

Figure 4. Setup of electrocoagulation.

$A_{(s)} \rightarrow A_{(aq)}^{n+} + ne^-$

$2H_2O_{(l)} \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^-$

$A_{(aq)}^{n+} + ne^- \rightarrow A_{(s)}$

$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-$

$A_{(aq)}^{n+} + nOH^- \rightarrow A(OH)_{n\,(s)}$

The hydrogen and oxygen produced in these reactions help to lift the flocs to the surface [46]. Perren et al. first conducted experiments on the separation of microplastics by the electrocoagulation method and achieved greater than 90% removal efficiency each time. They achieved a maximum efficiency of 99.24% at pH 7.5, a current density of 11 A/m^2, and a NaCl concentration of 0–2 g/L [45]. Elkhatib et al. experimented with electrocoagulation on real wastewater samples and gained 96.5% removal efficiency at pH 4 and 7, and a current density of 2.88 mA/cm^2 [47]. Shen et al. showed in their experiment that the Al anode performs better than the Fe anode in the removal of microplastics [48]. Xu et al. showed that heavy metals and microplastics could be taken out of wastewater treatment plants at the same time. They were able to do this with 95.16% and 97.5% removal efficiencies, respectively [49]. Akashru et al. accomplished removing 98% of microplastics from laundry wastewater with an optimal pH of 9 and a current of 2.16 A [50]. In their most recent work, Akashru et al. could achieve a 100% removal efficiency of polyethylene microplastics [51]. Electrocoagulation is one of the most promising and proven microplastic separation methods, which is also very easy to implement and cost-effective.

10. Thermal Degradation/Plastic to Fuel

Thermal conversion of microplastics is becoming very popular among researchers. Because of being a source of elemental carbon and hydrogen, plastic can be a significant fuel source if adequately utilized [52]. Two key obstacles to the successful thermal conversion of plastics are their low heat transfer and poor flow diffusion capabilities [53]. Recent advancements have utilized supercritical water to overcome this limiting parameter of traditional approaches and accomplished an effective conversion of microplastics to fuel products. Supercritical water functions as an organic solvent that effectively degrades microplastics more energy efficiently under optimized conditions [54].

Tavares et al. (2018) studied low-temperature co-gasification of microplastics with different biomass feed ratios and concluded that 50% PET + 50% biomass and 90% PET + 10% biomass feed had higher performance and achieved 63–66% H_2 molar fraction in syngas with a 9.2 MJ/Nm^3 lower heating value [55]. Bai et al. (2019) first conducted the gasification of acrylonitrile butadiene styrene (ABS) microplastics in supercritical water and found out that the degradation efficiency increases with increasing time and residence time. As the properties of supercritical water do not change with pressure, pressure has very little effect on efficiency. The efficiency of degradation decreases with the increasing concentration of feedstocks. Hydrogenation-induced gasification can improve the efficiency of degradation [56]. Bai et al. (2019) again performed gasification of polycarbonate in supercritical water and found the same previous result. Methane and hydrogen content increased and CO_2 decreased with increasing temperature [55]. Bai et al. (2019) executed another similar gasification process of PET microplastics where they again found that the efficiency increased with increasing temperature and resident time, but the pressure had very little or no effect on the efficiency. They achieved 98% carbon conversion at 800 °C and

23 MPa. The metal ions in the seawater promoted the depolymerization and hydrolysis of polymers, thus improving gasification efficiency [57].

Wang et al. (2019) evaluated the hydrothermal liquefaction performance of the Tetra Pak and found that a maximum bio-oil yield of 35.55% was achieved at 360 °C, 22 MPa, 30 min, and feed concentration of 20 wt.%. Maximum HHV of 48.747 MJ/kg and energy recovery efficiency of 46.49% were found at 420 °C, 20 MPa, 30 min residence time, and feed concentration of 20 wt.% [58]. Pyrolysis, gasification, and cracking are some processes used for thermal degradation. There is scope for a lot of improvements and research activities. These processes can obtain a range of hydrocarbons at various conditions. Therefore, the analysis of different parameters plays a crucial role in optimizing the process.

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