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Review

Microplastics in Water: A Review of Characterization and Removal Methods

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Abstract: Microplastics (MPs), as an emerging persistent pollutant, exist and accumulate in the environment, which has garnered them considerable global attention. While the origin, dispersion, distribution, and impact of MPs have been extensively documented, the characterization and removal strategies for MPs present ongoing challenges. In this literature review, we introduce in detail the advantages and disadvantages of seven characterization methods, from macroscopic to microscopic, from visual observation to microscopic characterization, and discuss their scope of application. In addition, 12 treatment schemes were summarized from the three treatment directions of physics, chemistry, and biology, including filtration, adsorption, extraction, magnetic separation, oil film separation, Fenton oxidation, electrochemical oxidation, persulfate advanced oxidation, photocatalytic oxidation, coagulation, electrocoagulation, foam flotation, anaerobic–anoxic–aerobic activated sludge, enzymatic degradation, bacterial degradation, and fungal degradation. Additionally, we present a critical assessment of the advantages and drawbacks associated with these removal strategies. Building upon the findings of our research team, we propose a novel approach to degrade MPs, which combines three-dimensional electrocatalytic oxidation technology with persulfate advanced oxidation technology. This advanced oxidation technology achieves 100% degradation of antibiotics in water, can degrade large molecules into environmentally harmless small molecules, and should also be a very good strategy for the degradation of MPs. Compared with two-dimensional electrocatalytic technology, the degradation efficiency is higher and the degradation cost is lower This review intends to propel further advancements for addressing the issue of MP pollution.

Keywords: microplastics; removal technologies; characterization methods

Citation: Li, Y.; Chen, P.; Tang, Y.; Yang, Y.; Zhou, C.; Bu, J.; Zhong, S. Microplastics in Water: A Review of Characterization and Removal Methods. *Sustainability* **2024**, *16*, 4033. https://doi.org/10.3390/su16104033

Academic Editor: Saif Uddin

Received: 29 March 2024
Revised: 27 April 2024
Accepted: 1 May 2024
Published: 11 May 2024

1. Introduction

1.1. Definition

In the past 70 years, the global production of plastic has exceeded 8 billion tons, and this number is still increasing rapidly. According to statistics, by 2050, the global annual production of primary plastic may exceed 34 billion tons. Plastics undergo a gradual decomposition process, resulting in the formation of small plastic fragments, through physical, chemical, and biological mechanisms. These fragments can be categorized into various sizes, such as megaplastics (more than 50 cm), macroplastics (5–50 cm), mesoplastics (0.5–5 cm), microplastics (MP, 0.1 μm–5 cm), and nanoplastics (NP, less than 1 μm) [1].

As far back as 2004, Thompson et al. from Plymouth University made a groundbreaking discovery of plastic debris in marine water and sediment, coining the term "microplastics" (MPs) [2]. MPs are defined as plastic fragments and particles with a diameter less than 5 mm [3–5]. In 2013, the Marine Waste Technical Group of the European Marine Waste Management Agency proposed a classification of microplastics into small microplastics (SMPs, 1 μm–1 mm) and large microplastics (LMPs, 1–5 mm) [6,7]. The particle size of MPs can vary from a few microns to a few millimeters, forming a heterogeneous mixture of plastic particles with different shapes, making them nearly imperceptible to the naked eye [8,9]. They are often described as the "PM2.5 of the sea", drawing a vivid analogy to airborne fine particulate matter.

1.2. Sources

Gaining insight into the origins of MPs was a crucial aspect of comprehending their formation. Plastic waste, encompassing packaging materials (PE, PP, PS, PVC, PET, PC, PEP, PMMA), medical devices (PVC, PE, PP, PS, PTFE), and agricultural films (PE, PVC, EVA), emerged as a significant contributor to the presence of MPs [10]. The degradation of plastic waste, whether through natural processes or human intervention, yielded fragments teeming with MPs, resembling detritus or scum [11–13]. Cleaning and washing products (EVOH, PU, PS, PP, PC) in daily life were also one of the sources of MPs [14–16]. Notably, Dris et al. discovered that clothing released a substantial amount of fibers (PTT, PET, PBT, PA, PAN, PVA, PU, PP, PVC, etc.) during the drying process, with natural drying methods exacerbating fiber shedding compared to machine drying [17]. In addition, the wear and erosion of textiles and microfibers from tire usage constituted another significant wellspring of MPs [18,19].

1.3. Discharge, Distribution, and Transportation

The migration of MPs occurs through surface runoff and atmospheric deposition, representing significant pathways for their dispersal. All kinds of plastics existing in soil and water will degrade into microplastics of different sizes through photolysis, weathering, hydrolysis, and microbial degradation. Microplastics circulate and transfer in water, soil, and the atmosphere through surface runoff, underground infiltration, atmospheric deposition, and atmospheric flow (Figure 1). Regrettably, sewage treatment plants within urban centers cannot handle these pollutants, leading to their ultimate accumulation within the vast expanse of the ocean [20,21]. Due to the characteristics of microplastics, such as being thin, small, and easily adsorbed, the introduction, migration, and transportation of microplastics in water are the fastest. Microplastics in land waters or oceans are suspended in the atmosphere by air currents and then moved around. Urban activities and the utilization of everyday household items play a pivotal role in the widespread distribution and transportation of MPs on land. From the wear and tear of tires to the flaking of paint, from plastic manufacturing to the textile industry, and from cosmetics to exfoliating agents and washing products, these seemingly innocuous elements all contribute to the proliferation of MPs [22,23].

Of particular significance are the superfine fibers emanating from our everyday apparel and bedding, which are released into the air and subsequently emerge as the primary source of atmospheric MPs. Under the influence of rainwater, these minute microfibers settle upon the land, infiltrating rivers and ultimately finding their way into the depths of the ocean [24]. The Philippines, India, Malaysia, China, and Indonesia are the top five countries responsible for annual marine plastic emissions. Rainfall, acting as a potent driving force, facilitates the transportation of MPs, while also serving as a conduit for their migration from the surface to the waterways. Astonishingly, the research team led by Leslie et al. made a groundbreaking discovery, detecting microplastics within the blood of human volunteers for the first time, further underscoring the omnipresence of these pollutants in our daily lives [25].

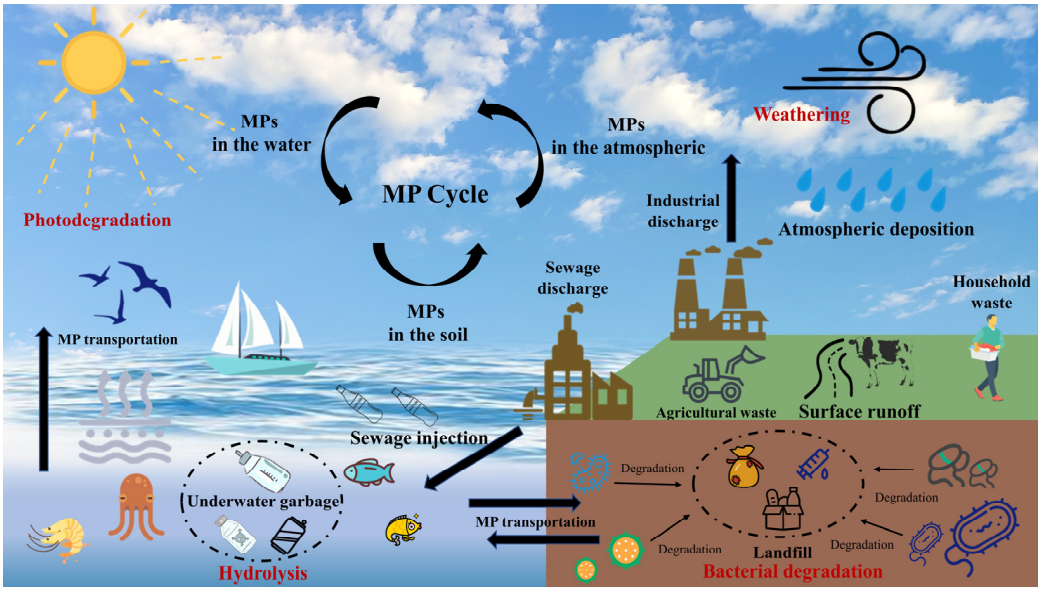

Figure 1. Cyclic process of emission, transfer, and decomposition of MPs.

Plants and animals, through a variety of pathways, absorb MPs from the atmosphere, soil, and water, perpetuating the continuous transfer and enrichment of these contaminants throughout the intricate web of the food chain. A momentous revelation emerged from the research conducted by Aves et al.'s team, as they detected microplastics within newly fallen snow in Antarctica, shedding light on the far-reaching extent of MPs' influence [26]. Thus, it becomes evident that MPs have permeated every facet of our existence.

1.4. Negative Effects

MPs in the environment affect biome composition and nitrogen cycling. Numerous studies conducted both domestically and internationally have revealed the propensity of MPs to permeate the very fabric of our ecosystem, infiltrating crops, fish, earthworms, chickens, bees, marine, and terrestrial animals, as well as humans, thereby impeding their growth, development, and reproductive capabilities [27,28]. MPs can adsorb other pollutants, and these vagabond MPs themselves and their adsorbed pollutions are easily consumed by mussels, zooplankton, and other organisms residing at the lower echelons of the food chain, and possess an inherent resistance to digestion within the confines of the stomach. Consequently, they accumulate and settle within the delicate tissues and bodily structures of humans, unleashing an onslaught of maladies and even death in their wake [29–31].

2. Characterization of MPs

The classification of MPs encompasses two distinct categories: primary MPs and secondary MPs [32,33], as illustrated in Figure 2. Primary MPs pertain to plastic granules derived from industrial products that find their way into the aquatic environment via rivers and sewage treatment plants. Examples include the minute particles encapsulated within cosmetic formulations, as well as plastic and resin granules utilized as raw materials in industrial processes. On the other hand, secondary microplastics arise from the physical, chemical, and biological transformations undergone by larger plastic waste, resulting in fragmentation and volume reduction [34–36].

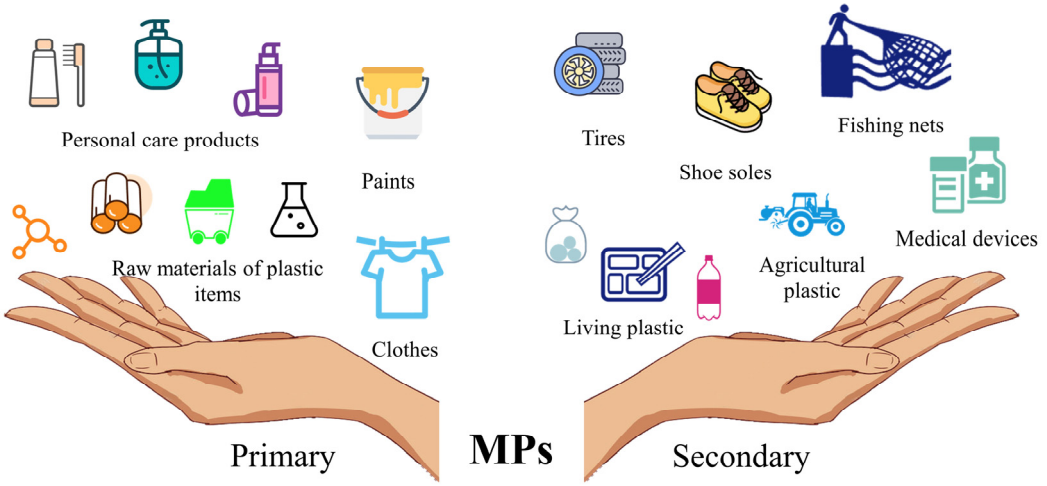

Figure 2. Sources of primary and secondary MPs.

Microplastics (MPs) have gained recognition as a burgeoning category of pollutants worldwide, warranting diligent attention from researchers in terms of detection and characterization [37,38]. Characterizing MPs poses several challenges, primarily due to the complex composition of environmental samples, which often comprise diverse substances that are difficult to differentiate from MPs. Consequently, elucidating the morphological attributes of MPs stands as a significant obstacle within the realm of MP research [39,40]. Presently, prevailing methods of characterization encompass visual discrimination, microscopic discrimination, scanning electron microscopy (SEM), atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FT-IR), Raman spectroscopy, and pyrolysis analysis [41–43].

2.1. Visual Discrimination

The method of visual identification primarily targets larger microplastics, ranging from 1 to 5 mm in size, which are predominantly found in coastal areas. This approach typically involves the use of tweezers and trays to directly separate and identify the particles [44]. However, the presence of numerous organic and inorganic substances in the general sample, which closely resemble the size and appearance of plastics, makes it challenging to differentiate them accurately. Occasionally, smaller but colorful plastics can be identified visually [45]. It is worth noting that naturally occurring fibers tend to produce white and transparent microplastics, while synthetic fibers often exhibit vibrant colors [46]. Although the visual method is straightforward and convenient, it can lead to significant errors due to the similarity between plastics and other substances in the sample. De Witte et al. devised a technique that involved touching the sample with a heated needle tip, allowing them to determine if the material was plastic based on whether it melted or curled. However, this method has its limitations, as the properties of certain plastics may not change unless the temperature of the needle tip is sufficiently high. Additionally, this approach is most effective when specific characteristics of the plastic are known beforehand [47]. While the visual method is easy to implement, it is prone to substantial errors.

2.2. Microscopic Discrimination

Traditional optical microscopy has been widely employed for the identification of microplastics measuring several hundred microns in size [48]. By enlarging the image, this method offers valuable insights into the surface texture and structural characteristics of the particles, enabling the differentiation of plastics from other materials with similar appearances. While this technique is capable of detecting smaller microplastics, accurate discrimination becomes challenging when dealing with colorless and shapeless particles measuring less than 100 μm [49]. It is worth noting that previous studies have uncovered

a significant discrepancy of up to 20% in the classification of plastics using microscopy, with transparent particles accounting for 70% of the misidentified samples, a finding later verified through spectral analysis [50].

2.3. Scanning Electron Microscopy

Scanning electron microscopy (SEM) employs a powerful electron beam to illuminate the sample, initiating interactions that generate secondary electrons. These electrons serve as valuable signals, revealing the intricate morphology of the specimen [51]. SEM yields high-resolution, magnified images of plastic particles, enabling the discrimination of minute microplastics and organic particles [52]. In a comprehensive study, Cooper et al. utilized SEM to meticulously examine the morphological characteristics of various plastic fragments collected from beach environments. Their meticulous observations confirmed that both mechanical and chemical weathering processes occurring on the shoreline induce the development of cracks, grooves, and notches on the surfaces of plastic fragments. Over time, these alterations contribute to the fragmentation of plastics into smaller particles [53]. Nevertheless, this technique is not without its challenges. For instance, samples must be examined in a vacuum environment, restricting the range of applicable specimens. Moreover, SEM provides only two-dimensional plane images, lacking height and directional information. Consequently, liquid samples cannot be observed using this method [54].

2.4. Atomic Force Microscope

Currently, the examination of microplastics (MPs) through the use of atomic force microscopy (AFM) allows for the detection of minute particles, reaching a minimum size of several microns, while providing a genuine three-dimensional representation of the surface topography [55]. Moreover, this method circumvents the need for special sample preparation and operates effectively under normal pressure, even in liquid environments. Demir-Yilmaz et al. employed atomic force microscopy to investigate the biophysical attributes of MPs, revealing their nanostructure characterized by rough, irregular, and hydrophobic surfaces [56]. By integrating AFM with microfluidics [57], it becomes possible to precisely assess the interaction between microalgae and MPs, while accurately determining their hydrophobic properties. Nevertheless, AFM presents limitations, including a restricted imaging range, slow imaging speed, and susceptibility to probe interference [58].

2.5. Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy (FT-IR) boasts numerous advantages, including its non-invasive nature, uncomplicated sample preparation, and qualitative precision, rendering it a favored technique for the structural analysis of materials [59,60]. Employing graphical analysis, FT-IR can circumvent false-positive outcomes in the absence of microplastics (MPs) and minimize misidentification of MPs lacking distinct coloration or material characteristics [61]. By utilizing infrared radiation to detect molecular vibration frequencies and distinct functional groups, FT-IR provides insight into the weathering degree of MPs through oxygen-demanding bonds. Nonetheless, this method is susceptible to interference from water and organic pollutants, posing challenges in detecting oxidation functional groups of MPs and MPs with diameters below 20 microns. These factors, whether directly or indirectly, impact the qualitative efficacy of FT-IR in identifying MPs [62]. To enhance the recognition accuracy of MPs, Wander et al. ingeniously combined Principal Component Analysis (PCA), a statistical feature extraction method based on minimizing the mean square error, with FT-IR, effectively reducing the data dimensions of MP samples and visually depicting particle familiarity [63,64]. In addition to identifying sample composition, FT-IR also permits quantitative analysis of MP quantities [65].

2.6. Raman Spectrometer

Raman spectrometry is an exquisite technique of vibrational spectroscopy, which relies on the captivating phenomenon of inelastic light scattering to bestow upon us mesmerizing vibrational spectra. This method has found wide application in the meticulous analysis of minute particles [66,67]. Not only does Raman analysis have the capability to unravel the identity of these particles, but it also holds the power to divulge precious insights into the composition of the samples under scrutiny. Astonishingly, the Raman spectrometer boasts remarkable sensitivity, capable of detecting particles as minuscule as 1 μm in size [68]. What further elevates the allure of this technique is its non-contact nature, which ensures the preservation of the pristine structure of the samples, and, in turn, facilitates subsequent analyses [69]. In contrast to its counterpart, FT-IR, Raman spectroscopy triumphs in the identification of both organic and inorganic additives and coatings, in addition to the matrix polymers. However, it is worth noting that the Raman signal from the matrix can easily be obfuscated by the more pronounced scattering from additives and coatings, rendering their identification a formidable task. Meanwhile, the presence of fluorescence in the samples poses the most formidable challenge to Raman detection. Infrared spectroscopy, on the other hand, proves to be a more suitable tool for the identification of additives and coatings, particularly when confronted with samples that exhibit fluorescence [70]. Nevertheless, it is essential to acknowledge that the efficacy of this characterization method is contingent upon the stringent demands imposed upon the samples.

2.7. Thermal Cleavage

Thermal cleavage analysis, an emerging spectroscopic technique that exploits the thermal stability of samples to discern changes in their physicochemical properties, has emerged as a promising tool for the identification of microplastics (MPs) [71]. The combination of thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) has proven effective in discerning polyethylene (PE) and polypropylene (PP) [72]. By integrating TGA with solid-phase extraction (SPE) and coupling it with thermal and inspiratory chromatography–mass spectrometry (TDS-GC-MS), one can harness the full detection potential of multiple approaches, revealing intricate details with exceptional resolution [73]. This methodology offers the advantage of direct identification of samples and mixed polymers, representing a relatively straightforward and expeditious means of analysis. However, it is crucial to note that this approach is inherently destructive, limiting its utility in chemical characterization alone, thereby precluding the acquisition of crucial information regarding the morphology, size, and quantification of microplastics [74]. Thus, ongoing efforts to refine and optimize thermal analysis are imperative to establish it as an efficient and widely adopted technology for microplastic detection.

3. MP Treatment Technologies

Currently, a plethora of approaches exist for addressing microplastics (MPs), categorically classified as physical, chemical, and biological treatment techniques (Figure 3). The physical methods encompass various strategies such as filtration [75], adsorption [76], extraction [77], magnetic separation [78], and oil film separation [79]. On the other hand, the chemical methodologies encompass Fenton oxidation, electrocoagulation, advanced oxidation technologies, coagulation, and foam flotation. Lastly, the biological approaches encompass the anaerobic–anoxic–aerobic activated sludge method, enzymatic degradation, bacterial degradation, and fungal degradation [80–85].

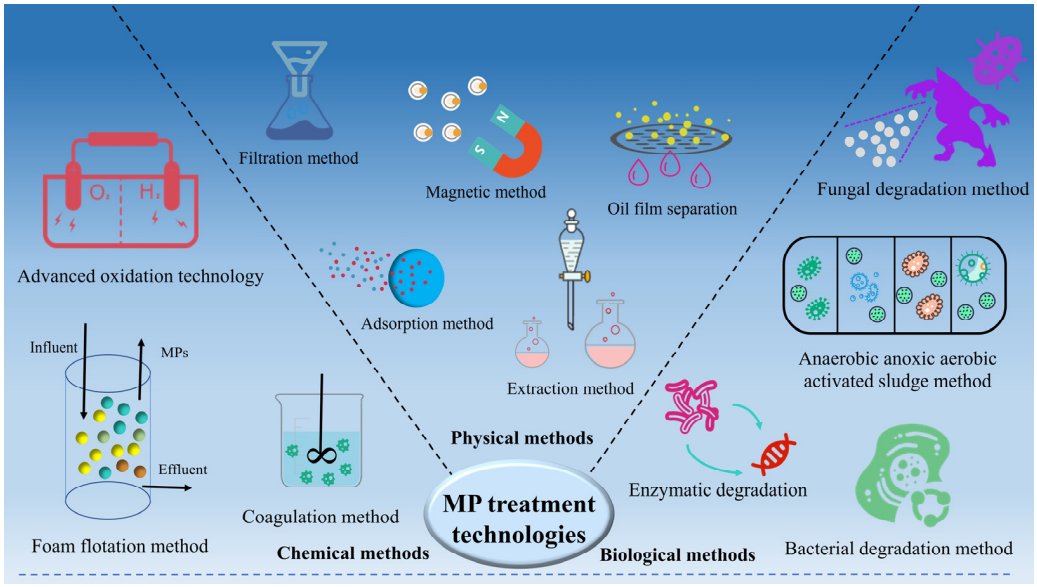

Figure 3. MP treatment technologies.

3.1. Physical Methods

3.1.1. Filtration Method

The process of filtration involves the interception of solid particles and other substances within a suspension, thereby separating them from the liquid medium. In the early stages of microplastic (MP) separation, the filtration method emerged as a widely employed technique due to its simplicity and rapidity of operation [86,87]. For instance, Tadsuwan et al. utilized a series of filters ranging from 5 mm to 0.05 mm in size to eliminate MPs from wastewater obtained from Thai municipal treatment plants, achieving a removal rate of 33.33% [88]. Wang et al. employed a biochar filter to effectively eliminate MPs with a diameter of 10 µm, resulting in a remarkably efficient removal exceeding 95% [89]. Similarly, Ziajahromi et al. employed gravel as a filtering medium to extract MPs from sludge and biosolids obtained from Australian wastewater treatment plants, resulting in a removal rate of 69–79% [90]. While the filtration method remains a common strategy for managing MPs, it is worth noting that it can generate smaller MPs, thereby augmenting the challenges associated with post-processing. This method only collects microplastics and does not achieve the purpose of eradication. Moreover, this method has higher requirements for the filter, and too high a cost will be invested if the processing volume is too large. In future studies, researchers should design more advanced filters to increase throughput and reduce treatment costs.

3.1.2. Adsorption Method

The adsorption technique entails utilizing a porous solid adsorbent to capture one or more types of adsorbates from the water sample's surface. Subsequently, appropriate solvents, or heating or blowing methods, are employed to release the adsorbate, thereby achieving the objective of separation and enrichment. Adsorption is frequently employed for the elimination of water pollutants [91–93]. Currently, adsorption is commonly employed for the removal of microplastics (MPs) from water [94,95]. For example, Wang et al. fabricated a natural biodegradable sponge material with exceptional mechanical properties by utilizing plant protein as a chemical crosslinking agent. A polystyrene MP waste solution was prepared using deionized water. The adsorbent's removal efficiency reached 38% with an adsorption time of 10 s. In simulated wastewater, the material exhibited an adsorption efficiency of 81.2% for MPs. Even after 20 cycles, the adsorbent maintained its rapid adsorption capability. The primary mechanisms of MP removal by the adsorption material are hydrophobicity and particle diffusion [96]. Sun et al. employed chitin and

graphene oxide (ChGO) as raw materials to fabricate a solid and compressible sponge adsorption material. Deionized water was used to prepare the MP waste solution. The adsorption rates of ChGO for pure polystyrene, carboxylic-acid-modified polystyrene, and amine-modified polystyrene were 89.8%, 72.4%, and 88.9%, respectively. This adsorption material primarily captures MPs through electrostatic interactions, hydrogen bond interactions, and π-π interactions. Additionally, the material exhibits excellent activation and regeneration capabilities [97]. Yuan et al. employed three-dimensional reduced graphene oxide as an adsorbent to remove polystyrene MPs. It was discovered that the main adsorption mechanism was the strong π-π interaction between graphene oxide and polystyrene MPs. Deionized water was utilized to prepare the MPs waste solution. The maximum adsorption capacity of three-dimensional reduced graphene oxide for polystyrene MPs was 617.28 mg/g. Furthermore, the material displayed remarkable regeneration capabilities [98]. The adsorption method offers the advantages of simple operation, minimal equipment requirements, and high efficiency. However, the cost, structural stability, and adsorption selectivity of the adsorbent restrict its widespread application. Moreover, the adsorption method solely separates MPs from water, necessitating the implementation of additional methods for the treatment of MPs in subsequent stages. In future studies, researchers need to design an adsorbent that is efficient in handling microplastics, has good recycling performance, and is easy to recycle.

3.1.3. Extraction Method

The utilization of extraction techniques has gained considerable attention for the treatment of industrial wastewater containing high concentrations of phenols, nitrogen heterocycles, dyes, heavy metals, and other pollutants [99,100]. In recent years, numerous scholars worldwide have devoted their efforts to the development and application of extraction methods for the treatment of microplastics (MPs) [101,102]. For instance, Li et al. employed a custom-designed separation and extraction apparatus to effectively isolate and extract MP particles, presenting a readily available device for MP extraction. This self-fashioned equipment successfully extracted three types of biodegradable MPs (polybutylene succinate, poly(adipic acid) butylene terephthalate, and polylactic acid) as well as four types of non-degradable MPs (low-density polyethylene, polystyrene, polypropylene, and polyvinyl chloride). The recovery rates for these MPs ranged between 92% and 99.6%, thus highlighting the accuracy and precision of their separation and extraction device [103]. In a separate study, Nuelle et al. implemented a two-step approach to extract MPs from sediment samples. The extraction recoveries for polyethylene, polypropylene, polyvinyl chloride, poly(ethylene terephthalate), polystyrene, and polyurethane (1 mm) were found to be as high as 91% to 99% [104]. Similarly, Han et al. employed an extraction method to isolate MP particles from soil and sediment samples. By refining the flotation process and flotation solution, they successfully extracted and separated six commonly found MP compounds, namely polyethylene, polyethylene terephthalate, polypropylene, polyvinyl chloride, polystyrene, and expanded polystyrene. The extraction recoveries achieved for MPs were remarkably high, ranging from 80% to 100% [105]. Wang et al. applied an extraction technique to separate styrene MP spheres of various sizes (0.05, 1.0, 2.6, 4.8, and 100 μm) from biosolid and soil samples. While styrene nanoparticles with a diameter of 100 μm could be extracted completely from biosolids and soil, the extraction efficiency for smaller particles ranged from 5% to 80% [106]. This method boasts the advantages of simple instrumentation, automated control, and high operational safety. However, it is worth noting that the cost associated with this method remains high, and the separation of the dissolved solute in the extraction solvent poses a challenge. In future studies, researchers should seek a green and economical extractant to treat MPs.

3.1.4. Magnetic Separation

Magnetic separation technology encompasses the application of magnetic fields to manipulate substances, often harnessed in the realm of water treatment [107]. Presently, magnetic separation finds frequent employment in the isolation of microplastics (MPs). As an illustration, Tang et al. devised hydrophobic iron nanoparticles for the magnetic separation and extraction of MPs. Remarkably, their findings reveal that this material effectively eliminates over 90% of MPs ranging from 10 to 20 μm and exceeding 1 mm in size from seawater. Furthermore, this material boasts an ability to remove 84% and 78% of MPs measuring 200 μm to 1 mm from freshwater and sediment, respectively [108]. In a separate study, Tang et al. synthesized magnetic carbon nanotubes, leveraging their magnetic properties to isolate MPs from aqueous solutions. When employing a dose of 5 g/L, the efficient removal for MPs reached a remarkable 100% within a span of 300 min. Even after undergoing four cycles of use, the efficiency remained at 80% for MPs at a concentration of 5 g/L. Scanning electron microscopy (SEM) images exhibited the adsorption of MPs onto the surface of magnetic carbon nanotubes [109]. The magnetic separation approach boasts notable advantages, such as its capacity for high-volume treatment, minimal generation of waste sludge, and the potential for long-range magnetic enhancement in separation. However, certain drawbacks persist, including the tendency for magnetic seeds, MPs, and other lipophilic/oleophobic substances to aggregate on surfaces. In future studies, researchers need to develop a suitable magnetic separation method for different MPs to improve the universality of this method as much as possible.

3.1.5. Oil Film Separation

Oil film separation represents a hydrophobic and density-agnostic technique, frequently employed in the realm of microplastic (MP) separation [110]. For instance, Crichton et al. introduced an innovative and economical oil film method for MP removal. Impressively, the efficient removal of total MPs, fibers, and particles reached 96.1% ± 7.4, 92.7% ± 4.3, and 99% ± 1.4, respectively, underscoring the immense potential of this approach in MP elimination [111]. In a similar vein, Mani et al. harnessed castor oil membranes to effectuate the separation of MPs from aqueous matrices, yielding an impressive average MP removal rate of up to 99%. Notably, this method achieved an MP removal efficiency of 74 ± 13% in the Rhine River, further solidifying its environmental friendliness, harmlessness, and efficacy in MP separation [112]. The method's virtues include its density-agnostic nature, cost-effectiveness, and low risk. However, it is worth mentioning that the separation funnel was prone to blockage during the separation process [113]. In future studies, researchers should work to solve the problem of separation equipment blockage and establish a set of treatment methods for different sizes of microplastics.

3.2. Chemical Methods

3.2.1. Fenton Oxidation and Advanced Oxidation Technology

Fenton oxidation technology finds extensive application in the realm of water treatment [114,115]. Presently, researchers have reported the utilization of chemical oxidation methods to address wastewater containing microplastics (MPs) [116]. For instance, Liu et al. employed the heat-activated $K_2S_2O_8$ oxidation process and the Fenton oxidation process in the treatment of MPs. $K_2S_2O_8$ generates a considerable quantity of sulfate radicals and hydroxyl radicals under Fenton-like and thermal activation, which facilitate the oxidation and degradation of MPs. Consequently, the scanning electron microscopy (SEM) diagram in Figure 4 demonstrates the deformation of the surface of polystyrene (PS) and polyethylene (PE), signifying a certain extent of degradation of MPs composed of these materials [117]. Prominent advanced oxidation technologies presently encompass electrochemical oxidation, persulfate advanced oxidation, and photocatalytic oxidation. Photocatalytic degradation of MPs also represents a prevalent approach [118,119]. For instance, Venkataramana et al. employed a 350 W metal halide lamp to irradiate polyethylene MPs, resulting in a weight reduction rate of 12.5% after 5 h, indicating the partial degrada-

tion of MPs through the photocatalytic method [120]. Uheida et al. proposed a sustainable and environmentally friendly photocatalytic technique for eliminating polypropylene MPs from water activated by visible light. Following two weeks of visible-light irradiation, the average particle volume decreased by 65% due to reduction. Gas chromatography–mass spectroscopy (GC/MS) analysis revealed that the predominant degradation by-products were ethynyloxy/acetyl radicals, hydroxypropyl, butyraldehyde, acetone, acrolein (propenal), and the pentyl group [121]. Additionally, electrochemical oxidation also represents a common method for wastewater treatment [122,123]. Kiendrebeogo et al. employed an electrochemical oxidation process to address the issue of synthetic polystyrene microplastics (MPs) in wastewater. Through the application of an electric field, a significant number of hydroxyl radicals and sulfate radicals were generated, showcasing their potent oxidizing capabilities against polystyrene MPs. Ultimately, the mineralization of polystyrene MPs into CO_2 was achieved. The removal efficiency reached an impressive 89 $\pm$ 8% within a span of 6 h, utilizing a Na_2SO_4 dosage of 0.06 M. SEM characterization instruments substantiated that the degradation of polystyrene MPs did not result in their fragmentation into smaller particles, but rather their direct conversion into gaseous products (Figure 5) [124].

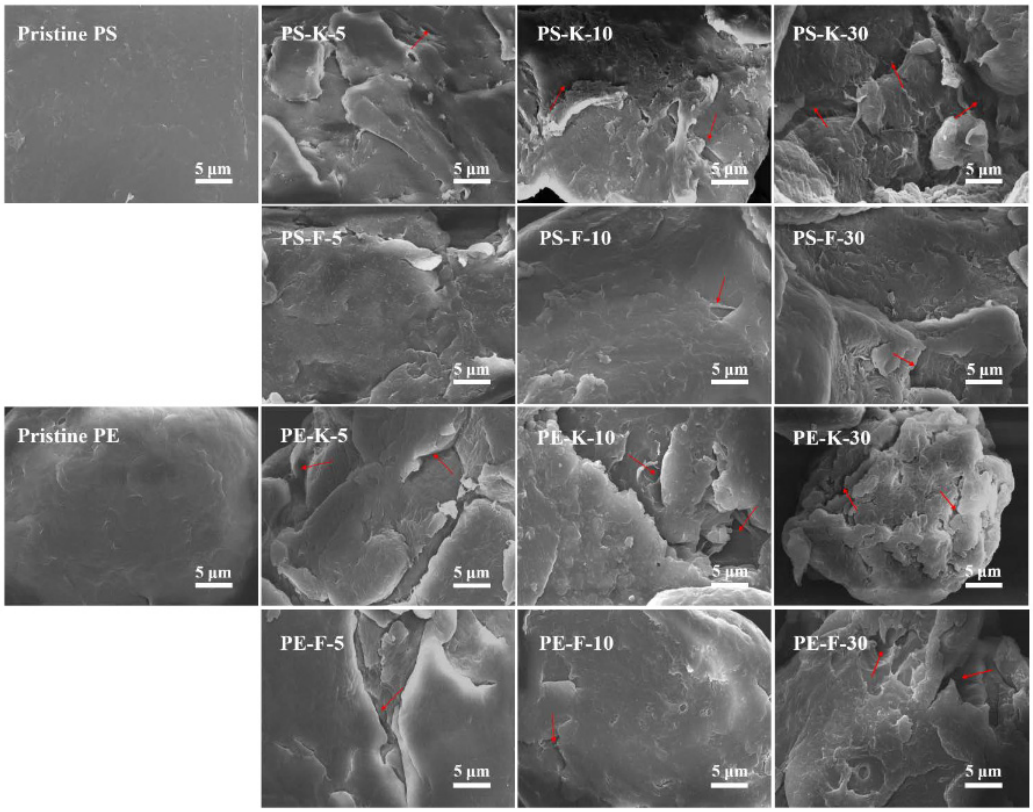

Figure 4. The FESEM images of PS and PE MPs with different alteration degrees. PS-K-5, PSF-5, PE-K-5, and PE-F-5 denote that PS or PE microplastics were altered in heat-activated $K_2S_2O_8$ and Fenton processes for 5 days. Reprinted with permission from ref. [117]. Copyright 2019, Copyright Xu X.H.

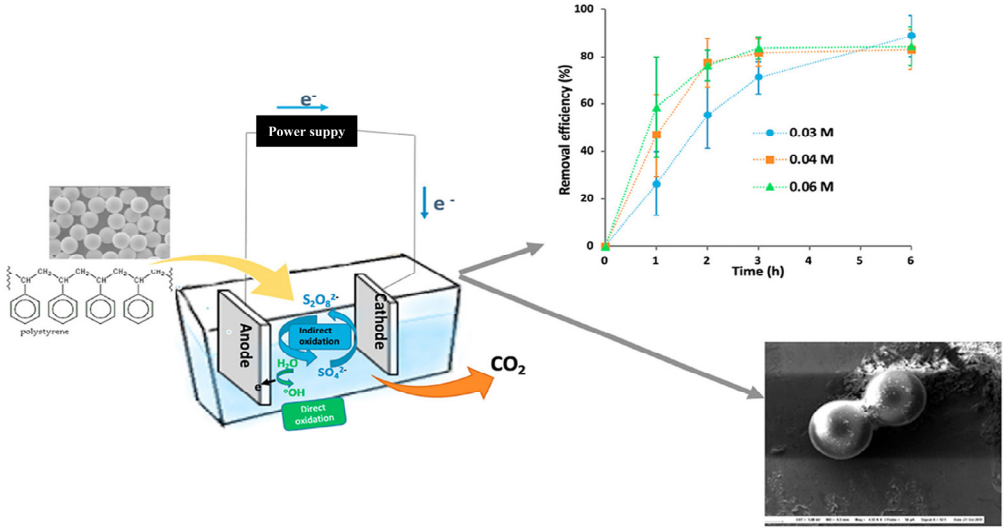

Figure 5. Degradation equipment, mechanism, and efficiency diagram of polystyrene MPs. Reprinted with permission from ref. [124]. Copyright 2021, Copyright Tyagi R.D.

Miao et al. adopted a two-dimensional electrocatalytic oxidation method to degrade polyvinyl chloride (PVC) microplastics. Following 6 h of electrocatalytic oxidation, remarkable dechlorination efficiency (75%) and weight loss (56%) were achieved for PVC. Mechanistic insights, as depicted in Figure 6, illustrated that polyvinyl chloride obtains electrons directly from the TiO_2/C cathode plate and undergoes dechlorination under elevated temperature conditions. Concurrently, hydroxyl radicals oxidize polyvinyl chloride microplastics, resulting in the formation of oxygen-containing groups such as C=O and O-H. Eventually, these substances are partially mineralized into CO_2 and H_2O. Gas chromatography–mass spectroscopy (GC/MS) and high-performance liquid chromatography (HPLC) analyses revealed that the predominant degradation by-products were alkenes, alcohols, monocarboxylic acids, dicarboxylic acids, and esters [125].

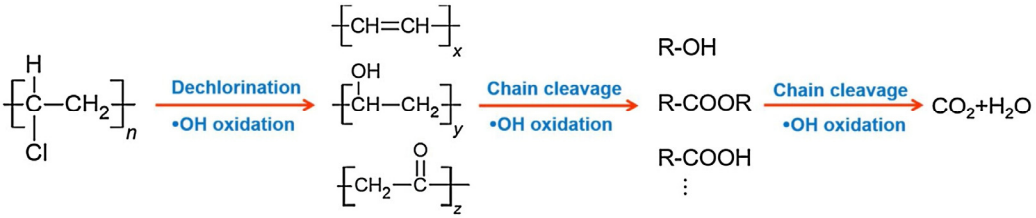

Figure 6. The proposed degradation process of polyvinyl chloride plastics. Reprinted with permission from ref. [125]. Copyright 2020, Copyright Wang X.H.

Fenton oxidation and advanced oxidation technology offer a multitude of advantages, including high removal efficiency, dependable and consistent outcomes, simple equipment, convenient operation and maintenance, and cost-effectiveness. However, it is important to acknowledge that these technologies also present a range of challenges, such as suboptimal treatment efficacy, elevated costs, the potential for secondary pollution, and stringent process requirements.

Based on our team's comprehensive investigation into electrochemical oxidation and persulfate advanced oxidation, we have devised a sophisticated water treatment system that combines three-dimensional electrocatalytic oxidation with persulfate advanced oxidation. Our findings indicate that the combination of electrocatalytic oxidation, PMS advanced oxidation, and waste coal cinder yielded the highest efficient removal (99.95%) and mineralization efficiency (90.16%) for sulfadiazine over a period of 90 min [126]. The three-dimensional electrocatalytic coupled PMS advanced oxidation system achieved an efficient removal and efficient mineralization of 99.56% and 88.63%, respectively, for sul-

famethazine within the same time frame [127]. Furthermore, we employed a self-assembled three-dimensional electrocatalytic oxidation degradation reactor to degrade sulfonamide, resulting in an efficient removal and efficient mineralization of 99.845% and 88.958%, respectively [128]. Similarly, sulfonamide exhibited an efficient removal and efficient mineralization of 99.867% and 89.675%, respectively [129]. Additionally, a meticulously prepared spherical bimetallic clay catalyst was utilized to degrade bromobenzonitrile, achieving a complete efficient removal of 100% [130]. These degradation systems generate a substantial amount of highly reactive oxygen species, which possess potent oxidation capabilities. Moreover, these degradation systems demonstrate remarkable recyclability. Furthermore, the presence of chloride ions enhances the degradation efficiency of these systems.

Based on the aforementioned reports, it was postulated that the integration of three-dimensional electrocatalytic oxidation with persulfate advanced oxidation would impart a fresh perspective on the degradation of microplastics (MPs). This treatment method is relatively new and its mechanism may not be clear. In future studies, researchers should broaden the study of the treatment mechanisms, so as to avoid the environmental impact of some degradation intermediates.

3.2.2. Coagulation Method

The coagulation technique involves the introduction of coagulants into wastewater, thereby destabilizing and aggregating the organic pollutants present into larger clumps of alum, measuring hundreds of microns or even millimeters. Subsequently, the pollutants in the wastewater could be eliminated through gravity sedimentation or other methods of solid–liquid separation [131]. Currently, coagulation is employed in the treatment of pollutants containing microplastics (MPs) [132,133]. For instance, Zhou et al. utilized poly-aluminum chloride (PAC) and $FeCl_3$ as coagulants to eliminate polystyrene (PS) and polyethylene (PE) MPs. As depicted in Figure 7, charge neutralization transpires between the flocculant and MPs. Scanning electron microscope (SEM) images reveal the occurrence of aggregation and adsorption between the MPs and the coagulant, while Fourier transform infrared (FTIR) spectra demonstrate the formation of novel chemical bonds during the interaction between the MPs and the coagulant. Furthermore, there is a discernible alteration in the zeta potential before and after adsorption, indicating the successful removal of PS and PE MPs [134]. Ma et al. employed aluminum-based ($AlCl_3 \cdot 6H_2O$) and iron-based salt ($FeCl_3 \cdot 6H_2O$) coagulants to eliminate polyethylene MPs. The findings indicate that aluminum salt outperforms iron salt in the removal of polyethylene. Notably, the efficiency of removal increases as the particle size of polyethylene decreases. Nevertheless, even when the dosage of aluminum-based salt was as high as 15 Mm, the maximum average removal rate reached a mere 36.89% [135]. Shahi et al. employed alum coagulant and alum composite cationic polyamine-coated sand coagulant to eliminate MPs from wastewater in drinking water treatment plants. The results demonstrate that the removal rate of the alum composite cationic polyamine-coated sand coagulant surpassed that of alum alone by 26.8%. The data underscore the significance of the particle size, morphology, and surface characteristics of MPs in the removal process within drinking water treatment plants [136].

Moreover, electrocoagulation serves as a technique employed for the eradication of pollutants through the application of a pulsed high voltage, thereby facilitating electrochemical reactions. Presently, electrocoagulation has found utility in the elimination of MP pollutants. For instance, Perren et al. employed electrocoagulation in the purification of synthetic wastewater containing varying concentrations of polyethylene MP spheres. Their findings corroborate that the efficacy of electrocoagulation in removing pollutants can surpass 90% when the pH level ranges from 3 to 10. Astonishingly, the removal rate achieved a staggering 99.24% at a pH value of 7.5 [137].

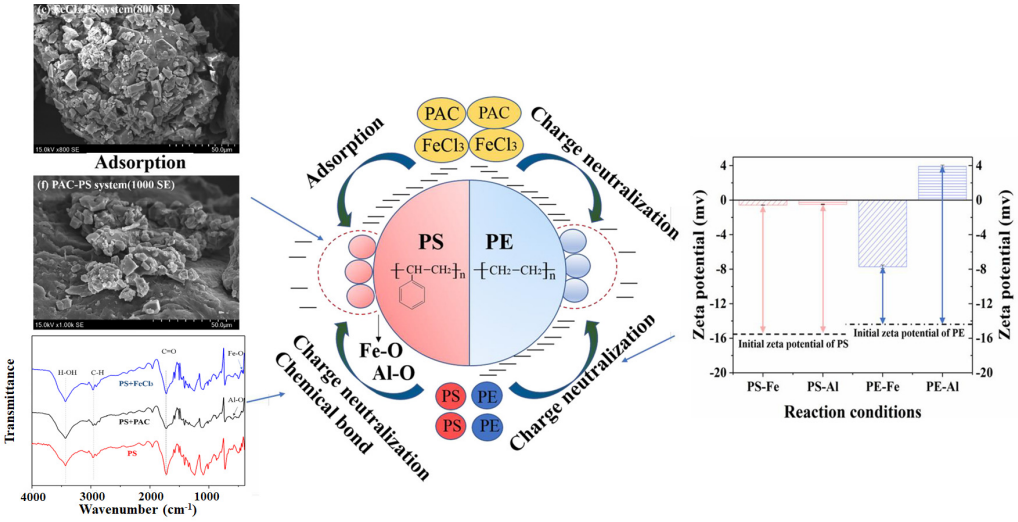

Figure 7. Diagram of the removal mechanism of polystyrene (PS) and polyethylene (PE) microplastics by PAC and FeCl3 coagulation. Reprinted with permission from ref. [134]. Copyright 2021, Copyright Zhang J.

In summary, the coagulation process exhibits numerous advantages, including its simplicity in operation, minimal equipment requirements, and swift treatment duration. Nevertheless, it is important to note that pH exerts a profound influence on this method, and many coagulants possess reducibility and coloration. Should the dosage be excessive, adverse consequences such as heightened chromaticity and diminished removal rates may ensue. In future studies, researchers should increase their exploration of the factors that affect this method and work out the most appropriate treatment scheme.

3.2.3. Foam Flotation Method

Furthermore, foam flotation represents a technique utilized for the separation of minerals from impurities. Raw ore powder is agitated with water and reagents, which selectively interact with the desired minerals to modify their surface properties. Subsequently, air is introduced into the mixture, causing the targeted minerals to rise to the top and form a froth. Currently, numerous researchers have employed this method for the removal of MPs [138,139]. For instance, Imhof et al. devised a foam-flotation-based approach for the separation of MPs, achieving a removal efficiency of 55% [140]. Additionally, Nguyen et al. have highlighted the presence of unpredictable factors that may impede the separation of MPs [141]. Talvitie et al. developed an air flotation technique to eliminate MPs from water, achieving an impressive removal efficiency of up to 95%, thereby reducing the MP concentration from 2 MP/L to 0.1 MP/L in an aqueous solution [142]. Enfrin et al. and Sun et al. advocate the use of foam flotation as a means to treat MPs, given its simple operation, low cost, and potential to mitigate MP discharge into sewage [143,144]. Additionally, Jiang et al. applied froth flotation for the removal of MPs from beach and lake sediments (Figure 8). In their study, sodium oleate was employed to restore the hydrophobicity of MPs, facilitating their effective removal from sediments [145]. Consequently, the foam flotation method offers advantages in its uncomplicated equipment and affordability. However, the experiment's reproducibility remains a significant challenge, with temperature exerting a substantial influence. Regrettably, few scientists have expounded upon the unstable performance of foam flotation, leaving it as a focal point for future research endeavors.

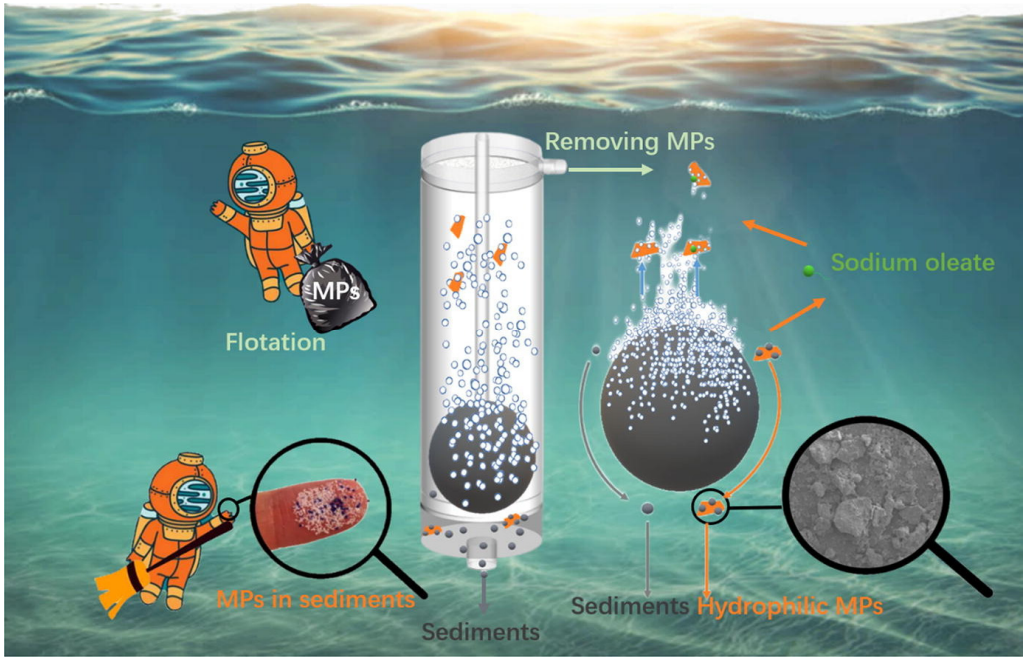

Figure 8. MP removal from sediments using froth flotation. Reprinted with permission from ref. [145]. Copyright 2022, Copyright Wang H.

3.3. Biological Methods

3.3.1. Anaerobic–Anoxic–Aerobic Activated Sludge Method

The anaerobic–anoxic–aerobic activated sludge (AAO) process was employed to eliminate organic pollutants in water through a combination of anaerobic, anoxic, and aerobic zones, along with different sludge return strategies. This technique primarily targeted the removal of BOD [146]. Presently, numerous researchers have applied this approach to address MPs [147,148]. For instance, Yang et al. introduced a technology based on the anaerobic–anoxic–aerobic activated sludge process to treat authentic MPs obtained from a sewage treatment facility in Beijing, resulting in a 54.47% removal rate [149]. Jia et al. proposed a similar approach for the treatment of real MPs in wastewater obtained from a wastewater treatment plant in Shanghai, achieving a removal rate of 26.01% [150]. Jiang et al. implemented an anaerobic–anoxic–aerobic activated sludge process to treat real MPs in wastewater derived from wastewater treatment plants in northern China, resulting in a removal rate of 16.9% [151]. Similarly, Liu et al. applied an anaerobic–anoxic–aerobic activated sludge process to treat authentic MPs in wastewater from a sewage treatment plant in a specific region of China, yielding a removal rate of 16.6% [152]. The AAO process offers advantages such as cost-effectiveness, a straightforward process flow, and a short hydraulic retention time. However, this method is time-consuming, exhibits low removal efficiency, is susceptible to bacterial demise, and generates a substantial amount of sludge. In future studies, researchers need to screen and domesticate a high-quality bacterial community that can achieve good results in the degradation of microplastics in different environments.

3.3.2. Enzymatic Degradation

Currently, the field of in situ degradation of microplastics (MPs) by enzymes under gentle conditions is a highly active area of research [153,154]. In this approach, either indigenous or introduced microorganisms are employed to degrade or metabolize MPs, transforming them into harmless end products. Biocatalysis itself embodies the principles of environmental friendliness, and an ideal enzyme possesses the ability to accomplish MP degradation with exceptional efficiency [155]. In 2016, Yoshida et al. pioneered the development and utilization of an enzyme capable of effectively breaking down polyethylene terephthalate plastics. However, the inherent instability of this enzyme hindered its

practical application in the field of biodegradation [156]. Subsequently, Son et al. utilized a thermally stable variant of PETase to degrade polyethylene terephthalate MPs. Nevertheless, this enzyme exhibited limited durability, with a significant loss of activity within 24 h at 37 °C [157]. Presently, numerous research groups have made substantial contributions to the study of PETase [158–160]. Recently, Cui et al. introduced a novel computational design strategy for enhancing protein stability, known as the Greedy Accumulated Strategy for Protein Engineering (GRAPE). As a result of this innovative approach, a catalytic enzyme called DuraPETase was engineered and its ability to degrade poly(ethylene terephthalate) MPs was successfully demonstrated. Figure 9A illustrates the degradation of poly(ethylene terephthalate) into smaller molecules or non-toxic substances. The scanning electron microscopy (SEM) image in Figure 9B clearly demonstrates noticeable alterations on the surface of poly(ethylene terephthalate) MPs. Furthermore, the high-performance liquid chromatography analysis in Figure 9C confirms the effective degradation of poly(ethylene terephthalate) MPs by DuraPETase enzymes [161]. The enhancement of ispetase stability was achieved through the utilization of state-of-the-art computational protein design techniques. This groundbreaking approach yielded a redesigned enzyme with remarkable resilience, effectively addressing the long-standing issues of enzyme instability and fragility. Importantly, this breakthrough opens up new possibilities for the utilization of biodegradable plastics. However, it is worth noting that the widespread implementation of this method is hampered by its prohibitive costs and the intricate process required for enzyme preparation [162]. In future studies, researchers should control treatment costs while maintaining the efficient treatment of microplastics.

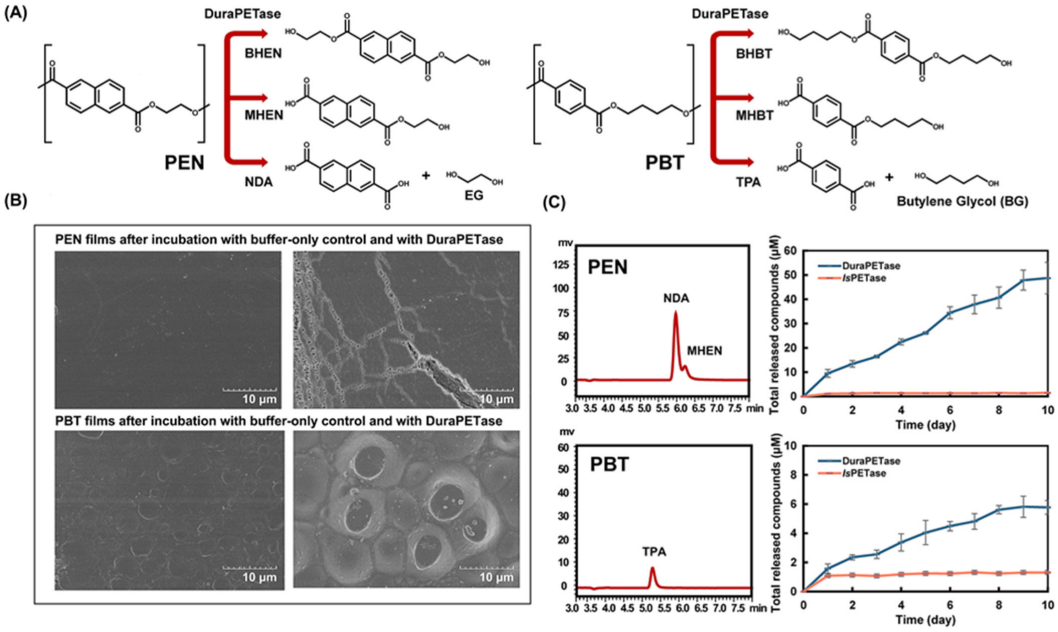

Figure 9. The degradation mechanism of PEN and PBT (**A**); the SEM images of PEN and PBT before and after degradation (**B**); HPLC chromatogram of the products released from the PEN and PBT films (**C**). Reprinted with permission from ref. [161]. Copyright 2021, Copyright Han X.

3.3.3. Bacterial Degradation Method

Bacteria, a prominent group of microorganisms, reign supreme as the most abundant lifeforms across all organisms. The morphological diversity of bacteria is striking, ranging from spherical to rod-shaped and even spiral forms [163,164]. Presently, bacteria find wide applications in the production of cheese, yogurt, wine, and antibiotics. Furthermore, their remarkable potential in wastewater pollutant degradation cannot be overlooked [165,166]. Researchers have harnessed the power of bacteria in the degradation of microplastics (MPs). These bacteria primarily originate from sediments, sludge, and MP-laden water

bodies [167–169]. For instance, Auta et al. isolated two pure bacteria from mangrove sediments and employed them in the degradation of polypropylene MPs. After a span of 40 days, the degradation rates for polypropylene MPs by Rhodococcus 36 and Bacillus 27 were recorded at 6.4% and 4.0%, respectively. The degradation process induced the formation of various porous structures and irregularities on the surface of the MPs, providing compelling evidence of the bacteria's efficacy in polypropylene MP degradation. Auta et al. employed Bacillus cereus and Bacillus gotthiilii bacteria to facilitate the degradation of various types of microplastics (MPs). Their findings revealed that Bacillus cereus achieved weight reductions of 1.6%, 6.6%, and 7.4% for polyphylene, polyphylene terephthalate, and polystyrene, respectively. On the other hand, Bacillus gotthielii displayed weight reduction rates of 6.2%, 3.0%, 3.6%, and 5.8% for polyphylene, polyphylene terephthalate, polypropelene, and polystyrene, respectively [170]. Yang et al. successfully isolated Enterobacter asburiae YT1 from plastic-eating waxworms and employed it in the degradation of polyethylene MPs. After a duration of 28 days, the weight reduction rate of polyethylene was observed to be 6.1% $\pm$ 0.3 [171]. Similarly, Shah et al. isolated a strain of Bacillus subtilis mza-75 from soil samples and utilized it to degrade polyurethane MPs. Following a 28-day period, the scanning electron microscope (SEM) image revealed the emergence of extensive crack formations on the polyurethane surface, while Fourier-transform infrared (FTIR) spectroscopy indicated a decline in the functional groups of polyurethanes. These phenomena collectively indicate the efficacy of Bacillus subtilis mza-75 in the degradation of polyurethane MPs [172]. Furthermore, Yoshida et al. isolated a strain of ideanella sakaiensis 201-f6 from contaminated samples and employed it in the degradation of polyethylene and polyethylene terephthalate MPs. Remarkably, after a duration of 60 days, the SEM image confirmed the capability of ideonella sakaiensis 201-f6 to degrade polyethylene and polyethylene terephthalate MPs [173]. In conclusion, the bacteria-mediated degradation of MPs represents a widely utilized treatment technology in the management of MPs. However, this approach is not without its drawbacks, including the complexity of bacterial culture, the stringent environmental conditions required for bacterial degradation, and the substantial time investment involved. In future studies, researchers should simplify the steps of bacterial culture and train more adaptable bacteria. On the one hand, the processing cost is reduced, and on the other hand, the anti-risk capability of this method is enhanced. At the same time, it is also necessary to pay attention to other hazards to the environment caused by bacteria that may leak during the treatment process.

3.3.4. Fungal Degradation Method

Fungi have been frequently employed for the degradation of hazardous pollutants [174,175]. Presently, numerous researchers have embarked on employing fungi for the degradation of microplastics (MPs) [176–178]. For instance, Yamada-Onodera et al. employed Penicillium simplicissimum YK fungi to degrade polyethylene MPs, leading to the subsequent observation of polyethylene MPs with reduced molecular weight after a 3-month period of liquid culture. These findings unequivocally demonstrate the remarkable proficiency of Penicillium simplicissimum YK fungi in degrading polyethylene MPs [179]. Volke-Sepúlveda et al. isolated and cultivated Aspergillus niger and Penicillium pinophilum fungi, which were then employed for the degradation of low-density polyethylene (TO-LDPE) MPs. After 31 months, Aspergillus niger and Penicillium pinophilum achieved weight reduction rates of 0.57% and 0.37% for TO-LDPE, respectively [180]. Devi et al. isolated and cultured Aspergillus tubingensis VRKPT1 and Aspergillus flavus VRKPT2 from discarded polyethylene waste, subsequently utilizing them for the degradation of high-density polyethylene (HDPE) MPs. After 30 days, Aspergillus tubingensis VRKPT1 and Aspergillus flavus VRKPT2 demonstrated weight reduction rates of 6.88 $\pm$ 0.1% and 9.34 $\pm$ 0.2%, respectively, for HDPE MPs [181]. El-Shafei et al. isolated and cultivated VRKPT1 and VRKPT2 fungi from the Nile Delta, employing them for the degradation of high-density polyethylene (HDPE) MPs. After 30 days, VRKPT1 and VRKPT2 achieved weight reduction rates of 6.02 $\pm$ 0.2% and 8.51 $\pm$ 0.1%, respectively [182]. In

conclusion, these fungi possess remarkable capabilities for the in vitro degradation of MPs. Nonetheless, this approach has certain limitations, such as the need for intricate bacterial culture, demanding environmental prerequisites for fungal degradation, and time-intensive processes. Consequently, further refinement is imperative for the fungal-mediated degradation of MPs. In future studies, researchers should optimize the conditions for fungi to process microplastics, so that fungi can treat microplastics in complex environments with the shortest time, the lowest cost, and the highest efficiency.

As elucidated earlier, Table 1 succinctly delineates the merits and demerits of various methodologies employed for the treatment of microplastics (MPs). Consequently, it is evident that substantial progress is yet to be made in the realm of eradicating MPs.

Table 1. Advantages and disadvantages of MP treatment methods.

Method		Advantages	Disadvantages	Reference
Physical methods	Filtration	Simple operation, high efficiency, high volume	Poor structural stability of adsorbent (membrane) and high cost	[183]
Physical methods	Adsorption	Simple operation, simple equipment, high efficiency	Poor structural stability of adsorbent and the risk of introducing secondary pollution	[184]
Physical methods	Extraction	Simple operation, simple equipment, high safety operation	The cost of this method was high and it was difficult to separate the solute after dissolving it in the extraction solvent	[185]
Physical methods	Magnetic separation	Less waste sludge, high efficiency, high volume	Surface agglomeration of magnetic seeds, MPs, and other lipophilic/oleophobic substances	[161]
Physical methods	Oil film separation	Simple operation, moderate cost, independent from density	A hydrophobic surface is required, organic contaminant entrainment	[110]
Chemical methods	Fenton oxidation	Simple operation, high efficiency, high volume	The equipment is easily blocked by a large amount of sludge, and the utilization rate of hydrogen peroxide is low	[186]
Chemical methods	Electrochemical oxidation	Mild reaction conditions, no secondary pollution, flexibility, simple operation, and controllability	Low mass transfer efficiency and low current efficiency	[187]
Chemical methods	Photocatalytic oxidation	Simple operation, simple equipment, high safety operation	The absorption range of photocatalyst is narrow, the utilization rate of light energy is low, some suspended solids and darker chroma will have a great impact, it is difficult to recover, and the electron–hole pair is easy to inactivate	[188]
Chemical methods	Persulfate advanced oxidation	Simple operation, simple equipment, high safety operation, low cost	The pH requirement is high, the catalyst recovery is difficult, and the generated redox potential of hydroxide is not as high as that of sulfate	[189]
Chemical methods	Coagulation	Simple operation, simple equipment, short treatment time	pH has a great influence on this method, and many coagulants have reducibility and color. If the dosage is large, it can easily cause high chroma and low removal rate	[190]
Chemical methods	Electrocoagulation	No requirement for chemical coagulants, less sludge	High electricity and conductivity are required, and oxidation is caused by electrodes	[132]
Chemical methods	Foam flotation	Simple operation, simple equipment, high safety operation, low cost	The repeatability of the experiment was very poor, and the temperature has a great influence	[191]
Biological methods	Anaerobic–anoxic–aerobic activated sludge	Low cost, high volume, simple operation	Time-consuming, low removal efficiency, easy death of bacteria, and a large amount of sludge	[192]

Table 1. *Cont.*

	Method	Advantages	Disadvantages	Reference
Biological methods	Enzymatic degradation	High efficiency and specificity	Complex operation process, high cost, and harsh reaction conditions	[175]
Biological methods	Bacterial degradation	High safety, low cost, and simple operation	Complex bacterial culture, high environmental requirements for bacterial degradation, high time consumption	[193]
Biological methods	Fungal degradation	High safety, low cost, and simple operation	Complex bacterial culture, high environmental requirements for fungi degradation, high time consumption	[172]

4. Challenges, Future Research, and Research Limitations

In this paper, a large number of existing studies on the characterization and treatment techniques of microplastics are reviewed. However, these characterization and treatment techniques have some shortcomings: their universality is poor, and it is difficult to use a single method to properly characterize and treat microplastics. In view of the current waste production, the pollution of microplastics in the environment may become more and more serious, and the difficulty of detecting and disposing of microplastics will become more and more difficult. Therefore, we need to pay more attention to the source of microplastics, the transfer route, the toxicity of degradation intermediates, and other aspects in future research processes.

4.1. Challenges and Suggestions

(1) MPs come from a wide range of sources, and the challenge remains of whether researchers can take certain measures from the time of plastic production to avoid the subsequent generation of MPs.
(2) There are many ways in which MPs are transferred, which forms a cycle in the environment; it is important that we dispose of MPs at the stage where we are most likely to dispose of them.
(3) Current research is mainly concerned with the removal rate of MPs, but it is ignored that MPs may produce toxic substances during the treatment process and cause other impacts on the environment.
(4) The removal rate of MPs mentioned in the literature is very high, but whether the treated MPs are transformed into other substances that are still harmful to the environment is unknown. And there is no standardized way to judge the extent to which a treatment is environmentally friendly.
(5) For biodegradable MPs, whether the degradation process has an impact on microorganisms, thereby causing harm to biological groups, and whether it will indirectly affect the environment are unknown.

4.2. Future Recommendations

(1) It is recommended to link a variety of characterization and treatment technologies to find a more universal characterization and treatment technology to solve the complex MP pollution situation.
(2) Toxicity studies are recommended to assess the toxicity of MPs' degradation intermediates and degradation products.
(3) At present, it seems that it may be easier to treat MPs in water, but they are more difficult to treat soil or the atmosphere, and it is recommended to develop a method that can deal with MP pollutants in soil and the atmosphere.
(4) It is recommended to establish a set of evaluation methods to systematically evaluate the degradation efficiency and toxicity of the degradation products of MPs.
(5) It is recommended to improve the classification of waste at the source and plastic recycling.

4.3. Research Limitations

The number of research papers on MPs has soared in recent years, but overall MPs are still understudied. Although many methods for characterizing and treating MPs have been summarized in this paper, there are still many methods that we have not summarized. Some of the methods described in this paper only describe a single characterization and treatment technology, and do not combine multiple methods to study MPs. As the study of MPs deepens, more and more technologies can be used to characterize and remove MPs, and more and more advanced methods will be derived.

5. Conclusions

The development of effective, sustainable, and uncomplicated methodologies for the eradication of microplastics (MPs) holds paramount significance in the amelioration of plastic pollution. In this study, we conducted a systematic appraisal of the techniques employed for characterizing and removing MPs. At the same time, according to the technical gaps not involved in the literature, some suggestions for future research are put forward. The characterization of MPs proved invaluable in discerning their diverse typologies. Moreover, we conducted a comprehensive evaluation of the merits and demerits associated with various removal technologies, encompassing filtration, adsorption, extraction, magnetic separation, oil film separation, Fenton oxidation, electrochemical oxidation, persulfate advanced oxidation, photocatalytic oxidation, coagulation, electrocoagulation, foam flotation, anaerobic–anoxic–aerobic activated sludge, enzymatic degradation, bacterial degradation, and fungal degradation. Drawing upon the findings of our research team, we proposed a viable and efficacious degradation system for the elimination of MPs. Each approach has its own advantages, but there are also major limitations. These physical methods have the advantages of simple operation and low cost, but they have certain limitations on the treatment effect of microplastics. Chemical methods have a good effect on the treatment of microplastics, but can easily to produce other substances that harm the environment. Biological methods are a new approach; they have the advantages of high efficiency and environmental protection, but their mechanism is not sufficient, and they need further research and development. However, it is imperative to note that numerous experiments have thus far been confined to laboratory settings, with limited exploration of removal techniques for minute MPs. Hence, expanding the scale of experimentation and devising strategies for the elimination of diminutive MPs emerge as the focal points for future researchers.

Author Contributions: Y.L.: Data Curation, Writing—Original Draft, Conceptualization, Methodology, Investigation, Formal Analysis. P.C.: Investigation. Y.T.: Investigation. Y.Y.: Investigation, Supervision. C.Z.: Investigation, Supervision. J.B.: Writing—Review and Editing, Supervision, Validation. S.Z.: Writing—Review and Editing, Visualization, Resources. All authors have read and agreed to the published version of the manuscript.

Funding: The National Natural Science Foundation of China (Grant No.21576295), the Hunan Provincial Natural Science Foundation of China (2019JJ50759), and the Fundamental Research Funds for the Central Universities of Central South University (2017zzts175 and 2018zzts371).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available on request from the authors.

Acknowledgments: This study thanks for the funding of National Natural Science Foundation of China (Grant No.21576295), the Hunan Provincial Natural Science Foundation of China (2019JJ50759), and the Fundamental Research Funds for the Central Universities of Central South University (2017zzts175 and 2018zzts371).

Conflicts of Interest: Author Jiaqi Bu was employed by the company Hunan Haili Chemical Industry Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conmpanylict of interest.

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