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Review

Aquatic Microplastic Pollution Control Strategies: Sustainable Degradation Techniques, Resource Recovery, and Recommendations for Bangladesh

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Abstract: Microplastics' dangers and the absence of effective regulation technologies have risen to prominence as a worldwide issue in recent years. South Asian countries, such as Bangladesh, are among the most threatened nations to face the drastic consequence of releasing microplastics into the aquatic environment. The research on managing and degrading microplastics is ongoing, however, sustainable techniques have not yet been found. To create a green and efficient microplastic management plan, we have compiled all the information on the existing removal and degradation techniques for microplastics and provided an overview of all the noteworthy methods that can be implemented in Bangladesh. In the portrayed biotic and abiotic techniques, coagulation and photocatalysis were found to be most efficient in removing microplastics (as high as 99%) in different studies. The concept of microplastic is new to the researchers of Bangladesh, therefore, the characteristics, occurrence, fate, and threats are briefly discussed in this paper. Sampling, extraction, and identification methods of microplastic in freshwater and sediment samples are also thoroughly specified. The sources of microplastic pollution in Bangladesh and possible strategies that can be implemented to minimize additional microplastic discharge into aquatic environments are discussed. Although Bangladesh was the very first country to ban polythene, the failure of the implementation of rules and regulations and a lack of management strategy made Bangladesh the 10th worst country in managing plastic waste. This work is a wake-up call for other researchers to conduct an in-depth investigation to improve microplastic degrading technologies and develop a sustainable strategy to end microplastic pollution in Bangladesh.

Keywords: microplastics; degradation; identification; policies; resource recovery

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1. Introduction

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 [1]. The majority of plastics are produced by factories that use fossil fuels [2]. Bakelite, the first synthetic polymer, was developed by a Belgian chemist named Leo Baekeland in 1907 [3]. In response to Baekeland's successes, major chemical companies began to invest in the development of novel synthetic polymers and other plastics. From a little over a million tons in 1950 to an astounding 368 million tons in 2019, the global production of plastic has increased dramatically. A yearly growth rate of 5% is indicative of this trend. Even while annual plastic production in Europe fell from 64.4 million tons in 2017 to 61.8 million tons in 2018, Asia's contribution to 51% of the world's plastics made it futile. Figure S1 presents the contribution of various sectors to plastic use.

Plastic was Bangladesh's 12th highest-earning sector in terms of export revenue in the 2017–2018 fiscal year, and, at the moment, Bangladesh is home to over three thousand different small and major enterprises that work with plastic. Due to the country's rapid economic development, Bangladesh's per capita consumption of plastics surged substantially from 2.07 kg in 2005 to 3.5 kg in 2014. This resulted in the daily production of 3000 tons of rubbish made of plastic, which accounted for 8% of all waste produced. In addition, between 2005 and 2014, the usage of plastic rose by 16.2% on a per capita basis, in comparison to a worldwide rate of around 25% [4]. It has been estimated that the market size of the plastic industry is close to 3 billion U.S. dollars, of which 2.2 billion U.S. dollars are local and 0.8 billion U.S. dollars are international, with further expansion being forecast. For example, in 2014, the annual use of plastic in Bangladesh was 545,300 tons, yet only 9.2% of that total was recycled [5]. The urban areas of Bangladesh generate 633,129 tons of waste plastic annually, of which only 51% is recycled. The remaining 49% may also be recycled, which would result in annual cost savings of 801 million USD. When it came to the management of plastic garbage, Bangladesh ranked as the tenth worst nation in the world. The recycled plastic flakes are the only products that are exported from the country. Considering the high calorific value of plastic trash, which ranges from 20 to 46 megajoule per kg (MJ/kg), it has been estimated that the gasification of daily plastic waste could produce between 5115 and 11,760 MWh/d of electricity. This range was derived by considering the fact that plastic trash has a high calorific value. To make Dhaka a more livable and cleaner city, the government has only recently started erecting two waste-to-energy production facilities in the city. One of these units will be located at the Amin bazar landfill, while the other will be located at the Matuail dump.

These improperly handled plastics will eventually end up in the water via drains, the wind, or floods. The river network in Bangladesh is one of the greatest in the world. It is home to about 700 rivers and streams, the whole of which, including tributaries, is projected to stretch for a combined total of 24,140 km [6]. After China and India, Bangladesh has the third-largest diversity of aquatic species in all of Asia [7]. Rivers play a significant role in facilitating the transport of plastic trash from land to waterways that eventually end up in the ocean. Over 72,845 tons of plastic are dumped into the ocean each year due to the rivers Ganges, Meghna, and Brahmaputra (abbreviated as GBM), which make up roughly 3.5% of the top ten rivers responsible for the most plastic pollution [8]. More than 60% of the rubbish that can be found on any of Bangladesh's four beaches is comprised of plastic debris [5]. Microplastics, which are defined as plastic particles less than 5 mm, are considered a potential environmental pollutant and have attracted a great deal of attention owing to their possible negative effects on living cells. Microplastics are categorized as either primary or secondary, depending on their sources. Plastic fragments, microfibers used extensively in personal care items, and synthetic fabrics are examples of primary microplastics. Secondary microplastics, on the other hand, result from the progressive fragmentation of unmanaged plastic waste via photolysis, abrasion, and/or microbiological degradation.

Because microplastics are so small, present technologies have difficulty retrieving them, increasing their omnipresence in the ecosystem [9]. To create a microplastic-free environment, the development of efficient microplastic degradation technologies and plastic recycling systems is vital. A significant number of microplastics were discovered in freshwater systems after several authors examined the sediments and surface water of various lakes, rivers, and reservoirs across the globe. The huge volume of microplastics in rich nations' freshwater systems suggests that Bangladesh's situation is far worse [5]. According to a study in 2020, there are more than 3000 published papers about microplastics worldwide, and 40% of them are based on land–water ecosystems [10]. The amount of microplastics in freshwater is very similar to that in seawater, and sometimes even higher. There have been very few studies to quantify the amount of microplastics in the aquatic environment in Bangladesh. For a long time, there have been no efforts in assessing aquatic microplastics. Recently, a few initiatives have been made, but the speed is still

insufficient [5]. From 2006 to 2020, 24 papers about plastic pollution were published in Bangladesh, with just 5 of them focusing on microplastics. Nine are about plastic pollution in the marine environment, and only one is about pollution in freshwater. It concludes that the research facilities, pace, infrastructure, and initiatives on aquatic microplastics still lack a lot in comparison to global studies. Collaboration with international research organizations or universities might accelerate the studies to assess the aquatic microplastic condition, future threats related to it, and remedies to it.

The major goal of this paper is to shed light on the aquatic microplastic situation in a growing nation such as Bangladesh and offer a microplastic degradation and management strategy to eliminate the danger. In this work, the destiny and sources of microplastics are comprehensively examined, and recommendations are provided for reducing microplastic pollution. This paper examines the most current advancements in microplastic removal methods in depth. The implications of factors such as coagulant type, ambient conditions, microplastic properties, catalyst type, etc., and removal procedures are explored in detail. The opportunity to reuse the removed microplastics is also investigated in this study. In addition, we combined the available techniques for sampling, extraction, and identification. As of now, very little research is being done on the catastrophic effect of microplastics in Bangladesh. Therefore, this study serves as a call to action for other researchers to examine the phenomena further and enhance microplastic degrading technologies.

2. Outline of Methodology

This paper is designed to give the reader a comprehensive scenario of the aquatic microplastic situation in Bangladesh, as well as managerial and scientific approaches to preventing and controlling it. Scientific papers on relevant topics were thoroughly examined. The current plan for mitigating the problems was discussed with some associated personnel. The table of contents for this paper was then prepared. After that, the relevant information from the journals was sorted out. This paper is divided into eight major sections. Plastic history, usefulness, problems related to plastic non-degradability, plastic pollution conditions in Bangladesh, aquatic microplastic conditions in Bangladesh, and current knowledge about aquatic microplastic pollution and degradation processes were discussed in the introduction section. The discharge of microplastics in nature, the fragmentation of plastics into microplastics, the fate of plastics after use, and the microplastic-related threat in Bangladesh were all explained in the latter section. The various degradation methods were then briefly addressed. It explained how to recover resources from plastics and implement managerial recycling strategies for a circular economy. From Bangladesh's point of view, the law on plastic pollution, the need for a national policy on aquatic microplastics, and some ideas for reducing the bad effects of microplastics were all highlighted.

3. Roadmap of Microplastic

Larger plastic fragments that are not eaten by marine animals are broken down into tiny bits by the sun and waves. Microplastics have replaced biodegradable alternatives in several personal care items such as facewash, toothpaste, and facial cream over the years [7]. A single bottle of facewash (150 mL) contains between 3 and 3.6 million microbeads, according to global standards. Primary microplastics from personal care items are flushed down the toilet into the sewerage system. Wastewater treatment plants cannot collect them, and they finally end up in nature. In Bangladesh, approximately 95% of the population is unaware of the negative health and environmental effects of microplastics. According to 2016 research, 7928.02 billion microbeads are released each month from three cities.

Figure 1 shows that personal care products such as facewash, detergent, and toothpaste are major culprits for releasing primary microplastic. Textile fibers might also be a source of microplastics in the environment. According to recent research, per m^2 of textile clothing, around 30,000–465,000 microfibers were discharged, which is comparable to 175–560 microfibers/g. As a result, Bangladesh could be contaminated by microplastics from the garment and textile industries, which account for 11.17% of the country's GDP,

84% of export revenues, and 20 million jobs. Another possible source of microplastics in the environment that enters water via rain or floods is emissions from car tires.

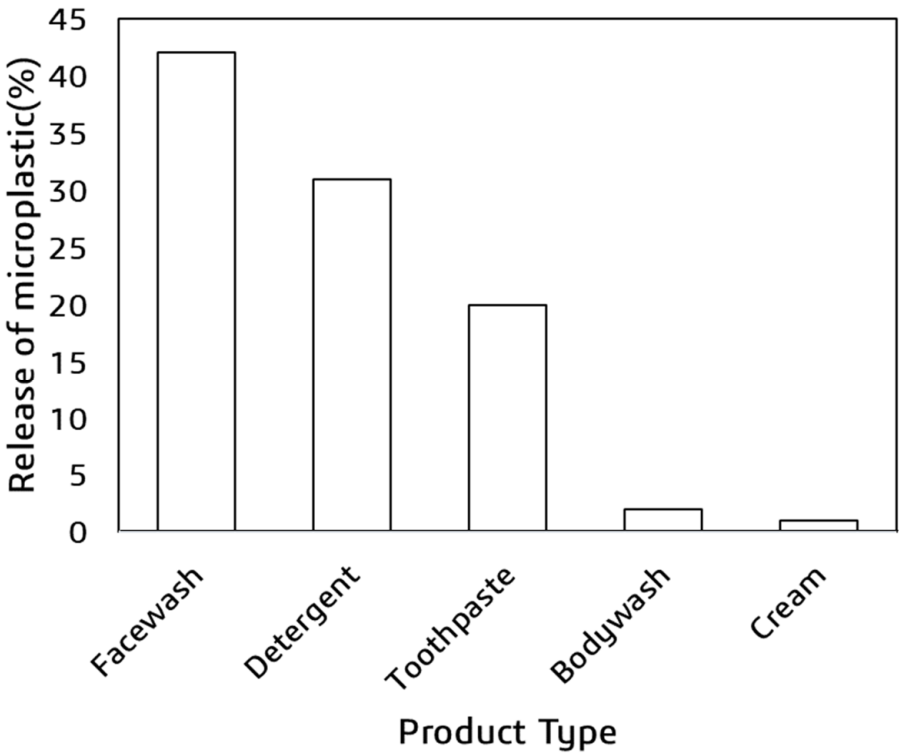

Figure 1. Contribution of various products in releasing microplastic.

Mismanagement of plastic waste is the major source of secondary microplastic emissions. According to studies on product lifespans, most plastic items are intended to be utilized for a short period of time, and 40% of the plastics are for single use. Single-use plastics such as straws, food packaging, and polythene are generally non-biodegradable and non-recyclable. They have been highlighted as one of the most severe ecological pollutants. Single-use plastic packaging from food and personal care goods accounts for 96% of Bangladesh's annual plastic waste of 87,000 tons. Sachets, which are fully non-recyclable, make up around a third of the overall trash. In Bangladesh, the majority of single-use plastics are not properly disposed of, and they end up in landfills, rivers, or the ocean. Figure 2 portrays the liability of different sectors for the most usage of single-use plastic. Food packaging and sachets are most accountable for plastic pollution.

There are now 8300 MT of virgin plastics on the planet, of which 6300 MT are garbage. Only 9 to 12% of all plastic garbage is recycled. The rest (79%) is deposited in landfills, incinerated, or dumped in nature. The majority of plastic debris ends up in ponds, lakes, and rivers, all of which eventually end up in the ocean. This movement is caused by wind, precipitation, surface runoff, and riverine transport because of their low densities and tiny sizes. Marine organisms mistake microplastics for plankton because of being identical in size [11]. Most of the zooplankton ingest microplastics and pass this on to higher trophic levels. A total of 30 species from 28 taxonomic orders of zooplankton have been identified to ingest microplastics [12].

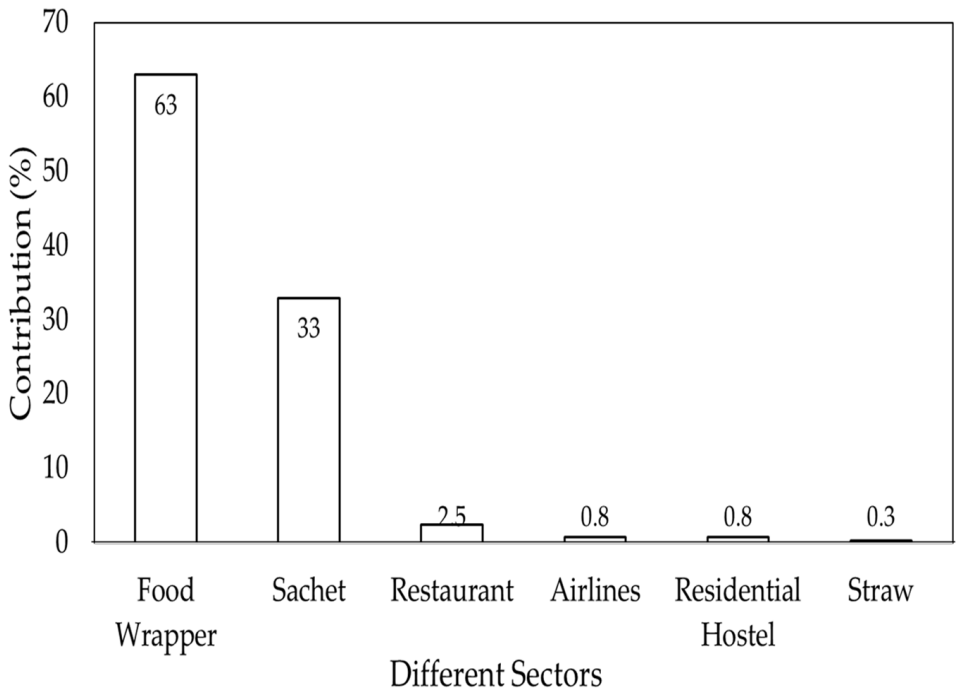

Figure 2. Usage of single-use plastic in different sectors of Bangladesh.

Setälä et al. (2014) identified the ability of microplastics to be transported between trophic levels, from copepods to microzooplankton (mysid shrimps) [13]. Costa et al. (2020) found the same result for copepods to jellyfish [14]. Additionally, laboratory experiments and field observations have shown that microplastics can be transferred indirectly from mussels to crabs [15], from Atlantic mackerels to gray seals [16], from plankton to fur seals [17], and from crustacean larvae to fish [18]. Figure 3 summarizes the whole discussion of several methods for producing an abundance of microplastics in nature and penetrating the food chain. Plastic can enter our food chain in many ways, but as we are concerned about aquatic microplastic, only penetration through fish is depicted.

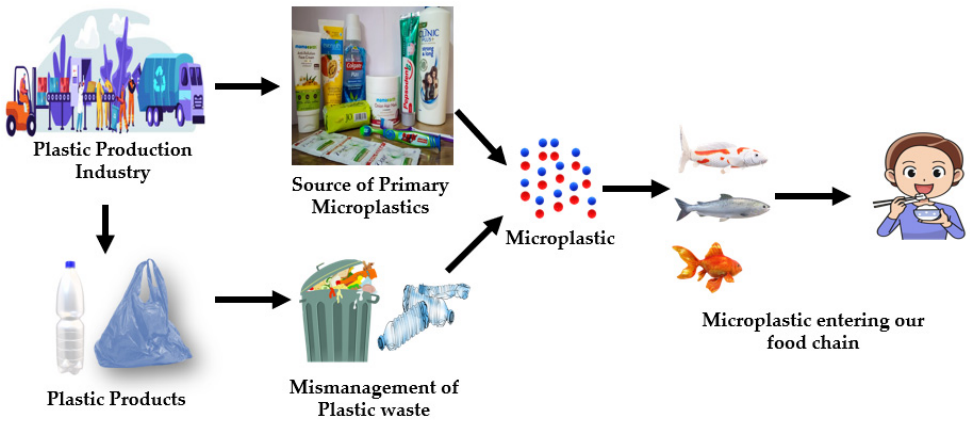

Figure 3. Lifecycle of microplastic: generation to food chain.

4. Microplastic-Related Threat in Bangladesh

Phytoplankton is an important ecological community in aquatic ecosystems, since they provide energy to food webs and play important roles in ecosystem functions such as carbon cycling [19]. The abundance of microplastics in the ocean has a detrimental effect on phytoplankton growth, leading to a change in the phytoplankton community and compromising the stability of the marine ecosystem. Sjollema et al. (2016) examined

the impact of microplastic pollution on the feeding, metabolism, and reproduction system of phytoplankton. They discovered that after being exposed to microplastics (250 mg/L), phytoplankton *Dunaliella tertiolecta's* photosynthetic rate fell by 45%. According to the study, large microplastic pieces floating in the ocean interfere with sunlight transmission, which affects how effectively phytoplankton perform photosynthesis. Microplastics also change the chlorophyll content of phytoplankton. Besseling et al. (2014) discovered that polystyrene nano-plastics inhibited the growth and development of *Scenedesmus obliquus* and significantly reduced the content of chlorophyll synthesis. An experiment conducted by James et al. (2022) revealed that the highest concentrations of microplastics significantly altered phytoplankton community abundance [19].

Marine animals mistake brightly colored microplastics for food. Through the consumption of fish, these microplastics enter our food chain. In a recent study in 2021, 48 fish from 18 species were gathered and analyzed, with 73.3% of the fish affected by microplastics. In all, 107 plastic particles were found in the guts of 35 fish. Salt is historically generated without refining by sun-drying microplastic-contaminated seawater. In 2020, a study found that raw salt had 2105 microplastics/kg, while refined salt had only 283 microplastics/kg. On the other hand, 5 kg of super-refined salt only had 4 microplastics.

In a recent study conducted in 2022, microplastics were discovered in extremely high amounts in sugar and tea bags. A staggering 10.2 tons of microplastic particles could be consumed annually by Bangladesh's 165 million people due to the sugar's high concentration of microplastics. Lesliea et al. (2022) have found microplastics in human blood at a rate of 77% (17 out of 22) [20]. Ragusa et al. (2022) detected microplastics in the human breast milk of 75% of 34 healthy mothers [21].

There are 500–20,000 microplastics per km of seawater in the Bay of Bengal [22]. According to another analysis, 443 microplastic particles were found in 3 marine species from the Bay of Bengal [23]. Moreover, there were 22 distinct microparticles identified in the digestive tracts of 2 shrimp species in the Bay of Bengal.

Because of their tiny size, microplastics provide a high surface area per volume for toxic pollutants to accumulate. Animals are negatively affected, both physically and chemically, by microplastics. Cellular necrosis and inflammation may occur in the digestive system due to microplastics. Microplastics are a complex combination of chemicals that are persistent, bio-accumulative, and hazardous [24]. Some marine organisms have been reported to have abnormal gene expression linked to microplastics they have consumed [25]. Ingestion of microplastics by marine organisms may result in internal abrasion, obstruction in the digestive tract, false satiation, aberrant swimming and lethargy, pathological stress, oxidative stress, reduced immunological response, and liver metastasis [26]. Moreover, photosynthesis-dependent water plants may perish if their sunlight is blocked by plastic accumulations on their surface. Fish and other aquatic organisms may die because of the breakdown of these organics by microorganisms, which in turn reduces the dissolved oxygen in the water. By clogging drains and causing floods, plastic waste impedes the flow of water. The Aedes mosquito, which kills tens of thousands of people each year because of its ability to reproduce in stagnant drain water, thrives in these conditions [5].

5. Sustainable Sampling and Identification Techniques

Quantifying microplastic pollution in our ecosystem helps us comprehend its severity [27,28]. A sustainable strategy must be established and used as soon as possible to assess microplastic contamination in a developing country such as Bangladesh, where plastic mismanagement is a major concern. The studied compartment greatly influences microplastics sampling in the aquatic environment. To investigate the population and distribution of microplastics in various contexts, sampling, extraction/purification, and identification/quantification are carried out [29].

5.1. Aqueous Phase Sampling

The alarming rate of microplastic discovery in the aqueous phase raises concerns about food chain contamination. To quantify and understand the severity of microplastics in the aquatic environment, a sustainable sampling technique must be chosen. In freshwater, microplastic is lower than sediments, but that makes it difficult to filter a representative sample. Neuston or plankton nets are used to gather water samples, and a flow meter measures the volume of each sample. These nets are available with a range of mesh sizes ranging from 50 to 3000 μm, with 300 μm being the mesh size that has been shown to be the most frequent across all investigations. The issue with mesh sizes less than 300 μm is that they are prone to clogging. Dris et al. [30] examined nets with mesh widths of 80 μm and 330 μm and found that the net with the smaller mesh size captured a much greater quantity of microplastics than the larger mesh size net. To avoid this problem, tandem nets with different mesh sizes are used to collect enough water volume and prevent clogging. This aids in the identification of tiny microplastics. Some of the study articles also used a volume reduction pump sampler and grab samples. Pump sampling either manually pumps water or utilizes a motor to pump water through an inline filter. The grab sample approach involves collecting water in a bucket and sieving it in the field. Plankton nets may not be enough for removing fibers and microscopic microplastics from water samples, according to some researchers. As a result, the pump sampling method combined with large-volume filtration is required to obtain trustworthy data.

5.2. Sampling of Sediments

Microplastics have been very resistant to degradation for decades to millennia. They are found in rivers, seas, and other water bodies and accumulate in sediments all over the world due to their unique properties. Due to variations in water volume and the dynamic behavior of water, microplastics in the water compartment may be diluted. However, dilution does not often occur in sediment compartments and, hence, the density of microplastic can be high in the sediment phase. The procedure for the microplastic sampling method varies with the sediment sample that needs to be collected. First, the collection area needs to be selected. Depending on the purpose of the research, the shore sediments are collected either perpendicular to the beach, parallel, or randomly chosen at various distances from the beach. The bulk of the research describes the collection of grid samples from the top sediment layer at depths of 2–5 cm. In other research, the sample is done with respect to the waterbody's lowest flotsam line. Plastic tools should not be used for any kind of microplastic sample because the microplastic formed by the tool will lead to erroneous findings. Tools such as hand spades and stainless-steel spoons are used to gather samples physically. For deeper sediment sampling, different kinds of grabs and corners are suggested. It is vital to remember that sediments obtained using a grabber or a box corer are disturbed; drill cores are used for undisturbed sediments. The whole procedure, from sample preparation to identification, must be assessed thoroughly so that it can provide excellent comparison across investigations.

5.3. Sample Separation and Extraction

The microplastic sample collected is not useful unless the microplastic is separated from the sample, because microplastics are very difficult to differentiate from other particles in the waterbody. For this reason, various techniques for mechanically separating microplastics and removing natural contaminants in the sample prior to the identification of the separated particles have been developed. The technique of density separation is the one that is used most often for the purpose of separating microplastics from the sample. Most microplastics have a density higher than water, and so they do not tend to float on water. For that reason, water-soluble salts are used to increase the density of the water–salt solution and separate the microplastic from the sample. So, in a high-density solution, while the microplastics float, other heavy particles in the water sample tend to settle, and, thus, the microplastic is separated. This method was first introduced by Thompson et al.,

and now the method is being fine-tuned by experimenting with different salts for separation. Saturated NaCl (1.2 g/mL) is the most used solution for density separation, but the most common microplastics such as polyoxymethylene, polyvinyl chloride (PVC), and polyethylene terephthalate (PET) cannot be separated properly by this method because of their high density. The other alternatives for sodium chloride are sodium iodide, sodium polytungstate, and zinc chloride. Even though sodium polytungstate is environmentally friendly and has a specific gravity of almost 1.6 gcm^{-3}, it is rarely used for density separation due to its high price. Zinc chloride is the cheapest option for density separation, and the specific gravity is between 1.6 and 1.7 gcm^{-3}. However, the issue with $ZnCl_2$ is that it is an ecological hazard, and, hence, cannot be discarded easily and so needs to be regenerated. Sodium iodide can also be a viable option due to its high specific gravity (1.6–1.8 gcm^{-3}). However, it is preferred to be used after a pretreatment via elutriation where most of the moderately dense microplastics are separated. For further separation, NaI is used for density separation. The combined approach is necessary due to the high cost of NaI. For density separation, Imhoff et al. developed a method using a microplastic sediment separator (MPSS; the size of 1.75 m), which can successfully recover 95.5–100% of microplastic under the 1 mm–5 mm size range. After density separation, a sieve or filtration is done with different mesh sizes, again to separate the microplastics. For now, density separation is the most used method for microplastic separation, but other methods such as elutriation, oil extraction, centrifugation, magnetic extraction, etc., are in the process of further development.

Some natural material remains once microplastics are separated and must be eliminated. Acidic/alkaline digestion, H_2O_2/reagent, Fenton's, and enzymatic digestion have been studied for this purpose. Chemical digestion, such as acidic/alkaline treatment, can break down microplastics, causing microplastic loss. According to the study, H_2O_2/reagent and Fenton's may also cause microplastic loss. Thus, potassium hydroxide has been suggested as a substitute [31]. Enzymatic digestion, on the other hand, may recover microplastic without damaging it. However, enzymatic digestion is expensive and takes a lot of processing because all enzymes have a preferred temperature and pH. As such, despite its many benefits, it is not a viable alternative and needs more research and development.

5.4. Sample Identification

To determine the microplastic composition and trace down potential sources, the recovered microplastic must be measured and subsequently studied. In earlier studies, microplastics were quantified visually. Larger particles were identified with the naked eye, whereas binocular microscopes or scanning electron microscopy (SEM) was used for small microplastics. However, this strategy frequently leads to erroneous quantification. To improve identification results, vibrational spectroscopy, such as Fourier transform infrared (FTIR) and Raman spectroscopy, are utilized. FTIR is a quick and accurate method, although it cannot detect particles smaller than 10–20 μm. Raman spectroscopy, on the other hand, can detect up to 1 μm, but is an expensive and time-consuming alternative. These methods are predicated on the principle that diverse functional groups of polymer particles may absorb energy and use it in useful ways. The minimal particle size that can be identified by the physical diffraction of the light is a limitation that is shared by both the FTIR-based and the Raman-based approaches. The results from these methods can also deviate because of the fouling, color-coated plastics, adsorption of materials, etc., of the microplastic because they inhibit the absorption of light and excitation of polymer molecules, which is the basis of vibration spectroscopy. That is why an alternative approach is using mass spectroscopy methods for the identification of microplastics. Pyrolysis combined with gas chromatography–mass spectrometry (py-GC–MS) is a mass spectrometry approach that may be used to classify and quantify microplastics in certain arrangements. This is a thermal degradation method that focuses on the determination of polymer compositions and additives. As the sample is combusted for analysis of the microplastic, this is a destructive method and cannot be used for any further analysis. Other than the Py-GC-

MS method, thermal desorption coupled with GC–MS (TDS-GC–MS), thermogravimetric analysis (TGA), SEM coupled with energy dispersive X-ray spectroscopy (SEM-EDS), etc., are used in several studies for microplastic identification [32–34].

6. Microplastic Removal and Degradation Techniques

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. Some of the most promising methods are discussed in the following sections.

6.1. 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 4). 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 [5]. Rummel et al. [35] 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.

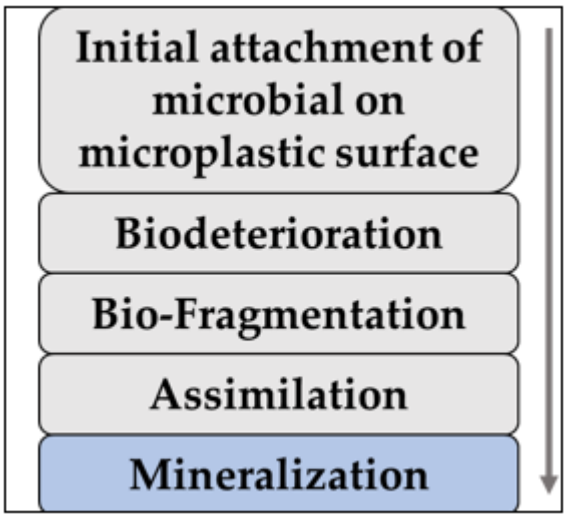

Figure 4. Steps in biotic degradation of microplastics.

Grooves in polyethylene microplastic have shown a tendency to harbor bacterial populations, as described by Zhang et al. [36]. As the Polyethylene (PE) microplastics aged, their rough surfaces and physiochemistry changed, making them a fertile breeding ground for bacteria [36]. 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 [37].

6.2. 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 [38]. 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 [38]. 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 [39]. *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 [40]. Shimpi et al. (2012) achieved a 9.9% biodegradation rate using *Pseudomonas aeruginosa* in only 0.94 months, using 10% of PLA in nanocomposites [41]. Table S1 (Supplementary File) summarizes the biodegradation assay condition strain and rate.

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.

6.3. 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 [42]. 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	[42]
Trichoderma harzianum	Mineral salt medium	3 months	-	40	[43]
Aspergillus tubingensis	Mineral salt medium	0.75 months	37	90	[44]
Phanerochaete chyrosporium	Soil buried (soil mixed with municipal sewage *sludge*)	6 months	-	-	[45]

6.4. Removal of Microplastics by Algae and Macrophytes

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 biotic breakdown of microplastics [46]. 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 [47]. 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 [48]. When algal enzymes in the liquid media come into contact with macromolecules on the surface of the plastic, biodegradation is started [49]. 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, 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%) [50]. 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) [51]. 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.

6.5. 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 [52]. Carbon fixation and nutrient cycling are two of these biofilms' most important roles in aquatic ecosystems [53]. 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 [54–56].

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 [57]. 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 (hydro-

lases) are engaged in the surface modification process [58,59]. 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 our aquatic habitats, more study is urgently required [60]. Data on the breakdown of microplastics in periphytic biofilms are summarized in Table S2 (Supplementary File).

6.6. 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 [61–66]. 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	[67]
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	[68]
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	[69]
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.	[70]

6.7. Degradation of Microplastics by Advanced Oxidation Process

The photocatalytic degradation of organic pollutants is a regular practice [71–77]. 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 5). Degradation of microplastics by advanced oxidation can be accomplished in two ways: 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.

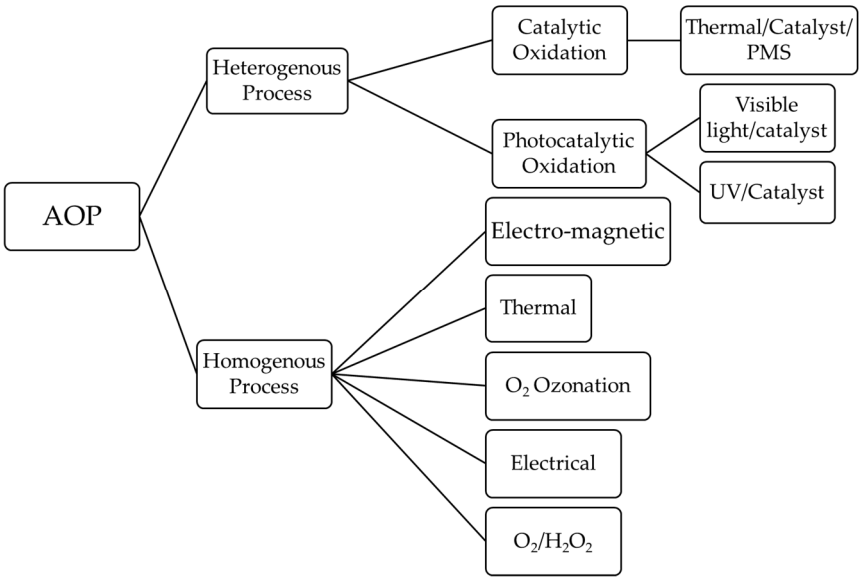

Figure 5. A diagram of the currently available advanced oxidation processes for the removal of microplastics.

6.7.1. Homogeneous AOPs

With their strong oxidation capabilities, AOPs have been able to efficiently break down or mineralize a broad variety of contaminants such as dyes, antibiotics, and persistent organic pollutants (POPs) [78–82]. This section is elaborated in Section S1 (Supplementary File).

6.7.2. Heterogeneous AOPs

Photocatalytic degradation is the major heterogeneous advanced oxidation process. It is a powerful technique for oxidizing pollutants that may be used under ambient conditions. Photocatalysts (such as TiO_2, ZnO, BiOCl, etc.) use the active species (such as OH, O_2^-, and hole (h^+)) created by photocatalysts under UV or visible light to break down microplastics to water and CO_2 [83]. It is now being researched for its ability to destroy microplastics. It has been widely studied and utilized in wastewater treatment facilities to employ photocatalysts to degrade various water pollutants. More study is needed to

improve the technology for use because the process is far more affordable, ecologically friendly, and non-toxic than other methods of deterioration. The mechanism of photocatalytic degradation is the interaction between reactive oxygen species (ROS) formed on semiconductor surfaces and the organic substrate, which breaks the chemical bonds of organic pollutants and causes their entire mineralization (Figure 6). In the photocatalytic oxidation process, the photon is absorbed by the photocatalysts. When the absorbed photon energy (E) exceeds the semiconductor's band gap energy (Eg), the electrons in the valence band (e) will move into the conduction band (CB), producing positive holes (h^+) in the VB [84]. Both species (e^- and h^+) react with OH^-, O_2, or H_2O to form highly reactive oxygen species (ROS), which start the decomposition of organic pollutants and plastics in the first place [85]. The reactions can be depicted in the following manner [86]:

(1) $hv TiO_2 \rightarrow h^+{}_{VB} + e^-{}_{CB}$
(2) $h^+{}_{VB}$ + microplastics$\rightarrow CO_2 + H_2O$
(3) $h^+{}_{VB} + H_2O \rightarrow \cdot OH + H^+$
(4) $\cdot OH$ + microplastics$\rightarrow CO_2 + H_2O$
(5) $O_2 + e^-{}_{CB} \rightarrow O\cdot_2{}^-$
(6) $O\cdot_2{}^- + H_2O \rightarrow \cdot OOH + OH^-$
(7) $2\cdot OOH \rightarrow O_2 + H_2O_2$
(8) $H_2O_2 \rightarrow 2\cdot OH$

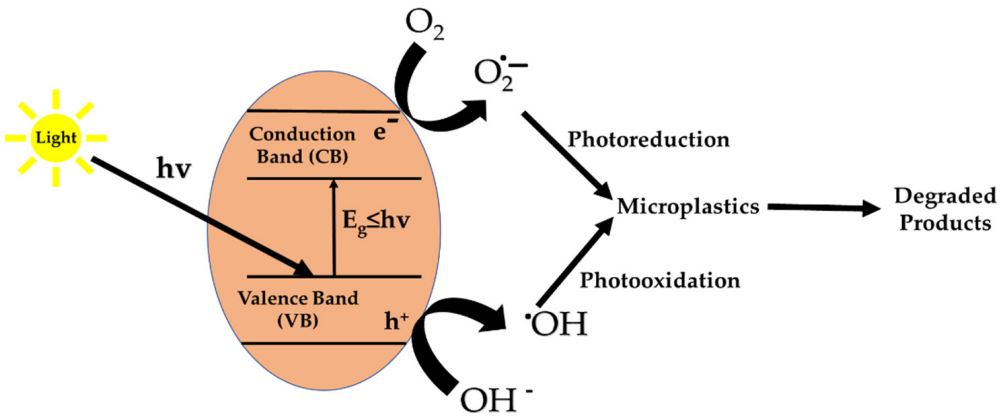

Figure 6. Mechanism for microplastic degradation using photocatalysis method [87].

Here, reactions 2–4 represent the oxidation reaction that takes place in the valence band, and reactions 5–8 refer to the degradation reactions that take place in the conduction band.

TiO_2, a traditional photocatalyst, has drawn the most attention in the breakdown of microplastics when compared to other photocatalysts. Numerous studies have been conducted recently on the photocatalytic degradation of microplastics utilizing TiO_2-based materials. A TiO_2-catalyzed photo process is frequently carried out under UV irradiation due to a comparatively high band gap of 3.2 eV. To degrade polystyrene microspheres and polyethylene powder in the solid state, Nabi et al. created a TiO_2 film as a catalyst that works under UV radiation. Better breakdown performance of polystyrene microplastics was reported utilizing TiO_2 under simulated UV light irradiation compared to minimal mass loss of polyethylene microplastics. They discovered that after 12 h of exposure to UV light at 254 nm, the degradation efficiency of 5 mm polystyrene microplastics reached 44.66% in the liquid phase. Under the same circumstances, this efficiency increased to 99.99% in the solid phase [88]. Two factors can be used to explain this greater conversion rate: (1) the particular surface hydrophilicity may promote the interaction between polystyrene microplastics and TiO_2, and (2) the improved formation and separation of charge carriers may hasten the production of $^{\bullet}OH$ and $O2^{\bullet -}$, which play a key role in the degradation process. To break down polyethylene and polystyrene under UV light, Nabi et al. used titanium dioxide (TiO_2) photocatalysts made in a lab [88]. To enhance the physicochemical properties of the photocatalysts, morphological modifications of TiO_2 were made during

their synthesis. Within 12 h of UV 365 nm exposure, Triton X-100-treated TiO_2 film showed the highest efficiency of 98.4% in the photocatalytic 400 nm polystyrene decomposition. After 24 h of UV 365 nm illumination, the removal efficiency for polystyrene with a size of up to 5 µm was 95.3% for 700 nm polystyrene and 93.5% for 1 µm polystyrene. In addition, 5 µm polystyrene decomposed almost entirely with 99.9% removal efficiency after 24 h when UV 254 nm was used in the experiment. For polyethylene degradation, the result was even more satisfactory. After 36 h of photoreaction, no traceable amount of polyethylene microplastic was observed. Using Raman spectroscopy, the degraded product was found mostly to be CO_2.

Because of their superior optical qualities, high redox potential, good electron mobility, and lack of toxicity, ZnO-based materials are also utilized as photocatalysts [89]. Tofa et al. also investigated the degradation of microplastic using ZnO nanorods, which break down low-density polyethylene using visible light. The efficiency of the nanorods was increased even further by adding platinum nanoparticles [85]. Compared to ZnO nanorods, the ZnO–Pt catalysts demonstrated a roughly 13% greater likelihood of oxidizing LDPE [37]. ZnO-based catalysts also showed high degradation for polypropylene microplastics in water. After 456 h of exposure to visible light, ZnO nanorods reduced the average particle volume by 65% compared to raw polypropylene microplastics [90]. This indicates that ZnO-based nanorods are another viable option for the removal of microplastics from water. Many other photocatalysts were studied over the years, and they are listed in Table S3 (Supplementary File).

6.8. Microplastic Treatment by Coagulation and Flocculation

For wastewater treatment of microplastics, one of the most feasible techniques could be coagulation and flocculation (Figure 7). To avoid exaggeration of information in the manuscript, this section is represented in Section S2 (Supplementary File). This section also contains Table S4.

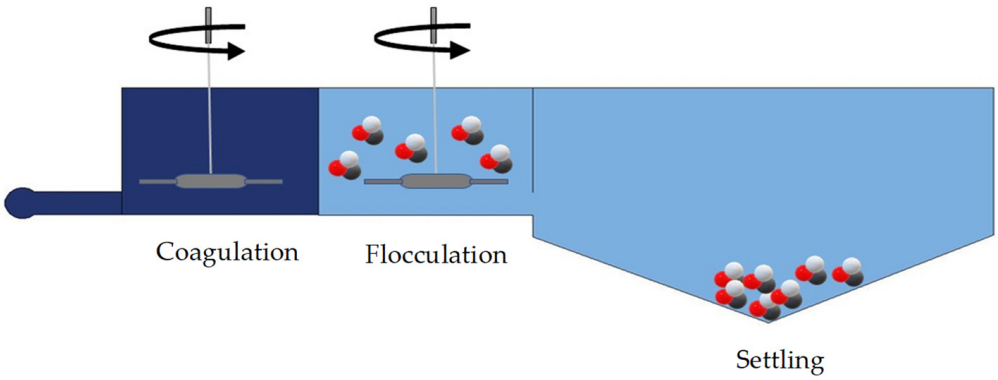

Figure 7. Coagulation, flocculation, and settling of microplastic.

6.9. 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 8). The following reactions occur in the electrocoagulation method [91]:

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

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

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

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

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

The hydrogen and oxygen produced in these reactions help to lift the flocs to the surface [92]. 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 [91]. 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 [93]. Shen et al. showed in their experiment that the Al anode performs better than the Fe anode in the removal of microplastics [94]. 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 [95]. Akashru et al. accomplished removing 98% of microplastics from laundry wastewater with an optimal pH of 9 and a current of 2.16 A [96]. In their most recent work, Akashru et al. could achieve a 100% removal efficiency of polyethylene microplastics [97]. Electrocoagulation is one of the most promising and proven microplastic separation methods, which is also very easy to implement and cost-effective (Table 3).

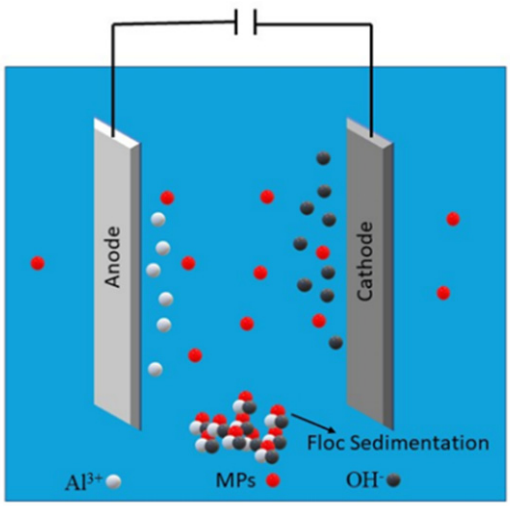

Figure 8. Setup of electrocoagulation.

Table 3. Outcome of different experiments for separation of microplastics using electrocoagulation.

Microplastics Source	Optimal Condition	Electrode	Efficiency	Ref.
Polyethylene microbead	pH = 7.5 NaCl concentration = 0–2 g/L Current density = 11 A/m^2 Time = 30 min	Al	99.24%	[91]
Real wastewater	pH = 4 Current density = 2.88 mA/cm^2	Al	96.5%	[93]
Polyester microplastic	pH = 4 Current density = 2.88 mA/cm^2	Al	98.5%	
Polyethylene	Electrolyte Concentration = 0.05 M pH = 7.2	Al	93.2%	[94]
Polymethylmethacrylate			91.7%	
Cellulose acetate for cigarette butt			98.2%	
PP from disposable surgical masks			98.4%	
Heavy metal and microplastics	pH = 6 Current density = 12 mA/cm^2 Time = 20 min	Al	97.5%	[94]
Laundry wastewater	pH = 9 Current density = 2.16 A Time = 60 min	Fe–Al	98%	[96]
PE	pH = 7 Current density = 20 A/m^2 Time = 10 min	Al–Fe	100%	[97]

6.10. 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 [98]. Two key obstacles to the successful thermal conversion of plastics are their low heat transfer and poor flow diffusion capabilities [99]. Recent advancements have utilized supercritical water to overcome this limiting parameter of traditional approaches and accomplished an effective conversion of microplastics to fuel products (Table 4). Supercritical water functions as an organic solvent that effectively degrades microplastics more energy efficiently under optimized conditions [100].

Table 4. Summary of research on the thermal degradation of microplastics.

Microplastics Source	Working Mechanism	Time	Temperature	Performance	Ref.
PET microplastics	Gasification in supercritical water, artificial seawater	10 min	800 °C, 23 MPa	98% Carbon conversion	[101]
Polycarbonate microplastics	Gasification in supercritical water	60 min	800 °C	50.8% Carbon conversion	[102]
Acrylonitrile butadiene styrene (ABS) microplastics	Hydrogenation induced gasification in supercritical water	60 min	800 °C, 23 MPa	97% Carbon conversion	[103]
Tetra Pak	Hydro-thermal liquefaction	30 min	360 °C, 22 MPa	Bio-oil yields 35.55%	[104]
			420 °C, 20 MPa	Energy recovery efficiency 46.49%	
PET + biomass	Gasification		900 °C	9.2 MJ/Nm^3 lower heating value, 63–66% H_2 molar fraction	[105]

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 [105]. Bai et al. (2019) first conducted the gasi-

fication 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 [103]. 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 [105]. 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 [101].

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.% [104]. 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.

6.11. Recent Developments and Emerging Technologies for Microplastic Removal and Degradation

Microplastic degradation is one of the most studied topics in recent times and many emerging technologies are being developed to be applied on an industrial scale [106]. The biotic and abiotic techniques discussed in this review paved the pathway for further development in this field and narrowed the knowledge gap about microplastic degradation. Membrane bioreactors (MBR) are one of the most promising technologies for microplastic as well as other persistent organic pollutant (POP) and heavy metal removal [107]. Municipal and industrial wastewater treatment is increasingly moving towards MBR technology. MBR technology has been studied for microplastic removal in recent studies, which show a high microplastic removal rate [108]. Twenty flat-sheet UF membrane cartridges (pore size 0.4 m) were utilized in a submerged MBR pilot by Talvitie et al. (2017) [106]. The final effluent had a very low microplastic concentration of 0.005 microplastic particles/L, since the MBR treatment eliminated 99.9% of microplastics from primary cleared wastewater. In 2019, Baresel et al. (2019) investigated a pilot-scale MBR-based wastewater treatment system using UF with membrane pore sizes of 0.2 m, followed by a biofilter with granulated activated carbon as the filter medium [109]. The outcome of the experiment showed the micropollutants were below the detection level and had a 100% microplastic removal rate. The area of research for MBR is now to reduce the maintenance cost and find mechanisms that reduce fouling. In reverse osmosis (RO), also a membrane technology, water is forced through a semi-membrane under pressure. A total of 90% of the microplastics in wastewater can be removed with this method. However, Sol et al. (2020) suggested that this method has a lot of drawbacks, including a high energy requirement, membrane fouling, and waste handling [110]. To remove low-density, non-biodegradable microplastics, dynamic membranes (DM) are a potential technique. This is because DM is inexpensive and simple to maintain, and uses little energy [111]. This technology is based on the formation of a secondary layer of filter cake. The filter cake provides the necessary resistance to filter the microplastics from passing through the membrane. Liu et al. (2020) investigated the effectiveness of a pilot-scale biofilter designed to remove pharmaceuticals, personal care items, and other organic micropollutants from WWTP effluents [112]. The biofilters had a drainage layer of roughly 1.1 m of stone wool, 40 cm of Filtralite®, and 10 cm of granite gravel from top to bottom. The biofilter's microplastic removal effectiveness, from the used

secondary WWTP effluent, was 78.5% in terms of particle number and 88.9% in terms of particle mass.

Another very promising study showed the usage of magnetic fields for microplastic separation. Grbic et al. (2019) advised adding iron-based magnetic nanoparticles to the water sample to trap microplastics before separating the combined particles with the use of a magnetic field [113]. However, very little is known about this process, and it is not applicable to all kinds of microplastics. The study shows a 49–90% removal of PE, PET, PS, and PVC microplastics from the sample. Another strategy is electrostatic separation, which involves sorting particles according to their mass while employing a low-energy charged beam. Felsing et al. (2017) passed microplastic samples through the different electrostatic fields and observed the microplastic particles being attracted to different fields due to their surface properties, and the experiment had a 90–100% removal rate [114].

Tang et al. (2022) reviewed the effect of metal nanoparticle–enzyme complexes on the biodegradation of microplastic. The review concluded that carbon particle–enzyme complexes improve the microplastic-degrading efficiency and recyclability of enzymes [115]. The usage of gold nanoparticles, from the reduction of hydrogen tetrachloroaurate solution by using an aqueous leaf extract of Ananas comosus, for microplastic degradation has been studied by Olajire et al. (2021) [116]. After 240 h of solar exposure, the generated gold nanoparticles demonstrated high photocatalytic degradation efficiency of 90.8% for LDPE film. In order to quickly remove PS-based microplastics from deionized water and synthetic freshwater, Tiwari et al. (2020) synthesized Zn–Al layered double hydroxide (LDH), with maximum sorption capacities of 164.49 and 162.62 mg/g, respectively [117]. Chen et al. (2012) created a melamine foam with a zirconium metal-organic framework coating to filter microplastic dispersion [118]. The system achieved a high microplastic elimination effectiveness of 95.5 $\pm$ 1.2% after three consecutive filtrations.

A study conducted by Tian et al. (2022) revealed that microplastics could be degraded in frozen solution at extremely fast rates [119]. The degradation rate was more than 60 times that of a room-temperature aqueous solution. The oxygen-to-carbon (O/C) ratio can be used to estimate the acceleration rate of PS degradation in the freezing system. In contrast to polystyrene in water (PS-W), where the O/C ratio was lower, the O/C in polystyrene in ice (PS-I) increased to a maximum value within 36 h of freezing at -20 °C with 2.5 mg L^{-1} PS. Additionally, it was discovered that feeding PS-I more dioxygen caused the O/C ratio to rise, which suggests that dioxygen promotes degradation at freezing temperatures. Surprisingly, the increase in the O/C ratio within 24 days is higher than that of heat-activated $K_2S_2O_8$ treatment and other major artificial degradation treatments. This study attributed the accelerated degradation to an unusual oxidizing reaction, in which microplastic particles are stimulated to an excited state and react with concentrated dioxygen to specifically produce $^1O_2$, which only takes place in the small liquid layer between ice crystals. This research also revealed that the highly active $^1O_2$ species initiates oxidation reactions that lead to further degradation of microplastics.

Herbort et al. (2018) found a new method to remove microplastics from water as an alternative to conventional flocculants by using sol-gel-induced agglomeration reactions to form larger particle agglomerates [120]. Sturm et al. (2021) used a mixture of organosilanes to get a high degree of PP- and PE-removal efficiency (97.5–99.4%) [121]. The sol-gel method did not produce any dissolved organosilanes, which further ensured that no organosilanes escaped with the effluent of the process and increased the reliability and applicability of the process.

Wang et al. (2022) have developed a robot made of polyurethane that can eat microplastics, which has seen success in shallow water [122]. It is 13 cm in size and has a swimming speed of up to 2.67 body lengths per second. As polyurethane is biodegradable, it will not be harmful even if accidentally consumed by a fish. The sampling of microplastics in the marine ecosystem can be accelerated by this technology.

7. Management of Plastic Wastes for the Prevention of Secondary Microplastic Generation

Plastic wastes provide a significant risk to the environment due to the fact that solar radiation, wind, and other environmental factors may cause the corrosion of mismanaged plastic wastes, which then results in the release of a large number of microplastics into the environment. Even though landfilling is the most common method for disposing of plastic garbage, there is still a possibility of harmful effects on the ecosystem due to the slow release of microplastics and other dangerous compounds. The emission of greenhouse gases is one of the unavoidable outcomes of incinerating plastic waste, even though this process has the potential to reduce plastic pollution. Every ton of waste that falls into this category includes roughly 79% combustible carbon, which results in significant emissions of greenhouse gases equal to around 2.9 tons of CO_2 [123]. During open burning, in addition to the emissions of carbon dioxide (CO_2), other harmful gases such as carbon monoxide (CO), nitrogen oxide (NO), and sulfur dioxide (SO_2) can also be emitted, along with a significant amount of ash that migrates and floats in the atmosphere, causing severe ecological damage. So, recycling is seen as the optimal and definitive solution for addressing the issue of microplastics that exists now and assuring the long-term viability of the usage of plastics. The Ministry of Environment, Forest, and Climate Change conducted an inquiry, the results of which led to the discovery that plastic and foam plastic wastes comprised 76% of the total rubbish collected from four sea beaches in the cities of Cox's Bazar and Chittagong. Table S5 represents waste collected from four sea beaches of Cox's Bazar and Chittagong.

In these alarming circumstances, time-proper steps were taken for effective plastic waste management to prevent the generation of secondary microplastics. Recycling plastic waste may aid in achieving the goal of green ecology. Additionally, it would help conserve natural resources, save energy, reduce various forms of pollution, and ease the burden of garbage disposal on the government [124]. Despite the fact that collecting plastic wastes or solid wastes comprises between 80 and 90% of the total budget for plastic waste management, open burning and landfills remain the primary methods used in disposing of plastic wastes or other solid wastes in Bangladesh [125]. Plastic waste management in Bangladesh can be broadly divided into four stages, which include collection, sorting, cleaning, and recycling (Figure 9) [4].

Waste collection is the first step in managing plastic waste. It requires a lot of labor and can be carried out from a variety of locations, including private residences, trash cans, garbage trucks, and landfills for plastic waste [126]. It is vital to ensure the cost-effectiveness of this collection process. Following the manual gathering of these trashes, primary traders or garbage pickers perform the preliminary selection process.

The second step is sorting waste. The needs and preferences of the potential manufacturers to whom it may be sold determine how plastic garbage is sorted. Depending on the color and kind of plastic, recycling can be done in a variety of ways. Different sorting techniques exist, including manual sorting, methods based on density, and selective dissolution sorting, which are practiced in Bangladesh [126]. Manual sorting is done by experienced personnel who have trained eyes [127]. In density-based sorting methods, float sink tanks or hydro-cyclones are used to sort objects. For substances such as polyolefins that have comparable densities, this approach is not appropriate. Additionally, since PVC and PET essentially have the same specific gravity, it is hard to separate them using this method [128]. In sorting by selective dissolution, the sorting operation is carried out by batch dissolution of mixed plastics utilizing solvents. By continuously observing the temperature and choosing the solvent, complete plastic separation is possible [126].

The cleaning process consists of two phases, i.e., washing and drying. Washing can be done before, after, or even during sorting at various stages of the reprocessing. In Bangladesh, both manual and mechanical washing is common. The manual washing is carried out in bathtubs, oil drums, or specially constructed basins. When the plastic trash is greasy, caustic soda, detergent, or hot water with soap is used to improve the cleaning [129]. On the other hand, mechanical washing is performed using blow plastic. In a mechanical washing system, a motor is attached to a water-filled basin, and the motor powers a set of

paddles at low speed. Since there are two ways of washing plastic waste, the methods for drying the washed items are different as well. In the case of manual drying, the cleaned plastics are laid out in direct sunlight. However, for mechanical drying, washed plastic items are dried using a dryer that operates at a very high temperature [4].

The most important part of plastic waste management is recycling. Based on the adopted approach, recycling can be categorized into two types, which include traditional recycling and advanced recycling [130]. The traditional recycling technique is the most common one, which is also known as mechanical recycling. Thermoplastic materials can be recycled using this technology. Melting plastics and turning them into new plastic goods is the main idea behind this process. Recyclers first melt the plastic before using a technique called injection molding to turn it into new items [130]. In comparison, advanced recycling is a chemical-based method that breaks down plastic materials [131]. This method is made up of three different techniques, which include pyrolysis, chemical recycling, and gasification. Pyrolysis is a method for converting plastic waste into crude oil. Chemical recycling is basically a process where a polymer is converted into a monomer that can be used to make new products such as nylons. Gasification, on the other hand, converts plastic to gas. Producers use the gas generated by this process to generate electricity [132]. The recycling procedure is determined by the facilities available and the product that a recycler wishes to produce. However, the plastic recycling process can also be divided into four major types, i.e., primary, secondary, tertiary, and quaternary [133].

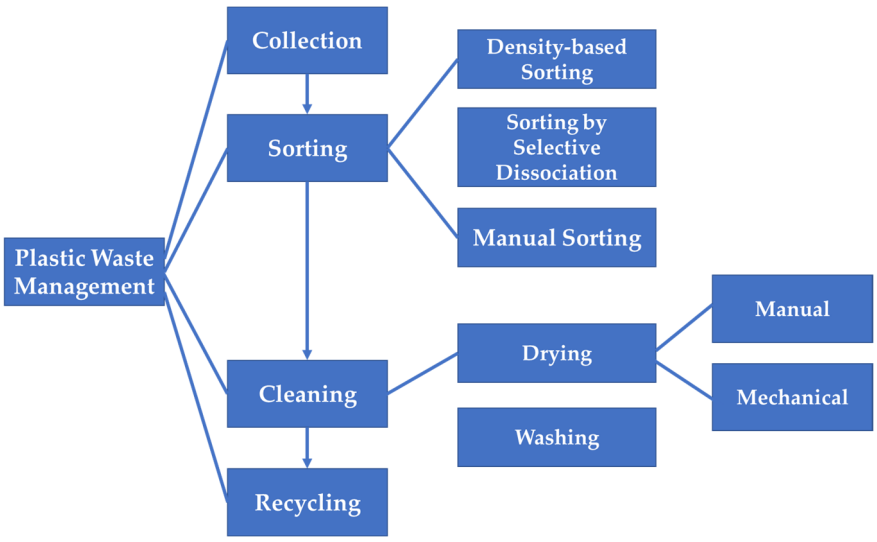

Figure 9. Various stages of waste management [134].

Using a primary recycling strategy, which is implemented in-plant and involves incorporating scrap materials directly into products of good quality without any pretreatment, it is possible to recycle scrap materials in a closed loop. Mechanical recycling is another name for the process of secondary recycling, which entails sorting, breaking, and extruding streams of mixed plastic rubbish to create new plastic goods. The first depreciation of a product's physical characteristics may be avoided by exercising stringent control over the circumstances in which the product is processed [135]. However, the gradual thermo-oxidative or hydrolytic scission of polymers may lead to a loss in quality and performance, which limits the profitability of mechanical recycling. The primary objective of tertiary recycling is to use chemical processes for the purpose of converting plastic wastes into oil or hydrocarbon components, or high-purity monomers by chemical bond scissions. These components or monomers can then be repurposed as raw materials and incorporated into plastic production lines, while the purpose of quaternary recycling, which is often referred to as energy recovery, is to generate multi-carbon products that have high-yielding heating values principally via the burning of plastic wastes.

8. Recommendations

In 1990, the Environment and Social Development Organization (ESDO) launched the first organized effort to combat plastic pollution. To combat plastic's impact on the environment, the Ministry of Environment and Forest (MoEF) proposed banning polythene in 1993, but the proposal was shot down by lawmakers. Finally, Bangladesh became the first nation to prohibit polythene on 1 January 2002 in Dhaka city, and on 1 March 2002, manufacturing and usage of polythene bags were outlawed across the country.

In 2002, an amendment was made to Article 1 of the Bangladeshi Environmental Conservation Act. The production and use of polythene bags were outlawed by Rule 6ka of Clause 5 of Section 9. Rule 6ka establishes the following penalties and punishments for infractions: for production, import, and marketing: ten years in prison, one million takas fine, or both; for sale, an exhibition for sale, storage, distribution, transportation, or use for commercial purpose: six months in prison, ten thousand takas fine, or both.

The legislation, however, has not been successful in reducing plastic use. In 2018, Transparency International Bangladesh (TIB) advocated for more law enforcement to crack down on the illicit production, sale, and usage of plastic. To limit the amount of waste material and specifically plastic garbage, the Ministry of Environment and Forests devised the National 3R (reduce, reuse, recycle) strategy for waste management. A ruling from the Supreme Court mandated a ban on single-use plastic in all coastal areas and lodging establishments by 2020. Nonetheless, the stunning news is that the present 5% tariff on polythene and plastic would be eliminated from the planned budget for 2022–23. There is now no plan in place to address the widespread problem of plastic pollution in water, much less the much smaller problem of microplastic contamination in water. The following points are recommended to fight against aquatic microplastic pollution:

1. Create a national policy for effectively managing plastic trash and preventing it from entering nature.
2. Improve municipal waste management systems to separate plastic waste at its source.
3. Through media ads and government and non-government actions, raise end-users' consciousness of plastic's harmful consequences.
4. Encourage entrepreneurs who recycle and reuse plastics to receive tax breaks and subsidies.
5. Provide national recognition and funding for alternatives to plastic products, such as jute bags, paper cups, bamboo straws, etc.
6. From the importation of raw materials through the sale of finished goods, charge a substantial tax on enterprises involved with plastic, causing people to avoid plastic items due to their high cost.
7. Impose strict bans on the use of single-use plastic in river transportation such as launches, ships, and tourist spots near rivers or lakes to prevent the direct discharge of plastic into the water.
8. Improve municipal wastewater treatment plant capability to gather more plastic.
9. Microbeads and microplastic usage in personal care products should be legally prohibited in Bangladesh.
10. Urgent legislation should be passed forbidding the manufacturing, use, and import of all single-use plastics.
11. Research: Research is the first and most important step to minimizing aquatic microplastic pollution. The following outline will help to proceed with conducting research in a systematic way:
    (i) The government should create a strategy to control microplastics at the source and in the environment.
    (ii) Identification and characterization of microplastics in surface water and sediments of Bangladesh's terrestrial and aquatic environments.
    (iii) Risk assessment of microplastics in terrestrial and aquatic biota based on concentrations, exposure times, forms, sizes, and tropic level transmission.

(iv) Risk evaluation of plastic additives and watery chemical and biological contaminants on biota and tropic transfer.
(v) Clarification of the hydrodynamic conditions (winds, currents, beach direction, etc.) that affect microplastic transport and movement, as well as their spatial and seasonal change.
(vi) Characterization and diversity study of microbial biofilm communities colonizing plastics and microplastics.
(vii) Standardization and harmonization of microplastic sampling, extraction, analysis, and identification to compare global findings.

Most plastic awareness programs are limited to educated people only. Poor, illiterate people do not even consider plastic as dirt; they think it is okay to throw plastic away into water bodies. So, a lot of mass awareness programs should be planned and executed among illiterate people.

9. Conclusions

The situation of aquatic microplastic contamination in Bangladesh is deteriorating continuously. The existing management approach cannot prevent plastics from entering the environment. There are several opportunities for feasibility studies of various microplastic degrading techniques to mitigate future negative effects. To promote the circular economy, authorities should put greater emphasis on plastic recycling. Energy recovery from plastic garbage might be a practical solution to improve plastic pollution conditions. In conclusion, it can be said that microplastic, an overgrowing threat to humankind, should be in our focus in the days forward, and a solution to microplastic pollution should be proposed and implemented immediately for the major sources of microplastic leakage. More studies should be done by researchers and the knowledge of the harmful impact of microplastic should be widespread to create awareness about this matter. This study is done with the help of future researchers, and so all the available information about microplastic degradation and management is reviewed in this paper.

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