sustainability

MDPI

Review

Microplastics in Aquatic and Food Ecosystems: Remediation Coupled with Circular Economy Solutions to Create Resource from Waste

Sunny Dhiman [1,†], Chhavi Sharma [1,2,*,†], Anu Kumar [1], Puneet Pathak [3] and Shiv Dutt Purohit [4,*]

[1] University Institute of Biotechnology, Chandigarh University, Mohali 140413, India; sunny.uibt@cumail.in (S.D.); anu.uibt@cumail.in (A.K.)
[2] University Centre for Research and Development, Chandigarh University, Mohali 140413, India
[3] Ayurvet Research Foundation, Chidana, Sonipat 131306, India; pathakpuneet26aug@gmail.com
[4] School of Chemical Engineering, Yeungnam University, 280 Daehak-Ro, Gyeongsan 38541, Republic of Korea
* Correspondence: chhavisharma19@gmail.com (C.S.); purohitshivdutt@gmail.com (S.D.P.)
† These authors contributed equally to this work.

Abstract: Microplastics (MPs) less than 5 mm in dimension are progressively becoming persistent in aquatic and food ecosystems and are a global concern. Microbeads (less than 1 mm) used in household cleaners, cosmetics, and apparel washing are the primary source, followed by secondary sources including broken-down plastic litter and waste. They are ingested by a range of aquatic animals, including zooplankton, crustaceans, and fish, and can enter human food chains in a variety of manners. Thus, microplastic pollution poses a detrimental effect on the overall ecological balance, including the aquatic ecosystem, food safety, and human health. Strategies such as microbial enzymes/biofilms and nanotechnology-based solutions to MPs biodegradation, the usage of substitute materials such as biodegradable plastics, and source reduction could be employed to mitigate microplastic pollution. In addition, the implementation of plastic waste into the circular economy, for example by applying the reduce, recycle, and reuse approach, could potentially serve as a sustainable solution to abate the adverse effects of plastics. Thus, plastic waste could contribute to a sustainable circular and climate-neutral economy as a result of its durability and recyclability. This review presents a comprehensive report on microplastic management and transformation strategies, reflecting bioremediation coupled with circular economy-based solutions to microplastic pollution. It also highlights future recommendations to stakeholders and for governmental policies for the reduction of plastic pollution by potentially utilizing plastic waste in a circular economy to generate wealth from waste. Overall, this article provides an exhaustive and essential overview of microplastic treatment procedures and their role in the circular economy, where plastic waste generated by aquatic and food-based ecosystems might possibly be managed and re-utilized.

Keywords: microplastics; remediation strategies; biofilms; nano-bioremediation; plastic waste management; circular economy solutions

Citation: Dhiman, S.; Sharma, C.; Kumar, A.; Pathak, P.; Purohit, S.D. Microplastics in Aquatic and Food Ecosystems: Remediation Coupled with Circular Economy Solutions to Create Resource from Waste. *Sustainability* **2023**, *15*, 14184. https://doi.org/10.3390/su151914184

Academic Editor: Jose Navarro Pedreño

Received: 14 August 2023
Revised: 17 September 2023
Accepted: 19 September 2023
Published: 25 September 2023

1. Introduction

Plastics play a significant role in almost every aspect of our everyday life as a result of their inclusive properties, such as being lightweight, robust, affordable, and durable [1,2]. However, the management of plastic waste is a topic of a global issue. Plastics can remain in the environment for as long as 500 years [2]. This is harmful to biodiversity and exhausts the ecosystem amenities required to support life [2]. It is predicted that the annual emissions of plastic waste may reach up to 53 million metric tons per year by 2030 [3].

Thermoplastics and thermoset plastics are the two key plastic categories. A thermoset plastic cannot be remelted while a thermoplastic can be melted again. The main categories of thermosets are epoxy resins, polyurethane (PU), silicones, and vinyl esters; thermoplastics include polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE),

polyvinyl chloride (PVC), polystyrene (PS), polyamide (PA), and polycarbonate (PC) [4,5]. Thompson et al. introduced the term "Microplastics" (MPs) for the small pieces of plastic that occur prominently in nature. MPs include microfibers, micro-flakes, pellets, spheroids, beads granules, or fragments and are either directly produced by anthropological activity or as secondary MPs as a result of the disintegration of larger plastic pieces through photodegradation, biodegradation, or through the mechanical route [6–10]. There exists a wide array of sources of microplastics, as shown in Figure 1, and the exposure levels from MPs from various individual sources are depicted in Table 1. This is a result of improper conduct, a lack of collecting methods, or transportation-related leaks [9]. Environmental plastic pollution affects ecosystems across the world, including polar regions and places where there is no obvious evidence of human activity [9]. It is not solely a regional issue of polluted water bodies and soils [11]. This is due to abiotic processes that break down plastic materials into fragments of innumerable dimensions, from the nanoscale to the microscale [11]. Nano- and microplastics have been found in tissues, human blood, and biological food chains throughout the world's interconnected aquatic waste systems [11,12]. These plastic remains interact with the ecosystem and function as carriers of hazardous substances that are detrimental to the environment and human health (Figure 2). To decrease plastic leakage into the environment, advanced imperative restrictions are anticipated to be implemented in the coming years. Bioremediation processes using biofilms and microbial enzymes that degrade plastic waste are quite effective but require further development. Circular economy-based production methods that transform plastic trash into new resources could be an eco-friendly choice in the current situation [13]. The "triple R principle"—"Reduce, Recycle, and Reuse"—could be used to apply the concepts of the circular economy to the management of plastic trash in additi on to prolonging the useful lifespans of materials and products [14]. Recycling is one of these operations. It is mostly implemented in high-tech infrastructures and requires significant resource, time, and financial inputs [14,15]. Nevertheless, some plastic fractions that result in goods of inferior quality when compared to the products made from feedstock constituents can be recycled [16]. Additionally, the value of recyclables fluctuates in the market [14]. Thus, more efficient and greener recycling solutions as well as novel enzyme-based bioremediation techniques will fuel future strategies targeted at improving the circularity of plastic waste and its profitability. Considering the circular (bio)economy, the biotechnology sector has recently offered new possibilities for waste circularity (mostly emphasizing microbial enzyme applications) [14]. Enzymatic bioprocesses can transform low-value waste obtained from biomass or fossil sources into new, marketable products that are as good or better than virgin materials, reducing the carbon footprints of freshly derived fossil feedstocks [14]. Several reviews are available on the types of plastics, health implications, potential remedies, and identification techniques for MPs [4,5]. Nevertheless, there is a dearth of collective contemplation in the literature regarding the potential of biotechnological approaches to current plastic waste treatments, considering the circularity of plastic waste, in order to produce products for value-addition. This review focuses on the origins of MPs and the problems related to them, MPs treatment strategies, and approaches to incorporate MPs into the Circular Economy concept. This review provides an overview and represents one of the earliest comprehensive reports amalgamating the current solutions for plastic waste management with special reference to bioremediation strategies. In addition, this review highlights the ways towards shifting the linear economy model to the circular (bio)economy principles, where the plastic waste generated from aquatic and food-based ecosystems could be managed and re-utilized for value addition. Moreover, future recommendations to those relevant organizations as well as policies that adopt a circular economy perspective towards plastic waste management and subsequent value-addition have been detailed.

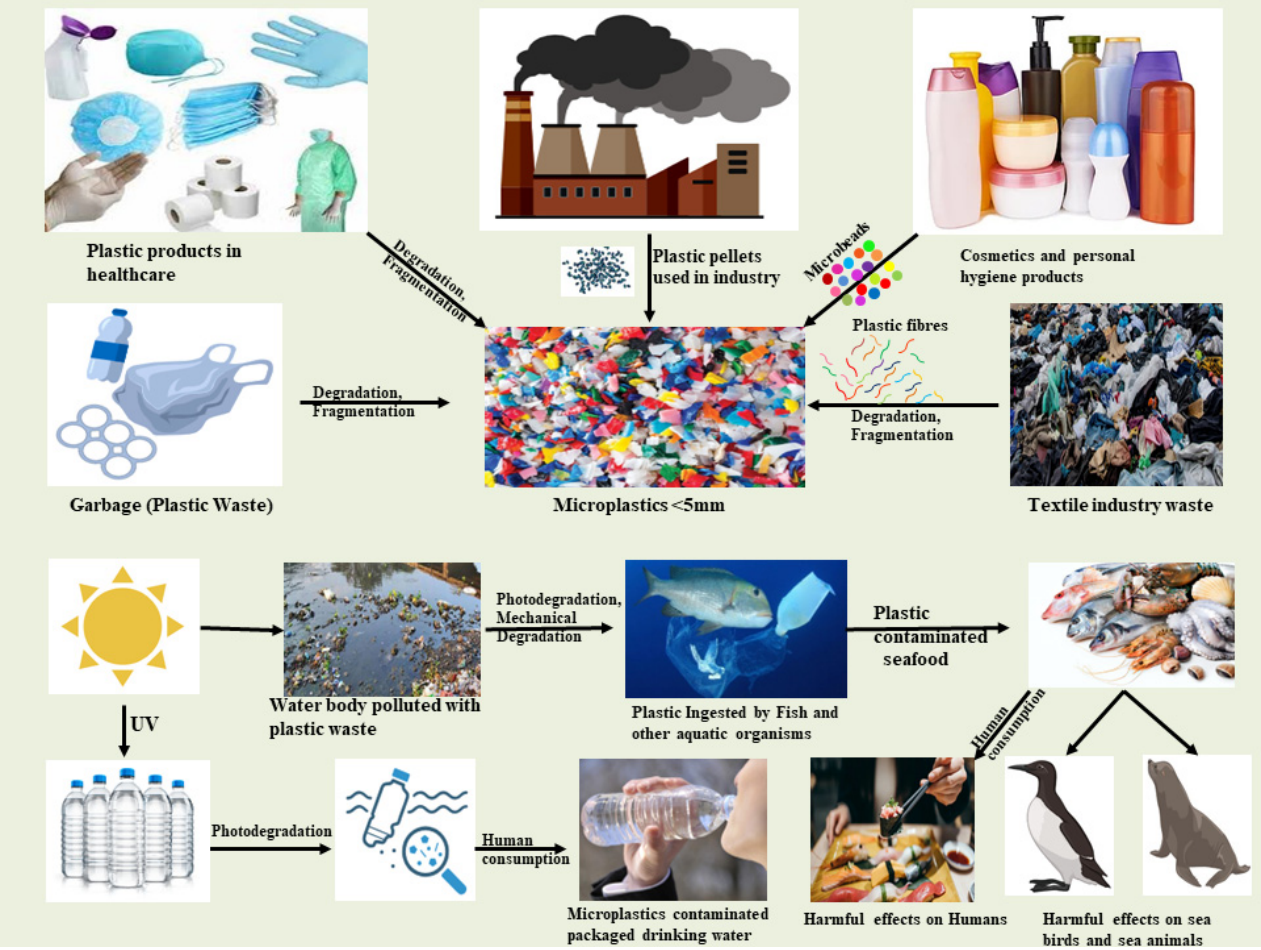
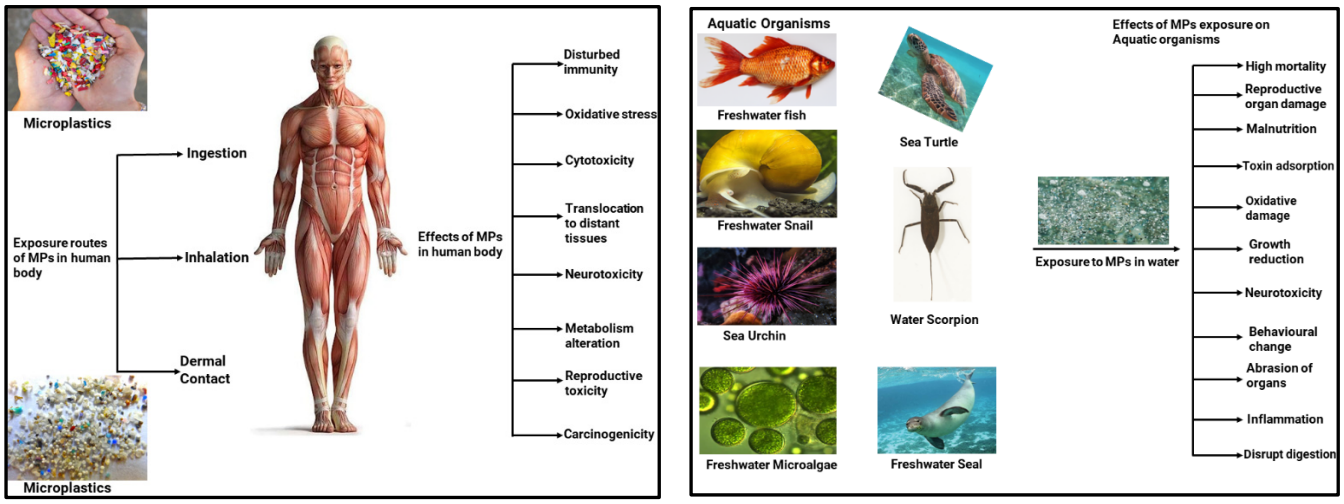


Figure 1. Sources, Origin and Impacts of MPs.



(**a**) (**b**)

Figure 2. Effects of MPs on the (**a**) health of humans and (**b**) aquatic organisms.

Table 1. MPs' exposure level through various individual sources.

Exposure Source	Polymer Involved	Level of Exposure	Estimated Consumption	Reference
Bottled mineral water	PET	1,531,525 particles per kg per body weight each day (adults) 3,350,210 particles per kg per body weight per day (children)	2 L per day (adults) 1 L per day (children)	[16]
Salts	PE, PP, PET, PU, PVC, PA	Up to 302 particles/person per year	4.8–18.01 g/day	[17]
Seafood	PE, polyester, semisynthetic cellulose	518–3078 particles/person per year	9.6–57 kg/year	[18]
Water and beverages	Anthropogenic debris	4400–5800 particles/person per year	2.2–3 L/day	[19]
Household dust fallout	–	13,730–68,414 particles per person per year	Evening meals	[20]
Vinegar	PE, butylated hydroxytoluene, Irganox, Erucamide	Up to 3.68 particles/kg/body weight/year (adults) Up to 16.08 particles/kg/body weight per year (children)	3.1 L per year	[21]
Infant feeding bottles	PP	14,600–4,550,000 particles per capita per day	–	[22]
Mussels	PET, PU	123–4620 particles/person per year	0.082–3.08 kg per year	[20]
Food contact materials	PP, PS, PE, PET	12–203 particles/person per week	4–7 takeout per week	[23]
Salts	PE, PP, PET, PS, polyacrylonitrile, PA	37 particles/person per year	3.95 g per day	[24]

PE: Polyethylene PP: Polypropylene; PS: Polystyrene: PET: Polyethylene terephthalate; PVC: Poly vinyl chloride; PU: Polyurethrane. PA: Polyamide.

2. MPs Treatment Strategies and Management

Physical, chemical, and bioremediation technologies can be used to clean up contaminated areas (Figure 3) [25].

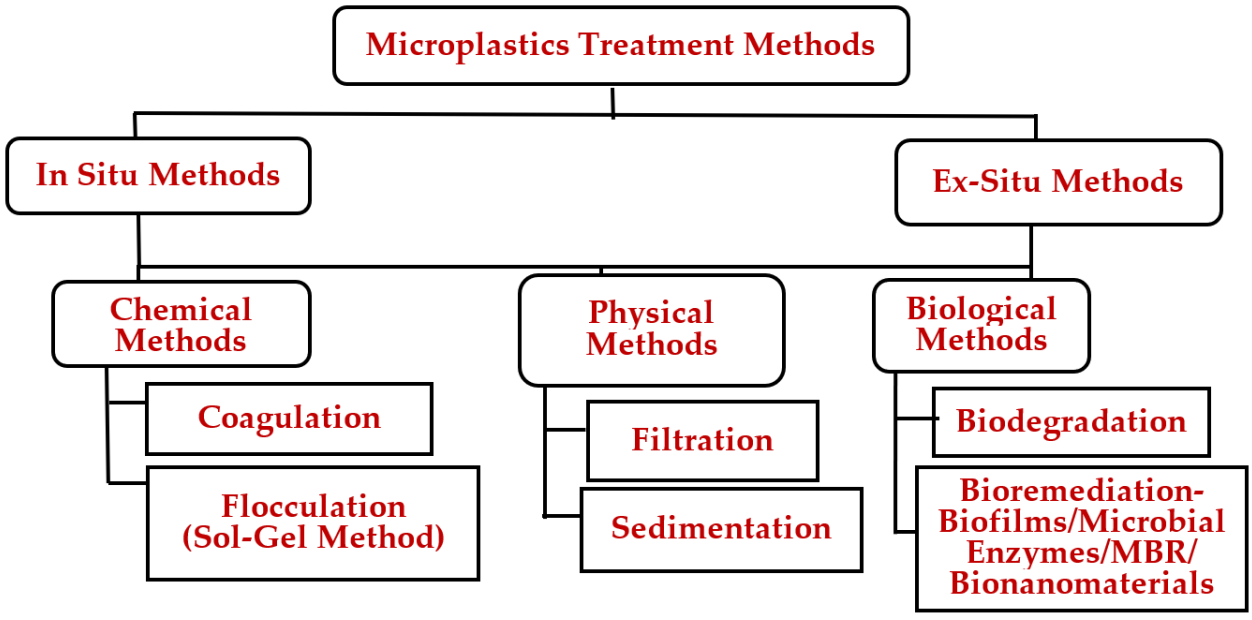


Figure 3. MPs Treatment Methods.

2.1. Physical Technologies

Remediation by physical means encompasses all the separation approaches employed in wastewater treatment [25]. Grids, flotation, primary sedimentation, screens, dissolved air flotation (DAF), disc filtering, and swift gravity sand filtration are among the various means of conventional wastewater treatment methods that successfully remove MPs, and these approahces are often used to improve the efficacy of advanced technologies such as membrane bioreactors and reverse osmosis [26]. Several novel technologies have undergone laboratory testing and have proven to be successful (Table 2) [25,27]. Before reaching the membrane bioreactor (MBR), MPs are usually removed using an ultrafine sieve (mesh dimension 0.2–2 mm) in order to avoid the fouling of the membrane [28]. Only 6% of the MPs were reportedly removed from the wastewater by grids [26,27]. Polyethylene terephthalate MPs can be removed using primary sedimentation, but polyethylene and polypropylene are challenging to remove because their low density causes their settling time to be greater than their traveling period in water. Particles that fail to settle following coagulation can be eliminated by employing disc filters. A disc-like fibre that functions as a barricade and captures particles greater than the diameter of the pore is typically employed as the filter media. Disc filters may remove between 40% and 96% of MPs from the atmosphere [29,30]. After several configuration operations, such as pre-sedimentation, coagulation-flocculation, and sedimentation, rapid gravity sand filtration may be an alternate method for removing MPs [31]. Usually, rough sand particles are employed in this method as the filtration medium, but silica and broken glass are appropriate alternatives [32]. The exclusion performance of silica-based rapid sand filters (RSFs) fluctuates from 86% to 98% based on the MP's form and the filter's dimensions [31].

Another intriguing technique is the use of dynamic membranes (DMs), which rely on the formation of a cake-like secondary supporting membrane or barrier. When wastewater is filtered via an aiding membrane, DMs are produced as a result of the particles and other foulants. A reduction in membrane performance, however, may occur as a result of extensive fouling [33]. According to Poerio et al. (2019), DMs are the most effective way to remove low-density microparticles [33]. According to Sol et al. (2020), the foremost drawback of this technology is obstruction of the filter, brought on by cake development, massive energy consumption, fouling of membrane, and/or management of waste [34,35]. Currently, the most effective technology for MP cleanup is MBR. It is a heterological assembly made up of a mutual combination of biological and physical remediation strategies involving the biological catalytic action as well as the physical separation utilizing microranged filtration or ultrafiltration. It becomes easier to separate MPs by filtration because of the breakdown of organic matter in the heterogeneous system. The MPs are then concentrated in the resultant retained stream [33]. MBR proved successful in eliminating 99.4% of MPs and minute anthropogenic litter from wastewater [36]. Nevertheless, this process is expensive, energy-intensive, and suffers from membrane fouling problems [34]. In addition to straightforward sand filters, biochar was shown to be a filter type that effectively removes MPs. By adsorbing, trapping, and entangling MPs on their surface, the biochar functions as a filter that separates MPs [37]. MPs are retained in charcoal filters because of the large size of pores. MPs are physically adsorbed between the biochar particles. For the elimination of bigger MPs, non-activated biochar is also taken into consideration. MPs can be removed from wastewater using biochar at a lower cost; however, the methods by which MPs are removed needs to be understood in greater detail [38]. In numerous studies, biochar was produced for removal of MPs using a variety of materials, including hardwood, corn, spruce bark, pine, etc., either alone or in conjunction with the pyrolysis process [37,38]. Additionally, it was reported that most biochar filters have shown to be successful at removing MPs in a variety of settings. Pine and spruce bark biochar-based adsorbents have demonstrated efficacy in eliminating MPs.

Table 2. Physical method of microplastics removal.

Sr No.	Method	Basic Used	Targeted MPs		Efficacy (%)	Reference
			MPs polymer types	Size (μm)		
1.	Colloidal coagulative gas aprons	Adsorption	Unsurfaced-coated polystyrene and Carboxyl-modified poly-(methyl methacrylate)	5	94	[39]
2.	Zirconium metal-organic structure-derived foams	Filtration	Varied MPs (nearly all types)	-	96–1.3	[40]
3.	Graphene oxide and Chitin sponges	Adsorption	carboxylate-modified polystyrene Polystyrene, and polystyrene modified with amine	-	90%, for neat polystyrene, 72.3% for carboxylate-based polystyrene and 89% for amine-functionalized polystyrene	[41]
4.	Dissolved air flotation	Both hydrophilic and hydrophobic contact and charge	Polyethylene, Nylon 66/PA66, Polyethylene terephthalate	-	32–38	[42]
5.	Disc filter	Based on Retention	varied MPs	>20	40–98.3	[30]
6.	Ionic Liquid Phases based on Magnetic Polyoxometalate	Adsorption	Polystyrene	1–10	90	[43]
7.	Biochar-derived adsorbents (biochar of spruce bark and pine)	Adsorption	Varied MPs	-	100% (Polyethylene units) and virtually 100% fleece-based fibers	[38]
8.	Filters consisting of Biochar	Adsorption and filtration	Microbeads of Polystyrene	10	above 95%	[37]
9.	Bio-based filter	Gravitational filter	Varied MPs	>100	79–89%	[44]
10.	Magnetized nanotubes of carbon	Adsorption	Varied MPs	-	100%	[45]
11.	Electrocoagulation	Flocculation and settling	Microbeads of Polyethylene	300–355	90–100%	[46]

2.2. Chemical Technologies

Chemical remediation technologies (Table 3) use a ligand-exchange-mediated uptake-complexation system to bind tiny fragments by employing synthetic materials such as aluminum and iron-based salts and added coagulants. As this results in the formation of substantial associations between the particles, larger contaminated particles are easier to separate [47]. Wastewater treatment technologies include oxidative ditch and traditional activated sludge methods. A modified form of activated sludge known as an oxidative ditch breaks down plastic via a protracted solid retention period; 97% of MPs are reportedly removed by oxidation ditches [48]. MPs can be made of a wide diversity of polymers with various characteristics and exterior chemistries [37]. Finding an appropriate flocculant is difficult because different functional groups have a significant impact on how flocculants interact with microplastics [49]. The majority of flocculants currently in use depend on either iron or aluminum, which restricts their applicability [49]. Although polyelectrolyte-

based flocculants are more pliable, their water solubility makes them potentially hazardous to aquatic life and habitats [50]. Herbort et al. developed an innovative technique using organosilanes to overcome this problem [51–53]. One organic group and three reactive groups combine to generate the monomeric silicone-based compounds known as organosilanes. In the initial stage of fixation, the collaboration between the microplastic's surface and the organic group causes the organosilanes to adhere to the surface and clump the MPs into agglomerates [52]. A solid hybrid silica gel is designed by the combination of three reactive groups in the second step of fixation. The water-induced sol-gel process is chemically driven by silica gel to fix the microplastics. The reactive groups are hydrolyzed into extremely reactive silanols during this sol-gel method, which then condenses and produces siloxane linkages. (Figure 4a) [54,55]. Inadequate microplastic removal efficiency was found in several investigations [30].

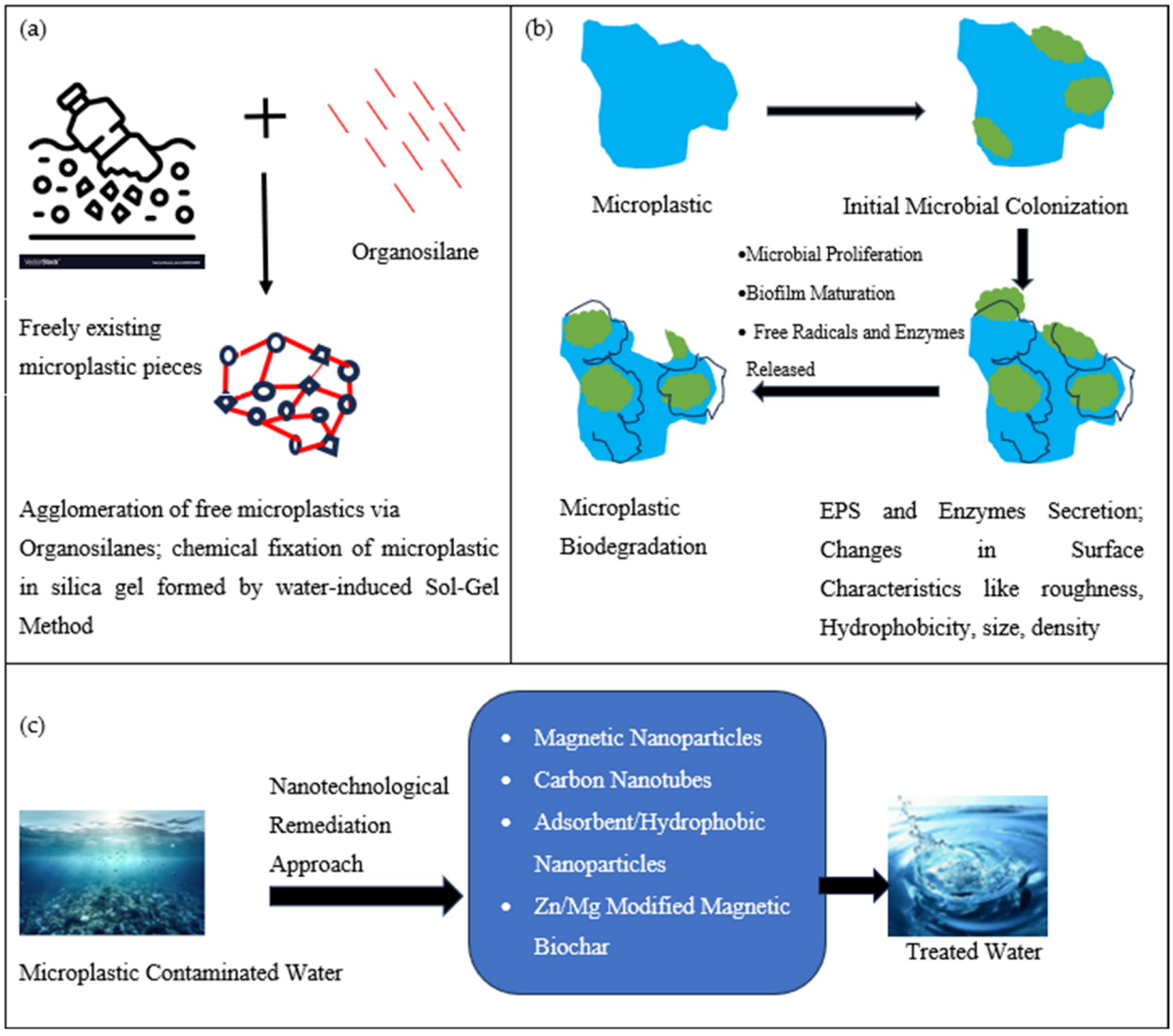


Figure 4. Some Methods of Remediation of Microplastics; (**a**) Agglomeration-fixation Process: Using organosilanes to filter out microplastics from water. Organosilanes adhere to the microplastic's surface and form bulky agglomerates and fix it via chemical means by forming silica through a sol-gel process in the presence of water; (**b**) Schematic representation of bioremediation of microplastics using biofilms; (**c**) MPs remediation through nanotechnology.

The novel organosilane-based technique, which combines a physical agglomeration process with a chemical fixing step brought on by water, results in strong particle development and stable agglomerates [52,53]. As a result, the organic groups can be adjusted to suit various surface chemistries and types of polymer. By altering reactive groups and organic groups, the reactivity of the organosilanes can be tailored to various water compositions [53,54]. This relatively new and understudied method has tremendous potential for use in the treatment of water and the removal of microplastics due to the enormous diversity and adaptability of organosilanes.

Currently, tap water on a pilot plant scale and demineralized water have both been utilized in laboratory testing to remove microplastics made of polyethylene and polypropylene [53,54]. Water compositions are examined for their effects on the removal process to examine the transferability to progressions in seawater and wastewater [56]. Dissolved ions, organic debris, and surfactant compounds can all have an impact on the sol-gel process and, consequently, the exclusion method.

Table 3. Chemical method of microplastics removal.

Method	Based on	Targeted MPs		Efficacy (%)	References
		MPs polymer types	Particle Size (μm)		
Coagulation along with sedimentation	Coagulation/settling	All	>10	>99	[37]
Coagulant of alum and alum along with sand coated with cationic polyamine	Coagulation with flocculation	Polyethylene-based	10–100	70–92.7	[57]
Coagulation/flocculation with polyamine-modified chemicals, iron, aluminum	Coagulation with flocculation	Polystyrene spheres	1 and 6.3	1micron particles removed with 95% efficacy and 6.3 micron with 76% efficacy	[58]
Activated carbon granules	Filtration	Nearly all types	1–5	57–61%	[37,51]
Inorganic-organic composite gels of silica	Interaction	Polyethylene, polypropylene, Polyethylene terephthalate	-	-	
Ozone	Degradation via chemical means	All types	-	90	[29]
Agglomeration caused by alkoxy-silylation	Agglomeration	Polyethylene, polypropylene	Not dependent on dimension, kind and quantity	-	[53]
Impact of branched and linear alkyl trichlorosilane	Adsorption + agglomeration + filtration	polyethylene, (both High-density and low density) and Polypropylene-derived MPs	1–1000	97.8	[54]
Photocatalysis	Heterogeneous photocatalysis induced via visible light and triggered by nanorods of zinc oxide	Polyethylene (Low-density)	-	30	[59]

Table 3. *Cont.*

Method	Based on	Targeted MPs		Efficacy (%)	References
Photocatalysis	Protein-based porous N-TiO_2 semiconductor resulting in green photocatalysis degradation	Polyethylene (high density)	-	-	[60]
Coagulation/flocculation by salts of aluminum and iron	Coagulation with flocculation	Polyethylene	-	-	[49]
Coagulation/flocculation using polyamine, iron, and aluminum-derived compounds	Coagulation with flocculation	Polystyrene beads	1 and 6.3	95.2% for 1 µm MPs; 75.5% for 6.3 µm MPs	[58]

2.3. Biological Technologies

2.3.1. Bioremediation Strategies to Mitigate Microplastic Pollution

Microbial Enzymes-Mediated Bioremediation

Microbial enzyme technology could be effectively used to achieve circularity for plastic waste. Microbes are the best candidates for minimizing environmental plastic waste because they can manufacture enzymes for consuming plastic as their energy source (Table 4). Only seven of the twelve different microbial phyla are known to contain suspected microbial plastic degraders [61]. This suggests that there is considerable untapped potential for the detection of enzymes that can achieve fragmentation of plastics in the bacterial and fungal phyla. It has already been established that several microbial enzymes, including laccases, hydrolases, lipases, and peroxidases, break down synthetic plastics. Though there is less research on the differences between bacterial and fungal enzymes, their various physiologies are likely going to have a different effect on how rapidly plastic breaks down [62]. Most enzymes of fungal origin have integrated enzymatic machinery for depolymerizing and mineralizing plastic according to related studies [63,64]. As microbially originated enzymes are more stable when compared to their animal and plant counterparts, the idea of leveraging microorganisms as a way to obtain beneficial enzymes for degrading plastic is becoming more and more popular. A well-known example of a bacterial strain that can break down polyethylene terephthalate (PET) is *Ideonella sakaiensis* 201-F6. More than 50 million tonnes of PET, the most produced synthetic polymer, is manufactured annually on a global scale [65]. IsPETase and IsMHETase, two serine hydrolases that resemble cutinases, were generated by strain 201-F6 [66]. PET decomposition occurs in two stages. In the preliminary step, an IsPETase induces a nick in the PET polymer chain that generates hydroxyethyl (HE)-terminal and terephthalic acid (TPA) PET chains. From the two PET chains with those termini, bis- and mono-(2-hydroxyethyl) terephthalic acid (BHET) and MHET, respectively, are later synthesized [67]. The subsequent digestion of these substances resulted in the production of terephthalic acid (TPA) and ethylene glycol (EG) [67–69]. EG and TPA are transformed into water and carbon dioxide, respectively, through assimilation and mineralization [66,70]. Nonetheless, IsPETase has undergone structural modifications, utilizing a variety of biotechnological methods, due to its outstanding enzymatic activity against PET. Several cutinases have also been shown to break down PET. Cutinases have been found in bacteria such as *Thermobifida fusca* and fungi such as *Fusarium solani pisi* [71,72]. Both groups' cutinases are a member of the ß-hydrolase superfamily and have analogous spatial arrangements. Despite certain similarities, there is no sequence homology between bacterial and fungal cutinases. Cutinase subfamilies that are prokaryotic and eukaryotic can thus be categorized [73]. Using microbial pre-treatment, it has been observed that *T. fusca* cutinase (Tfc) improves PET breakdown.

Thermobifida and *Thermomonospora* genera have been recognized as PET degraders [74–76]. The catalytic triad, consisting of MHETase, tannase, and PET hydrolase, can efficiently break down PET [77,78]. Structural research reveals that these enzymes have disulfide links and/or folds that provide them temperature stability. The cutinases that break down PET have been investigated in the fungal phyla *Humicola* and *Fusarium*. The bioinformatics-based study examined the function of PET hydrolases in degradation [79]. Metagenomic-based research revealed the presence of nearly 800 or more PET hydrolases in the strains of archaea and bacteria from terrestrial and marine environments. *Pseudomonas pelagia* cutinase is involved in the degradation of polyester [80]. *P. pertucinogena* can also be used to clean polyesters [81]. Polylactic acid, polycaprolactone, and bis(benzoyloxyethyl)-terephthalate can all be hydrolyzed by the genome-based esterases MGS0156 and GEN0105 [77]. The 3D structure of MGS0156 revealed the modified/hydrolase fold with a hydrophobic active domain and a lid site. TfH is the principal enzyme investigated from *Thermobifida fusca* for the breakdown of PET. PmC, PsC (*Pseudomonas mendocina*, *Fusarium solani*), HiC (*Humicola insolens*), Cut190 (*Saccharomonospora viridis*), LC-cutinase (having compost metagenome origin), lsPETase (*Ideonell asakaiensis*), and Tfcut2 (*Thermobifida fusca*) are all PET degrading enzymes [82–85]. Further testing of the prospective strains that could secrete the enzymes that degrade PET could contribute to their effective elimination on a global scale. Polyurethane (PU), which is created through the condensation of polyisocyanates and polyols, is coupled to urethane linkages [77]. In 1968, fungi were discovered to be the key contributive aspect in the degrading of polyurethane [86].

Innovative Biotechnological Methods to Augment Enzyme Activities against Microplastics

New approaches must be devised to overcome any putative restrictions of microbial enzymes in the MPs bioremediation process. Recent studies have demonstrated that biotechnological techniques strengthen the stability and structure of enzymes. The structural-based modeling method frequently used in protein engineering produces enzyme variations with increased enzyme performance and thermal-stable characteristics. Son et al. developed an IsPETaseS121E/D186H/S242T/N246D strain with increased thermostability and substrate binding efficiency [87,88]. The hydrolyzing action of mutant *T. fusca* thermally stable cutinase (TfCut2) displayed in the *E. coli* model was 12.7 times superior when compared to wild-type TfCut2 [89]. Thus, the growth of an improved and efficient microbial strain via site-directed mutagenesis may better facilitate MP bioremediation. Substantial biotechnological research is underway to produce biofuels from microalgae. In addition, several studies have noted the microalgae's potential for bioremediation. Numerous functional expression investigations on a diatom and a green alga were conducted [80–91]. A study by Mohanan et al. unveiled that intracellular lipases can be cloned and expressed [92]. These lipases efficiently broke down polymers with short and medium chains, pointing to a workable bioremediation strategy for the biodegradation of microplastics. Other cutting-edge methods, such as enzyme immobilization and nanotechnology, have started to garner interest for potential imminent applications to eliminate MPs. A possible strategy for reducing microplastic was revealed by PETase's site-directed immobilization process on magnetic nanoparticles [93]. It is worthwhile to carefully examine the cooperative behaviors of microbial associations and the enzymatic output of different microbial networks. Because microorganisms have seemingly limitless potential and are constantly adapting to their surroundings, it is anticipated that additional study in this field will rapidly unveil practical methods for biodegradation to be used at a larger scale.

Table 4. Microbial enzyme-mediated bioremediation.

Sr No.	Strain	Source/Type of Sample	Recognized Enzyme	Molecular Mass (kDa)	Mps Polymer Types	Dimension (µm)	Ref.
1.	*Bacillus subtilis*	Soil	Polyurethanase	28	Impranil (PU)	0.002	[94]
2.	*Pseudomonas aestusnigri VGXO14*	marine sand polluted with Crude oil	Hydrolase	32	Impranil (PE-PU)	0.1	[81]
3.	*Thielavia terrestris CAU709*	Soil	Cutinase TtcutA	25.3	PET in film form	5	[95]
4.	*Synechococcus* sp. *PCC 7002*	Culture	Esterase Hydrolase	-	Nanosphere of PE	0.0002–0.0099	[96]
5.	*Thermobifida fusca KW3 (DSM 6013)*	Culture	Hydrolase TfCut2	-	nanoparticles of PET	0.1–0.16	[97]
6.	*Ideonella sakaiensis 201-F6*	recycling site of PET bottle	PETase	24	film of PET	6	[66]
7.	*Aspergillus flavus PEDX3–*	Wax moth gut	multicopper oxidases (similar to laccases)	-	LDPE	<0.2	[27]
8.	*Amycolatopsis orientalis* ssp. *orientalis*	Culture	PLAase III PLAase II PLAase I	18 19.4 24	microfilm and powder of PLA	0.3–0.5	[98]
9.	*Humicola insolens*	Novozym© 51,032 (a commercial product)	Cutinase	32	Particles of PET	5	[68]

PU: Polyurethrane; PE: Polyethylene; PET: Polyethylene terephthalate; PLA: Poly lactic acid; LDPE: Low Density Polyethene.

2.3.2. Biofilms-Mediated MPs Remediation

Microorganisms swiftly colonize the microplastic surface to form a persistent biofilm when they are introduced into an aquatic environment [99]. Certain bacteria in biofilms can break down organic contaminants along with facilitating the adherence of pollutants by microplastics [100]. However, more notably, the collaboration of microplastics with biofilms may change the chemical and physical characteristics of the polymer surface, resulting in the biological degradation of the microplastics. Table 5 depicts the biofilm-forming microbes for MPs biodegradation. Early investigations into biofilms and microplastics concentrated on the sorption of heavy metals onto plastic surfaces, the connection between biofilms and toxins, and the effects of biofilm establishment on the microplastics [101]. Scientists have recently begun to investigate how biofilms affect the environmentally friendly biodegradation of microplastics. *Rhodococcus ruber* was shown to colonize and produce biofilms on polyethylene (PE) surfaces [102]. According to Hadad et al. (2005), the typical molecular mass of the PE samples was diminished to 14% and 21%, respectively [102]. Thus, investigation as to whether the progress of biofilms could modify the physicochemical features of the MPs began [103]. In an environment with a substantial quantity of methane gas, significant surface degradation of microplastics treated with biofilms has also been seen; this can endorse the surge in bacterial aggregation [104]. Water and carbon dioxide are the sole remaining byproducts of microplastic breakdown, which have no detrimental influence on the environment [104]. Significant surface degradation of microplastics treated with biofilms has also been seen in an environment with high amounts of methane gas, which may encourage the formation of bacterial aggregation [104]. In the natural environment, biofilms are both widely dispersed and accessible [104], [39]. The ecological threat posed by microplastics in the environment has also been projected by scientists to be

amplified by biofilms, which operate as transporters and may boost the adsorption of MPs to contaminants in the ecosystem [42,105,106]. When glucose is used as an external carbon source, microplastics are found to degrade more quickly than natural biofilms [107]. Other studies, on the other hand, have hypothesized that biofilms can encourage the adsorption of MPs to environmental contaminants, acting as carriers and escalating the ecological danger of MPs in the ecosystem [42,105,106]. According to one study, as soon as microplastics are added to an aqueous environment, bacteria quickly colonize their surfaces and produce biofilms that encourage the adsorption of the microplastics to contaminants in the environment [40]. However, if the biofilm is grown and established beforehand under artificial circumstances before being treated with microplastics, the problem can be largely eliminated. Implementing the technology of biofilm deterioration of MPs to the in-situ cleanup of microplastics in freshwater sources or integrating it into the source treatment of microplastics can also adsorb the additional environmental contaminants along with degrading microplastics in the aqueous environment. As to how adsorbed contaminants should be properly addressed, more study is required. Strategies to effectively deal with adsorbed pollutants also require further research. Breaking down microplastics with biofilms could be a relatively sustainable development strategy [104,107]. Today, there are two primary categories of biofilm cultivation techniques: laboratory cultivation and in situ cultivation. In situ, cultures are typically employed to examine how microplastics behave in the environment after adhering to biofilms. In several studies on environmental behavior and for the evaluation of wastewater treatment systems for microplastic biofilm disintegration, laboratory cultures have been used. Biofilms can be produced artificially using natural water sources by extracting epiphytes and transferring them to a lab. Microplastics were added after biofilms or cultures had developed, and the degradation of the microplastics was examined [104]. However, the flora of the biofilm might not be identical to that of the in situ culture. A laboratory culture can significantly curtail the culture period and incorporate external variables in order to regulate the quantity and ability of biofilm growth to mitigate MP pollution. Laboratory cultivation is the name given to this procedure. To regulate the speed and accuracy of biofilm development in a laboratory setting, external stimuli can be added, but the culture period can be significantly cut. However, the flora of the biofilm may not be identical to that of the in situ culture. Diverse aspects affecting the biofilm development on microplastic surfaces include the type of plastic polymers and their physicochemical properties: pH, Salinity, temperature, and ultraviolet radiation [104]. An earlier study found that a maximum deterioration of 20% could occur. The main reason for this is that microorganisms take some time to change the inherent properties of microplastics, which include high molecular weight, structural stability, vast surface area, and hydrophobicity. Moreover, there are several phases involved in the biodegradation of microplastics, none of which can take place at the same time. Microplastics deteriorate through changing the hydrophobicity and roughness of their surfaces. The degradation of microplastic biofilms begins with this process, which is followed by further steps. Organisms physically breakdown plastics during the ensuing extremely slow biodegradation phase by cutting, grinding, or assimilating the waste [39]. Therefore, the full deterioration process takes a long time. Another aspect that, to some extent, additionally influences the degradation of such materials is the pace and nature of biofilm growth on the surfaces of microplastics. In conclusion, while employing biofilms to degrade microplastics is a possible strategy, the level of degradation is currently insufficient.

Table 5. Microorganisms involved in biodegradation of microplastics in various literature.

Sr No.	Microorganism Name	Microorganism Category	MPs Polymer Types	Efficacy (%)	References
1.	*Rhodococcus ruber*	Bacteria	PE	8	[108]
2.	*Zalerion maritimum*	Fungus	PE	43	[109]
3.	*Acinetobacter gerneri*	Bacteria	Impranil DLN	_	[110]
4.	*Bacillus muralis*	Bacteria	PET	_	[111]
5.	*Aspergillus* sp. *S45*	Fungus	Polyester PUR film	15–20	[112]
6.	*Penicillium* sp.	Fungus	polyester/polyether film; Impranil DLN	8.9	[113]
7.	*Bacillus subtilis*	Bacteria	PE	9.26	[114]
8.	*Pleurotus sajor caju PVC film*; *Poliporus versicolor*	Fungus	PVC film	_	[115]
9.	*Mycobacterium* sp. *NK0301*	Bacteria	PVC film (Plasticized)	_	[116]
10.	*Paenibacillus urinalis NA26*; *Microbacterium* sp. *NA23*; *Pseudomonas aeruginosa NB26*; *Bacillus* sp. *NB6*	Bacteria	PS-based film	_	[117]
11.	*Rhodococcus* sp. *Strain 36*; *Bacillus* sp. *Strain 27*	Bacteria	PP MPs	4–6.4	[118]
12.	*Stenotrophomonas panacihumi*	Bacteria	PP film	_	[119]
13.	*Sphingobium*, *Novosphingobium*	Bacteria	PS	_	[120]
14.	*Proteobacteria*, *Deinococcus-Thermus*, *Gammaproteobacteria*, *Alphaproteobacteria*, *Cyanobacteria*	Bacteria	PE	_	[104,107]

PE: Polyethylene PP: Polypropylene; PS: Polystyrene: PET: Polyethylene terephthalate; PVC: Poly vinyl chloride.

Microplastics are degraded by biofilm microorganisms because macro-polymers cannot be used by these organisms directly. Several extracellular oxidases and hydrolases break down the macromolecular polymers into oligomers and monomers once microplastics have entered the biofilm, followed by the bacteria picking up and start converting these short-chain polymers [39]. Finally, microplastics can mineralize in the presence of bacteria and create water and carbon dioxide. To eliminate microplastics, the biofilm approach normally requires four steps (Figure 4b). Prokaryotes, fungi, and bacteria first congregate on the surface of microplastics and modify them. The subsequent phase of microbial degradation entails the disintegration of microplastic additives and monomers. Following this, biologically induced enzymes or free radicals attack microplastics and their additives, eroding them and resulting in mechanical instability. In the fourth stage, microorganisms destroy microplastics as an effect of microbial filament disintegration and water penetrating the polymer matrix [121]. The key stage of degradation is thought to be the second step. Plastic products typically have a variety of additives added to them in order to enhance or modify their mechanical and chemical performance. These additives are left behind when plastic trash is transformed into microplastics, and their presence significantly slows down the breakdown of microplastics. The microplastics cannot be destroyed until the additives have been leached from their interiors during the ensuing degradation process. Microorganisms can break down polymer additives to promote the establishment of biofilms and the preliminary adherence of bacteria to the external surface of the particles [121]. In this procedure, the creation of biofilms is encouraged, which aids the biofilms in breaking down the microplastics as well as the additives. By identifying and cultivating microbes that have a significant impact on that process and then utilizing them to obtain the optimum results, the complexity of microplastic breakdown can be decreased.

2.3.3. Membrane Bioreactor

At both real and pilot scales, various technologies have been researched to remove microplastics from sewage from industrial and municipal sources [106]. A reliable method for removing microplastics from wastewater in actual wastewater treatment facilities or on a modest scale is the membrane bioreactor (MBR) [30]. Many studies revealed that the MBR process had an efficacy of removing between 64.4 and 99.9% of particles [30,122]. Membrane bioreactors, in contrast to conventional activated sludge procedures, combine the biologically activated sludge process and membrane separation to more effectively remove microcontaminants in industrial and municipal wastewater treatment plants [123]. Baresel et al. investigated the exclusion of several types of micro-contaminants involving microplastics and organic compounds using a membrane bioreactor and a granulated active carbon-based biofilter with a hydraulic retention period of 10 h [123]. A biological reactor was followed by an ultrafiltration system.

2.3.4. Nanobioremediation: Bionanomaterials-Based MP Degradation

Plastics may not entirely decay for more than 500 years [124]. The use of nano-bioremediation technologies could drastically shorten this time. Although bioremediation technology is environmentally favorable due to its low mechanical and chemical stability, it is less effective and takes more time [125]. The remediation process could be accelerated by integrating nanotechnology with bioremediation while posing no risk to supplementary biological arrangements [126]. Owing to the enhanced activity of nanoparticles and the ability for in-situ action, tailored nanomaterials have the potential to be more efficient and less expensive than current methods [127]. Nanomaterials can function as membrane filters, flocculants, catalysts, or adsorbents (Figure 4c). An adsorbent, for instance, can adsorb MPs in water. Adsorption, an exothermic mass transfer process, involves the physical or chemical attachment of a molecule to a firm solid surface via the interface of liquid and gas. MPs can be removed from water using membrane filters, whereas MP breakdown is accelerated by catalysts. The aggregation of colloidal particles is facilitated by flocculants [128]. The water system's resulting floc facilitates filter separation. Activated carbon is the most often implemented solid adsorbent in both commercial and household water filtration because of its high porosity and sizable surface area [129]. However, considering the vast expense, this method is largely ineffective. Due to their efficiency and low cost, several carbon allotropes and functionalized carbon nanomaterials are now employed [130]. Nano-scaled green semiconductors are extremely effective at removing MPs from wastewater when employed as photocatalytic agents. Nanomaterials are of significant interest for photocatalysis, owing to their substantial surface-to-volume ratio, a feature that allows more impurity oxidation than the average bulk material and results in improved catalytic activity [131]. Here, a sequence of photooxidation and photoreduction events brought on by the transfer of electrons to the adsorbed molecule is what causes the MPs to degrade [132]. It has been asserted that, compared to spherical nanoparticles, hexagonal nanorods have a larger surface area. Being crystalline, nanorods are powerful and useful [131,133]. In the past, the most common flocculants were inorganic compounds such as aluminum sulphate and ferric chloride. These compounds can produce a lot of sludge in the environment and are sensitive to pH fluctuations. Nonetheless, the sludge's metal ions may move into the groundwater and cause significant problems. Recently, there has been significant interest in polymer flocculants as a potential substitute for inorganic flocculants (flocs) due to their capacity to produce enormous, coherent aggregates. Because the produced flocs have a large surface area (sorption capacity), low-temperature slow-settling aggregates respond well to flocculants. Although synthetic polymers are very effective, they are not biodegradable, poorly soluble, and challenging to recycle from post-process waste. They may therefore stress the ecosystem. The magnitude of the random coils or the radius of gyration, which is the favored configuration in solution, determines how much biopolymers or other natural polymers flocculate [134,135]. They are simply stable and inoperable at low dosages, but they can be easily functionalized to boost their

effectiveness [135]. The addition of nanoscale components can significantly improve the functionality of biopolymers. Due to its simplicity of use, improved performance, lower energy cost, and longer service life, nano-bioremediation is particularly advantageous and effective at the laboratory level [136]. Table 6 lists the effectiveness of numerous bionanomaterials for remediating MPs. A non-woven cellulose fabric served as the foundation for the water filtration membrane created by Jalvo et al. [136]. The hydrophilicity, elasticity modulus, and tensile strength of the fabric were all greatly improved by the nanocrystal or nanofiber coating. Additionally, it increased the negative (positive) surface charge for cellulose-based (chitin-based) transformations [136]. Compared to other commercially available membranes, electrospun lignin-zeolite composite nanofiber membranes exhibit better flux and penetration rates. The mechanical properties of the nanocomposite are additionally enhanced by uniformly dispersed zeolite nanoparticles and post-treatment heating. The tensile strength and modulus were dramatically increased by the addition of 1 wt% zeolite nanoparticles. This bionanomaterial was successful in pre-filtering a variety of MPs [137]. Girbic et al. created the separation method known as magnetic extraction [138]. To aid magnetic recovery, they created hydrophobic Fe nanoparticles that adhere to plastic. Up to 92% to 93% of the MPs in seawater, 84% of the MPs in freshwater, and 78% of the MPs in sediments could be recovered using these nanoparticles [138]. Recently, a hydrophobic magnetite nanoparticle was created using an aerial component of the *Anthemis pseudocotula* plant extract. These nanoparticles can achieve comparable benefits with less harm to the ecosystem [139]. In a related study, a solution of glucose and Fe_3O_4 was swiftly and readily converted into an extremely porous and evenly dispersed carbon-Fe_3O_4 composite using a one-pot microwave synthesis process. This composite assisted as an absorbent, and an external magnet was effectively used to remove the MPs that adhered to its surface from the water [140]. As a special natural bio-flocculant, lysozyme amyloid fibrils were used. The flocculant has been referred to as a nanomaterial due to its tiny dimension. Considering a remarkable turbidity removal efficacy of 98.2% for dispersed polystyrene MP and 97.9% for humic acid, this flocculant displays a positively charged surface over an extensive pH range. According to Wang et al., a new photocatalytic Au-Ni-TiO_2 micromotor-based passive particle removal technique has been revealed [141]. The micromotor (30 nm) was made from TiO_2 particles (700 nm) coated with gold and nickel (10 nm). They suggested two methods for removing MPs. Individual micromotors removed material via phoretic interactions, whereas chained assemblies moved objects by pushing or shoveling. The latter technique is advantageous for MP removal in real-world settings since it operates effectively without the need for water or fuel in the diluted peroxide solution. They demonstrated that matter could be removed by light-driven micromotors using arrays of materials and shapes [141]. Figure 4c illustrates how nanotechnology is used to remediate MPs. It has recently been reported to produce plant-based, hydrophobic magnetic nanoparticles utilizing an aerial portion of the *Anthemis pseudocotula* plant. These nanoparticles can yield similar outcomes with lesser environmental damage [142]. Controlling the nanomaterial size, which is crucial for photocatalysis, is the main challenge in green synthesis. Advances in green technology will soon be made as a result of the extensive study on green synthesis techniques.

Table 6. Classification of bionanomaterials according to their functions and basic mechanism involved in MPs.

Sr No.	Nanomaterials Functionality	Action Mechanism	Nanomaterials Used in MPs Remediation
1.	Adsorbent	MPs and nano-adsorbent interact to cause adsorption to occur. Hydrophobic, electrostatic, hydrogen-bond, electron conjugate, π-π electron interaction, and complexation are some possible forms of this relationship	composite membranes made of nanofibers of lignin and zeolite [137] Fe nanoparticles (Hydrophobic in nature) [138] Magnetized biochar functionalized with Magnesium and Zinc [37] Carbon-based magnetic nanotubes [45] C@Fe_3O_4 composite [140]
2.	Filter membrane	MPs can be successfully separated from the effluent using nano filters using nanoscale sieves	Cellulose nanocrystals impregnated non-woven [136] TEMPO-oxidized cellulose nanofibers impregnated with unwoven cellulosic fibre chitin nanocrystals permeated Non-woven cellulose fabric [136]
3.	Flocculant	Charge neutralization is the basis for this technique. The positively charged flocculant balances out the MPs negative charge, causing flocs to form. By using filtering or sedimentation, these flocs can be split	Lysozyme amyloid fibrils [143]
4.	Catalyst/Photocatalyst	When exposed to UV radiation, they form reactive species, which lead to the destruction of MP	Micromotor based on Au@Ni@TiO_2 [141]

3. Circular Economy Solution to Plastic Waste and Challenges in Its Implementation

The classic linear, make, use, and discard economy paradigm is opposed by the circular economy. According to Barra et al. [14], the circular strives to conserve resources for as long as possible, make the most of them while they are being utilized, and recuperate and revive goods and constituents at the termination of their productive lifespans. The circular economy encourages a manufacture and consumption pattern that is uplifting and reformative by design. The circular economy is viewed as central to reducing plastic pollution [144,145]. The sustainable design of plastic goods, strengthening of regulations that govern the production, recycling, and use of alternate resources, as well as the intentional inclusion of microplastics in products, the development and research of biodegradable plastics and bioplastics, and the improvement of wastewater treatment facilities are all important tools for reducing microplastic contamination and promoting the circular economy [13,144–146]. The goals of the circular economy, with examples of how these objectives could be reached by modern science and technical innovation, were outlined as follows:

3.1. Plastic Production from Alternate Feedstocks

Alternative feedstocks include naturally occurring biopolymers, sewage sludge, and food items. Bio-based materials include cellulose, oils, and starches [147,148]. It is possible to manufacture some polymers utilizing harmless and biodegradable materials [149]. Additionally, environmentally suitable alternatives for the flame retardants that are added to plastics have been discovered, which may eliminate the need for some hazardous chemicals in the production of plastics [150].

3.2. Use of Plastic Waste as a Resource

A few examples of the collection and retrieval of plastic trash for re-manufacturing into novel high-value products include the constructing of roads, the manufacturing of biobricks and biocomposites for a multitude of industrial uses, the building of furniture, as well

as the production of clothing and footwear [151,152]. Despite significant challenges, plastic waste has also been converted into liquid fuel and implemented as fuel in a waste-to-energy cycle [153]. Chemical recycling can be used to recover the petrochemical components of plastic polymers and turn them into new plastics, and recycling techniques, including re-fabrication, chemical recycling, and organic recycling, can turn them into new products. For instance, Zhu et al. have successfully created chemically recyclable and reusable plastics with indefinite reusage [154]. Studies have also revealed the potential for biobased recycling of waste plastics, as polyethylene plastic, which accounts for a sizeable portion of manufactured plastics worldwide, may be destroyed by bacteria and caterpillars [66].

3.3. Redesign Plastics Manufacturing Processes and Products

This could be potentially attained by implementing approaches such as greener production, discontinuing single-use plastic, as well as fabricating products with extended use [155]. For instance, eliminating microplastics from toothpaste and shampoo, developing tyres and clothing to have less wear and tear, and so forth. Another redesign tactic might be to offer cleaning of particular maintenance products in bulk with refillable plastic ampules to get rid of single-use bottles. This style has already been used in products including replenish bottles, petainer packaging, and splosh [156]. As an alternative to single-use bottles, the usage of refillable and returnable reusable drinking bottles, can reduce material costs and greenhouse gas emissions [157].

3.4. Collaboration between Companies and Customers

Collaboration between companies and customers must be increased in order to raise knowledge of the beneficial effects of reducing the use of unneeded plastics and throw-away culture, stimulating recycling, and boosting the value of plastic products. Harnessing waste products from one business as a source of raw materials for another is one way to do this (industrial symbiosis) [153,158]. The advantages to the environment and climate from recycling plastic waste through industrial symbiosis have been underlined in numerous analyses [159]. By augmenting garbage collection systems and developing successful take-back initiatives, households may participate in the symbiosis process [25]. Another option for reusing plastic waste is to support supportable corporate depictions that view items as amenities and promote the allocation and leasing of plastic goods. Providing reliable information platforms that trace the flow of plastic resources into the economy, giving data on the composition of plastic products, fostering cross-value chain communication, knowledge sharing, and building on existing international institutional networks' experiences are all viable strategies.

3.5. Circular Economy Roadblocks in the Plastic Sector

There are multiple obstacles to the attainment of a circular economy in the plastics industry. First, it is expensive to alter the currently in-use linear plastics production infrastructure. Second, hazards and large upfront investment costs when switching to the circular model must be considered. Third, complicated global supply systems for production and consumption are required. Fourth, there is a lack of support for small and medium-sized firms when expanding circular models. Moreover, there are difficulties in business-to-business collaboration, such as transaction costs and product makers' resistance to change, which may be the result of ignorance. Because incentives favor the linear production and use paradigm, circular products are not competitive. Furthermore, key legislation hardly ever considers plastics, there exist unfavorable restrictions and a lack of standards, and there is insufficient data monitoring and reporting, particularly in underdeveloped nations. All these factors contribute to lack of consumer interest or knowledge, as well as resistance to accepting recycled goods.

Thus, the circular economy model will need to become more competitive and a demand-pull for circular plastic products would need to be created to overcome these challenges. It will also be required to collaborate with the business community to promote

change and with the general public to encourage societal changes and increase demand for circular products. Therefore, it is crucial to stop unnecessary plastic production, use, and disposal [14]. This can be accomplished in many ways, such as removing excessive plastic packaging from products, discontinuing the needless usage of micro-sized plastics in personal care items, and encouraging the practice of recyclable and regenerative plastic substitutes, such as wooden cutlery in place of single-use plastic cutlery and cellulose-based materials in place of plastic packaging and bags [13].

Consumers should be made aware of products that include microplastics, and sustainable and environmentally friendly alternatives should be pushed. This has been demonstrated by initiatives undertaken by large cosmetic companies to quit using microbeads by emailing consumers with non-plastic substitute goods consisting of walnut husks, oatmeal, granulated sugar, nanomaterials such as bacterial cellulose, or other waste lignocellulosic material [160]. Additionally, the strength, stiffness, fatigue life, and further anticipated aspects of bituminous mixes can be greatly improved by the inclusion of waste plastic in miniature quantities (approximately 5–10% by weight of bitumen), leading to an improvement in the performance and lifetime of pavements [161]. The removal of plastics from the environment would be made possible by effective oversight, recycling, and an environmentally sound disposal technique.

4. Policies Regarding MPs Management

Microplastic pollutant cleaning including pollution source control and remediation should be the two main focuses of policies and initiatives intended to minimize microplastic pollution. The Microbeads Free Water Acts (2005), implemented by the US government, banned the removal of plastics from the environment starting in 2017 and promoted the adoption of biodegradable alternatives to traditional plastic polymers, such as polylactide (PLA) and polyhydroxyalkanoates (PHA). Nevertheless, this is only feasible in a small number of nations. This action will improve the recycling of plastic and the usage of plastic as a fuel. To properly separate MPs and prevent them from entering rivers and oceans, wastewater treatment facilities must be upgraded and improved. Many nations have passed legislation taxing plastic bags and, in some cases, outlawing their usage. To properly separate and prevent microplastics from entering rivers and oceans, wastewater treatment facilities will also be upgraded and improved. The Ministry of Environment, Forests, and Climate Change of the Government of India has made public the Plastic Waste Management Amendment Rules, 2021, which ban some single-use plastic items with poor use and a high potential for littering by 2022 [162]. Further research and development in the field of bioremediation strategies, such as the biodegradation of microplastics using microbes, are required to eliminate plastic waste to a greater extent [163].

Plastic shopping bags have been thickened from fifty microns to seventy-five microns and one hundred twenty microns to reduce the quantity of waste they produce. As an outcome of the rise in thickness, the plastic can also be reused. The resulting single-use plastics, including polystyrene and expanded polystyrene, were prohibited from being produced, imported, stockpiled, distributed, marketed, and used under the Plastic Waste Management Amendment Rules, 2021 [162].

The list of items that are banned includes balloons with plastic sticks, earbuds with plastic sticks, candy sticks, plastic flags, polystyrene (Thermocol) for decorations, ice cream sticks, plates, glasses, and cups, as well as cutlery such as spoons, forks, and knives, straws, wrapping or packing films around sweet boxes, trays, cigarette packets, invitation cards, and plastic or PVC banners that are less than 100 microns thick. The Law on the Prevention and Control of Environmental Pollution by Solid Wastes (LPCEPSW), which regulates waste disposal facilities, forbids the disposal of plastics in rivers, lakes, and reservoirs, and promotes the circular economy, is in charge of controlling plastic pollution in China [160]. Fiscal policy measures, such as direct surcharges, duties, carbon or supply taxes, and tariffs on specific forms of plastic, such as plastic bags, disposable tableware, and other one-time-use commodities, may be necessary to deter the use of non-essential

plastic and other unsustainable behaviors. These actions can also help increase plastic recycling's effectiveness, financial viability, and acceptance. Additional regulatory and policy measures are required, involving recycling targets, increased producer responsibility, container deposit laws, obligatory circular/eco-design norms and requirements, public procurement policies, restrictions on the disposal of plastics in landfills and incinerators, and absolute prohibitions on some plastic products, such as single-use plastic bags.

5. Conclusions and Future Perspectives

Plastics are one of the most crucial breakthroughs in global industry, but they are also having a progressively detrimental influence on the ecosystem and human health, including climate change, marine pollution, biodiversity loss, and chemical exposure. Microplastics (MPs) are a rising cause of freshwater and soil pollution. In this scenario, swift intervention needs to be taken. MPs could be eliminated using an assortment of physical, chemical, and biological cleansing techniques. A potential microplastic remediation method would combine bioremediation with renewable-source biodegradable plastic. Nonetheless, there is a pressing need to advance these technologies even further. Microplastics that degrade via biofilms are environmentally favorable. Nevertheless, there are unavoidable drawbacks, such as prolonged degradation timeframes and inadequate degradation rates. Future studies should consider enhancing biofilm development speed and quality to speed up the process by which biofilms break down MPs. Functional strains obtained through strain improvement techniques may greatly improve microplastic degradation efficiency. It is crucial to thoroughly assess the enzymatic output of various microbial networks as well as the cooperative actions of microbial consortia. Enzyme combinations have also shown improved degrading action against complex polymers and might be thought of as a pertinent approach to microplastic bioremediation, particularly for MPs that are resistant to treatment. The considerable flexibility and modifiability of organosilanes, as well as their reactivity with diverse polymers, may be exploited in the degradation of MPs. The circular economy solutions to the plastic industry would be tremendously advantageous to manage plastic waste. Some practical methods for implementing a circular economy in the plastic sector involve generating polymers from substituted non-fossil fuel feedstocks; maximizing plastic waste as a resource; and redesigning industrial plastic processes and products to improve durability, reusability; and waste prevention. In addition, promoting sustainable business models that retail plastic products as services and ensuring the adoption of fiscal and monitoring measures are other examples of circular economy solutions to plastic waste. This would promote recycling and boost the value of plastic products (Figure 5). The triple R principle stating "Reduce, Reuse, and Recycle" for reimagining the use of plastic waste must be aptly employed with strict regulations to mitigate the adverse effect of MP's pollution. Nonetheless, it is estimated that plastic pollution will continue to escalate without coordinated action by the public, governments, and global collaborations in design, development, production, usage, and disposal. Thus, indomitable management strategies and strict legislation are mandatory for the remediation of microplastics. Moreover, novel enterprises will aid in generating a circular economy for plastics by establishing material recovery amenities, endorsing segregation of domestic waste, and supporting the community inclusion of workers within the informal waste-picking sector.

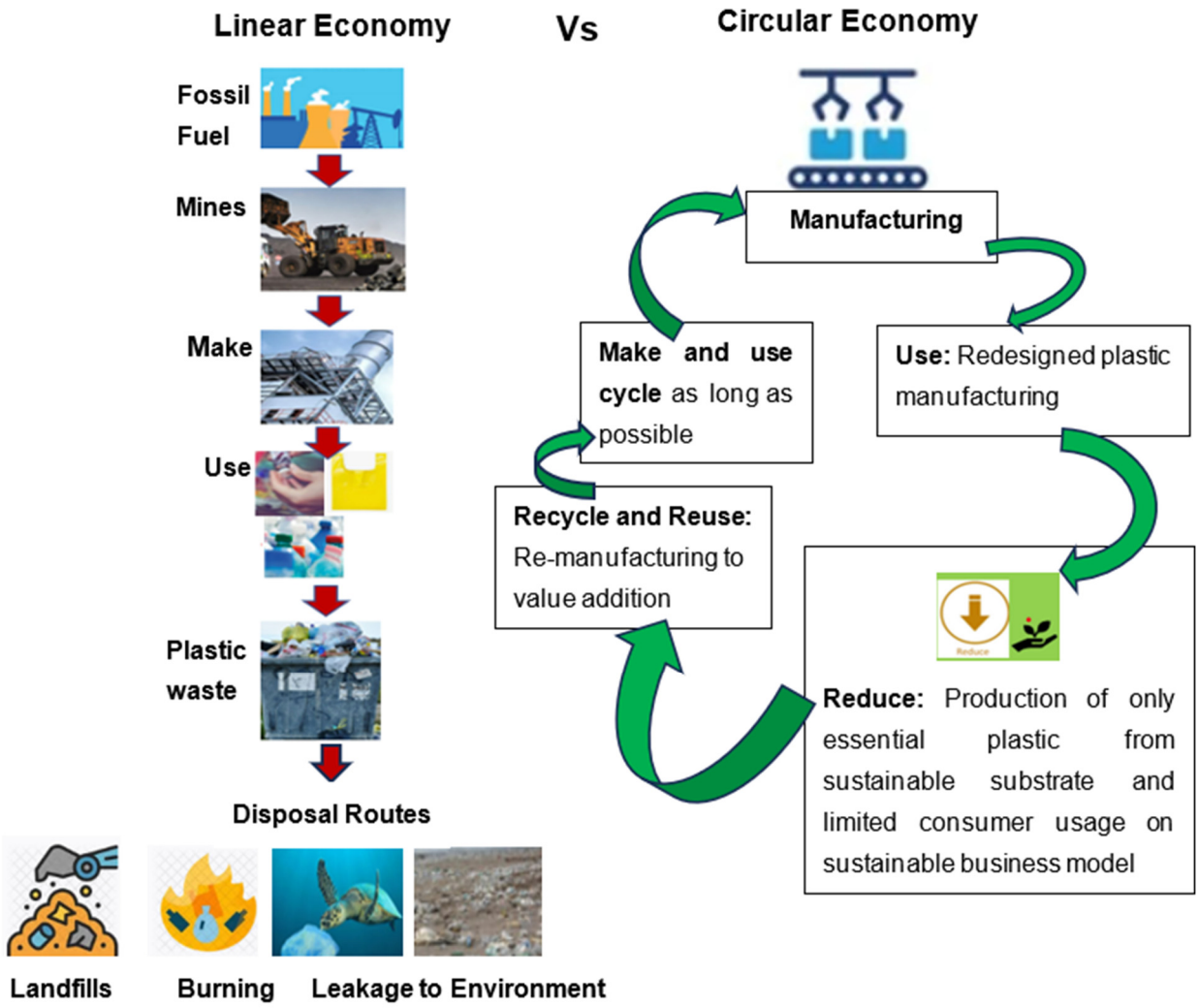


Figure 5. Envisaging a Paradigm Shift Toward Circular Plastic Economy from Linear Plastic Economy: A Sustainable Approach to Engender Resource from Waste.

Author Contributions: Conceptualization, C.S. and S.D.; methodology, C.S. and S.D.; writing—C.S.; writing—review and editing, C.S. and S.D.; visualization, S.D.P., A.K. and P.P.; supervision: C.S., S.D. and S.D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sridhar, A.; Kannan, D.; Kapoor, A.; Prabhakar, S. Extraction and detection methods of microplastics in food and marine systems: A critical review. *Chemosphere* **2021**, *286*, 131653. [CrossRef] [PubMed]
2. Geyer, R.; Jambeck, J.R.; Law, K.L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **2017**, *3*, e1700782. [CrossRef] [PubMed]
3. Orlando, M.; Molla, G.; Castellani, P.; Pirillo, V.; Torretta, V.; Ferronato, N. Microbial enzyme biotechnology to reach plastic waste circularity: Current status, problems and perspectives. *Int. J. Mol. Sci.* **2023**, *24*, 3877. [CrossRef] [PubMed]
4. Udovicki, B.; Andjelkovic, M.; Cirkovic-Velickovic, T.; Rajkovic, A. Microplastics in food: Scoping review on health effects, occurrence, and human exposure. *Int. J. Food Contam.* **2022**, *9*, 7. [CrossRef]

5. Andrady, A.L. The plastic in microplastics: A review. *Mar. Pollut. Bull.* **2017**, *119*, 12–22. [CrossRef]
6. Thompson, R.C.; Olsen, Y.; Mitchell, R.P.; Davis, A.; Rowland, S.J.; John, A.W.G.; McGonigle, D.; Russell, A.E. Lost at Sea: Where Is All the Plastic? *Science* **2004**, *304*, 838. [CrossRef]
7. Avio, C.G.; Gorbi, S.; Milan, M.; Benedetti, M.; Fattorini, D.; D'Errico, G.; Pauletto, M.; Bargelloni, L.; Regoli, F. Pollutants bioavailability and toxicological risk from microplastics to marine mussels. *Environ. Pollut.* **2015**, *198*, 211–222. [CrossRef]
8. Smith, M.; Love, D.C.; Rochman, C.M.; Neff, R.A. Microplastics in seafood and the implications for human health. *Curr. Environ. Health Rep.* **2018**, *5*, 375–386. [CrossRef]
9. Andrady, A.L. Microplastics in the marine environment. *Mar. Pollut. Bull.* **2011**, *62*, 1596–1605. [CrossRef]
10. Cole, M. A novel method for preparing microplastic fibers. *Sci. Rep.* **2016**, *6*, srep34519. [CrossRef]
11. Cole, M.; Webb, H.; Lindeque, P.K.; Fileman, E.S.; Halsband, C.; Galloway, T.S. Isolation of microplastics in biota-rich seawater samples and marine organisms. *Sci. Rep.* **2015**, *4*, 4528. [CrossRef] [PubMed]
12. Yee, M.S.-L.; Hii, L.-W.; Looi, C.K.; Lim, W.-M.; Wong, S.-F.; Kok, Y.-Y.; Tan, B.-K.; Wong, C.-Y.; Leong, C.-O. Impact of microplastics and nanoplastics on human health. *Nanomaterials* **2021**, *11*, 496. [CrossRef] [PubMed]
13. King, S.; Locock, K.E. A circular economy framework for plastics: A semi-systematic review. *J. Clean. Prod.* **2022**, *364*, 132503. [CrossRef]
14. Barra, R.; Leonard, S.A.; Whaley, C.; Bierbaum, R. *Plastics and the Circular Economy: A STAP Document*; Scientific and Technical Advisory Panel (STAP) to the Global Environment Facility (GEF), UN Environment: 2018; Scientific and Technical Advisory Panel: Washington, DC, USA, 2018.
15. Shanker, R.; Khan, D.; Hossain, R.; Islam, T.; Locock, K.; Ghose, A.; Sahajwalla, V.; Schandl, H.; Dhodapkar, R. Plastic waste recycling: Existing Indian scenario and future opportunities. *Int. J. Environ. Sci. Technol.* **2022**, *20*, 5895–5912. [CrossRef]
16. Zuccarello, P.; Ferrante, M.; Cristaldi, A.; Copat, C.; Grasso, A.; Sangregorio, D.; Fiore, M.; Conti, G.O. Exposure to microplastics (<10 μm) associated to plastic bottles mineral water consumption: The first quantitative study. *Water Res.* **2019**, *157*, 365–371. [CrossRef]
17. Gündoğdu, S. Contamination of table salts from Turkey with microplastics. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* **2018**, *35*, 1006–1014. [CrossRef]
18. Barboza, L.G.A.; Vethaak, A.D.; Lavorante, B.R.; Lundebye, A.-K.; Guilhermino, L. Marine microplastic debris: An emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* **2018**, *133*, 336–348. [CrossRef]
19. Kosuth, M.; Mason, S.A.; Wattenberg, E.V. Anthropogenic contamination of tap water, beer, and sea salt. *PLoS ONE* **2018**, *13*, e0194970. [CrossRef]
20. Catarino, A.I.; Macchia, V.; Sanderson, W.G.; Thompson, R.C.; Henry, T.B. Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environ. Pollut.* **2018**, *237*, 675–684. [CrossRef]
21. Makhdoumi, P.; Naghshbandi, M.; Ghaderzadeh, K.; Mirzabeigi, M.; Yazdanbakhsh, A.; Hossini, H. Micro-plastic occurrence in bottled vinegar: Qualification, quantification and human risk exposure. *Process Saf. Environ. Prot.* **2021**, *152*, 404–413. [CrossRef]
22. Li, D.; Shi, Y.; Yang, L.; Xiao, L.; Kehoe, D.K.; Gun'ko, Y.K.; Boland, J.J.; Wang, J.J. Microplastic release from the degradation of polypropylene feeding bottles during infant formula preparation. *Nat. Food* **2020**, *1*, 746–754. [CrossRef] [PubMed]
23. Du, F.; Cai, H.; Zhang, Q.; Chen, Q.; Shi, H. Microplastics in take-out food containers. *J. Hazard. Mater.* **2020**, *399*, 122969. [CrossRef] [PubMed]
24. Karami, A.; Golieskardi, A.; Keong Choo, C.; Larat, V.; Galloway, T.S.; Salamatinia, B. The presence of microplastics in commercial salts from different countries. *Sci. Rep.* **2017**, *7*, 46173. [CrossRef]
25. Picó, Y.; Barceló, D. Analysis and prevention of microplastics pollution in water: Current perspectives and future directions. *ACS Omega* **2019**, *4*, 6709–6719. [CrossRef] [PubMed]
26. Parashar, N.; Hait, S. Occurrence and removal of microplastics in a hybrid growth sewage treatment plant from Bihar, India: A preliminary study. *J. Clean. Prod.* **2022**, *376*, 134295. [CrossRef]
27. Zhang, J.; Gao, D.; Li, Q.; Zhao, Y.; Li, L.; Lin, H.; Bi, Q.; Zhao, Y. Biodegradation of polyethylene microplastic particles by the *Fungus aspergillus* flavus from the guts of wax moth *Galleria mellonella*. *Sci. Total Environ.* **2020**, *704*, 135931. [CrossRef] [PubMed]
28. Zhang, Q.; Xu, E.G.; Li, J.; Chen, Q.; Ma, L.; Zeng, E.Y.; Shi, H. A review of microplastics in table salt, drinking water, and air: Direct human exposure. *Environ. Sci. Technol.* **2020**, *54*, 3740–3751. [CrossRef]
29. Hidayaturrahman, H.; Lee, T.-G. A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process. *Mar. Pollut. Bull.* **2019**, *146*, 696–702. [CrossRef]
30. Talvitie, J.; Mikola, A.; Koistinen, A.; Setälä, O. Solutions to microplastic pollution—Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Res.* **2017**, *123*, 401–407. [CrossRef]
31. Sembiring, E.; Fajar, M.; Handajani, M. Performance of rapid sand filter—Single media to remove microplastics. *Water Supply* **2021**, *21*, 2273–2284. [CrossRef]
32. Soyer, E.; Akgiray, Ö.; Eldem, N.Ö.; Saatçı, A.M. On the use of crushed recycled glass instead of silica sand in dual-media filters. *CLEAN—Soil Air Water* **2013**, *41*, 325–332. [CrossRef]
33. Poerio, T.; Piacentini, E.; Mazzei, R. Membrane processes for microplastic removal. *Molecules* **2019**, *24*, 4148. [CrossRef] [PubMed]
34. Sol, D.; Laca, A.; Laca, A.; Diaz, M. Approaching the environmental problem of microplastics: Importance of WWTP treatments. *Sci. Total Environ.* **2020**, *740*, 140016. [CrossRef] [PubMed]

35. Andrady, A.L. (Ed.) *Plastics and the Ocean: Origin, Characterization, Fate, and Impacts*; Wiley: Hoboken, NJ, USA, 2022.
36. Michielssen, M.R.; Michielssen, E.R.; Ni, J.; Duhaime, M.B. Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. *Environ. Sci. Water Res. Technol.* **2016**, *2*, 1064–1073. [CrossRef]
37. Wang, Z.; Sedighi, M.; Lea-Langton, A. Filtration of microplastic spheres by biochar: Removal efficiency and immobilisation mechanisms. *Water Res.* **2020**, *184*, 116165. [CrossRef]
38. Siipola, V.; Pflugmacher, S.; Romar, H.; Wendling, L.; Koukkari, P. Low-cost biochar adsorbents for water purification including microplastics removal. *Appl. Sci.* **2020**, *10*, 788. [CrossRef]
39. Zhang, K.; Hamidian, A.H.; Tubić, A.; Zhang, Y.; Fang, J.K.; Wu, C.; Lam, P.K. Understanding plastic degradation and microplastic formation in the environment: A review. *Environ. Pollut.* **2021**, *274*, 116554. [CrossRef]
40. Chen, X.; Chen, X.; Zhao, Y.; Zhou, H.; Xiong, X.; Wu, C. Effects of microplastic biofilms on nutrient cycling in simulated freshwater systems. *Sci. Total Environ.* **2020**, *719*, 137276. [CrossRef]
41. Sun, C.; Wang, Z.; Chen, L.; Li, F. Fabrication of robust and compressive chitin and graphene oxide sponges for removal of microplastics with different functional groups. *Chem. Eng. J.* **2020**, *393*, 124796. [CrossRef]
42. Wang, J.; Guo, X.; Xue, J. Biofilm-developed microplastics as vectors of pollutants in aquatic environments. *Environ. Sci. Technol.* **2021**, *55*, 12780–12790. [CrossRef]
43. Misra, A. Design and Environmental Applications of Polyoxometalate–Ionic Liquid (POM–IL)—Based Molecular and Composite Materials. Ph.D. Thesis, Universität Ulm, Ulm, Germany, 2021.
44. Liu, F.; Nord, N.B.; Bester, K.; Vollertsen, J. Microplastics removal from treated wastewater by a biofilter. *Water* **2020**, *12*, 1085. [CrossRef]
45. Tang, Y.; Zhang, S.; Su, Y.; Wu, D.; Zhao, Y.; Xie, B. Removal of microplastics from aqueous solutions by magnetic carbon nanotubes. *Chem. Eng. J.* **2020**, *406*, 126804. [CrossRef]
46. Perren, W.; Wojtasik, A.; Cai, Q. Removal of microbeads from wastewater using electrocoagulation. *ACS Omega* **2018**, *3*, 3357–3364. [CrossRef] [PubMed]
47. Padervand, M.; Lichtfouse, E.; Robert, D.; Wang, C. Removal of microplastics from the environment. A review. *Environ. Chem. Lett.* **2020**, *18*, 807–828. [CrossRef]
48. Alramthi, S.M.; Ali, G.H.; Elthagafi, A.M.; Eldosari, S.H.; Zhu, B.-K.; Safaa, H.M. Oxidation Ditches for Recycling and Reusing Wastewater Are Critical for Long-Term Sustainability—A Case Study. *Sustainability* **2022**, *14*, 16737. [CrossRef]
49. Ma, B.; Xue, W.; Hu, C.; Liu, H.; Qu, J.; Li, L. Characteristics of microplastic removal via coagulation and ultrafiltration during drinking water treatment. *Chem. Eng. J.* **2018**, *359*, 159–167. [CrossRef]
50. Kolya, H.; Kang, C.W. Bio-Based Polymeric Flocculants and Adsorbents for Wastewater Treatment. *Sustainability* **2023**, *15*, 9844. [CrossRef]
51. Herbort, A.F.; Schuhen, K. A concept for the removal of microplastics from the marine environment with innovative host-guest relationships. *Environ. Sci. Pollut. Res.* **2016**, *24*, 11061–11065. [CrossRef]
52. Herbort, A.F.; Sturm, M.T.; Schuhen, K. A new approach for the agglomeration and subsequent removal of polyethylene, polypropylene, and mixtures of both from freshwater systems—A case study. *Environ. Sci. Pollut. Res.* **2018**, *25*, 15226–15234. [CrossRef]
53. Herbort, A.F.; Sturm, M.T.; Fiedler, S.; Abkai, G.; Schuhen, K. Alkoxy-silyl induced agglomeration: A new approach for the sustainable removal of microplastic from aquatic systems. *J. Polym. Environ.* **2018**, *26*, 4258–4270. [CrossRef]
54. Sturm, M.T.; Herbort, A.F.; Horn, H.; Schuhen, K. Comparative study of the influence of linear and branched alkyltrichlorosilanes on the removal efficiency of polyethylene and polypropylene-based microplastic particles from water. *Environ. Sci. Pollut. Res.* **2020**, *27*, 10888–10898. [CrossRef] [PubMed]
55. Brinker, C.J.; Scherer, G.W. *Sol–Gel Science: The Physics and Chemistry of Sol–Gel Processing*; Academic Press: Cambridge, MA, USA, 1990.
56. Schuhen, K.; Sturm, M.T.; Herbort, A.F. Technological Approaches for the Reduction of Microplastic Pollution in Seawater Desalination Plants and for Sea Salt Extraction. In *Plastics in the Environment*; Gomiero, A., Ed.; IntechOpen: London, UK, 2019; ISBN 978-1-83880-492-3.
57. Shahi, N.K.; Maeng, M.; Kim, D.; Dockko, S. Removal behavior of microplastics using alum coagulant and its enhancement using polyamine-coated sand. *Process Saf. Environ. Prot.* **2020**, *141*, 9–17. [CrossRef]
58. Rajala, K.; Grönfors, O.; Hesampour, M.; Mikola, A. Removal of microplastics from secondary wastewater treatment plant effluent by coagulation/flocculation with iron, aluminum and polyamine-based chemicals. *Water Res.* **2020**, *183*, 116045. [CrossRef] [PubMed]
59. Tofa, T.S.; Kunjali, K.L.; Paul, S.; Dutta, J. Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods. *Environ. Chem. Lett.* **2019**, *17*, 1341–1346. [CrossRef]
60. Ariza–Tarazona, M.C.; Villarreal-Chiu, J.F.; Barbieri, V.; Siligardi, C.; Cedillo-González, E.I. New strategy for microplastic degradation: Green photocatalysis using a protein-based porous $NTiO_2$ semiconductor. *Ceram. Int.* **2019**, *45*, 9618–9624. [CrossRef]
61. Gambarini, V.; Pantos, O.; Kingsbury, J.M.; Weaver, L.; Handley, K.M.; Lear, G. PlasticDB: A database of microorganisms and proteins linked to plastic biodegradation. *Database* **2022**, *2022*, baac008. [CrossRef] [PubMed]

62. Waring, B.G.; Averill, C.; Hawkes, C.V. Differences in fungal and bacterial physiology alter soil carbon and nitrogen cycling: Insights from meta-analysis and theoretical models. *Ecol. Lett.* **2013**, *16*, 887–894. [CrossRef]
63. Nikhil, B.; Adhyaru, D.; Thakor, P. Production of xylanase by Aspergillus flavus FPDN1 on pearl millet bran: Optimization of culture conditions and application in bioethanol production. *Int. J. Res. Chem. Environ.* **2012**, *2*, 204–210.
64. Zhu, N.; Liu, J.; Yang, J.; Lin, Y.; Yang, Y.; Ji, L.; Li, M.; Yuan, H. Comparative analysis of the secretomes of Schizophyllum commune and other wood-decay basidiomycetes during solid-state fermentation reveals its unique lignocellulose-degrading enzyme system. *Biotechnol. Biofuels* **2016**, *9*, 42. [CrossRef]
65. Bornscheuer, U.T. Feeding on plastic. *Science* **2016**, *351*, 1154–1155. [CrossRef]
66. Yoshida, S.; Hiraga, K.; Takehana, T.; Taniguchi, I.; Yamaji, H.; Maeda, Y.; Toyohara, K.; Miyamoto, K.; Kimura, Y.; Oda, K. A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* **2016**, *351*, 1196–1199. [CrossRef] [PubMed]
67. Joo, S.; Cho, I.J.; Seo, H.; Son, H.F.; Sagong, H.-H.; Shin, T.J.; Choi, S.Y.; Lee, S.Y.; Kim, K.-J. Structural insight into molecular mechanism of poly(ethylene terephthalate) degradation. *Nat. Commun.* **2018**, *9*, 382. [CrossRef] [PubMed]
68. Carniel, A.; Valoni, E.; Nicomedes, J.; da Conceição Gomes, A.; de Castro, A.M. Lipase from *Candida antarctica* (CALB) and cutinase from *Humicola insolens* act synergistically for PET hydrolysis to terephthalic acid. *Process Biochem.* **2017**, *59*, 84–90. [CrossRef]
69. Knott, B.C.; Erickson, E.; Allen, M.D.; Gado, J.E.; Graham, R.; Kearns, F.L.; Pardo, I.; Topuzlu, E.; Anderson, J.J.; Austin, H.P.; et al. Characterization and engineering of a two-enzyme system for plastics depolymerization. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 25476–25485. [CrossRef]
70. da Costa, C.H.S.; dos Santos, A.M.; Alves, C.N.; Martí, S.; Moliner, V.; Santana, K.; Lameira, J. Assessment of the PETase conformational changes induced by poly(ethylene terephthalate) binding. *Proteins: Struct. Funct. Bioinform.* **2021**, *89*, 1340–1352. [CrossRef]
71. Chen, S.; Su, L.; Billig, S.; Zimmermann, W.; Chen, J.; Wu, J. Biochemical characterization of the cutinases from *Thermobifida fusca*. *J. Mol. Catal. B Enzym.* **2010**, *63*, 121–127. [CrossRef]
72. Stavila, E.; Arsyi, R.; Petrovic, D.; Loos, K. *Fusarium solani* pisi cutinase-catalyzed synthesis of polyamides. *Eur. Polym. J.* **2013**, *49*, 834–842. [CrossRef]
73. Chen, S.; Tong, X.; Woodard, R.W.; Du, G.; Wu, J.; Chen, J. Identification and characterization of bacterial cutinase. *J. Biol. Chem. J. Biol. Chem.* **2008**, *283*, 25854–25862. [CrossRef]
74. Danso, D.; Chow, J.; Streit, W.R. Plastics: Environmental and biotechnological perspectives on microbial degradation. *Appl. Environ. Microbiol.* **2019**, *85*, e01095-19. [CrossRef]
75. Kawai, F.; Oda, M.; Tamashiro, T.; Waku, T.; Tanaka, N.; Yamamoto, M.; Mizushima, H.; Miyakawa, T.; Tanokura, M. A novel Ca^{2+}-activated, thermostabilized polyesterase capable of hydrolyzing polyethylene terephthalate from *Saccharomonospora viridis* AHK190. *Appl. Microbiol. Biotechnol.* **2014**, *98*, 10053–10064. [CrossRef]
76. Ru, J.; Huo, Y.; Yang, Y. Microbial degradation and valorization of plastic wastes. *Front. Microbiol.* **2020**, *11*, 442. [CrossRef] [PubMed]
77. Bhatt, P.; Pathak, V.M.; Bagheri, A.R.; Bilal, M. Microplastic contaminants in the aqueous environment, fate, toxicity consequences, and remediation strategies. *Environ. Res.* **2021**, *200*, 111762. [CrossRef] [PubMed]
78. Taniguchi, I.; Yoshida, S.; Hiraga, K.; Miyamoto, K.; Kimura, Y.; Oda, K. Biodegradation of PET: Current status and application aspects. *ACS Catal.* **2019**, *9*, 4089–4105. [CrossRef]
79. Danso, D.; Schmeisser, C.; Chow, J.; Zimmermann, W.; Wei, R.; Leggewie, C.; Li, X.; Hazen, T.; Streit, W.R. New insights into the function and global distribution of polyethylene terephthalate (PET)—Degrading bacteria and enzymes in marine and terrestrial metagenomes. *Appl. Environ. Microbiol.* **2018**, *84*, e02773-17. [CrossRef]
80. De Jesus, R.; Alkendi, R. A minireview on the bioremediative potential of microbial enzymes as solution to emerging microplastic pollution. *Front. Microbiol.* **2023**, *13*, 1066133. [CrossRef]
81. Bollinger, A.; Thies, S.; Knieps-Grünhagen, E.; Gertzen, C.; Kobus, S.; Höppner, A.; Ferrer, M.; Gohlke, H.; Smits, S.H.J.; Jaeger, K.-E. A novel polyester hydrolase from the marine bacterium *Pseudomonas aestusnigri*—Structural and functional insights. *Front. Microbiol.* **2020**, *11*, 114. [CrossRef]
82. Müller, R.-J.; Schrader, H.; Profe, J.; Dresler, K.; Deckwer, W.-D. Enzymatic degradation of poly(ethylene terephthalate): Rapid hydrolyse using a hydrolase from *T. fusca*. *Macromol. Rapid Commun.* **2005**, *26*, 1400–1405. [CrossRef]
83. Ronkvist, A.M.; Xie, W.; Lu, W.; Gross, R.A. Cutinase-catalyzed hydrolysis of poly(ethylene terephthalate). *Macromolecules* **2009**, *42*, 5128–5138. [CrossRef]
84. Sulaiman, S.; Yamato, S.; Kanaya, E.; Kim, J.-J.; Koga, Y.; Takano, K.; Kanaya, S. Isolation of a novel cutinase homolog with polyethylene terephthalate-degrading activity from leaf-branch compost by using a metagenomic approach. *Appl. Environ. Microbiol.* **2012**, *78*, 1556–1562. [CrossRef]
85. Wei, R.; Breite, D.; Song, C.; Gräsing, D.; Ploss, T.; Hille, P.; Schwerdtfeger, R.; Matysik, J.; Schulze, A.; Zimmermann, W. Biocatalytic degradation efficiency of postconsumer polyethylene terephthalate packaging determined by their polymer microstructures. *Adv. Sci.* **2019**, *6*, 1900491. [CrossRef]
86. Darby, R.T.; Kaplan, A.M. Fungal susceptibility of polyurethanes. *Appl. Microbiol.* **1968**, *16*, 900–905. [CrossRef] [PubMed]
87. Son, H.F.; Joo, S.; Seo, H.; Sagong, H.Y.; Lee, S.H.; Hong, H.; Kim, K.J. Structural bioinformatics-based protein engineering of thermos-stable PETase from *Ideonella sakaiensis*. *Enzym. Microb. Technol.* **2020**, *141*, 109656. [CrossRef] [PubMed]

88. Meng, X.; Yang, L.; Liu, H.; Li, Q.; Xu, G.; Zhang, Y.; Guan, F.; Zhang, Y.; Zhang, W.; Wu, N.; et al. Protein engineering of stable IsPETase for PET plastic degradation by Premuse. *Int. J. Biol. Macromol.* **2021**, *180*, 667–676. [CrossRef] [PubMed]
89. Furukawa, M.; Kawakami, N.; Tomizawa, A.; Miyamoto, K. Efficient degradation of poly(ethylene terephthalate) with *Thermobifida fusca* cutinase exhibiting improved catalytic activity generated using mutagenesis and additive-based approaches. *Sci. Rep.* **2019**, *9*, 16038. [CrossRef]
90. Kim, J.W.; Park, S.-B.; Tran, Q.-G.; Cho, D.-H.; Choi, D.-Y.; Lee, Y.J.; Kim, H.-S. Functional expression of polyethylene terephthalate-degrading enzyme (PETase) in green microalgae. *Microb. Cell Factories* **2020**, *19*, 97. [CrossRef]
91. Moog, D.; Schmitt, J.; Senger, J.; Zarzycki, J.; Rexer, K.-H.; Linne, U.; Erb, T.; Maier, U.G. Using a marine microalga as a chassis for polyethylene terephthalate (PET) degradation. *Microb. Cell Factories* **2019**, *18*, 171. [CrossRef]
92. Mohanan, N.; Wong, C.H.; Budisa, N.; Levin, D.B. Characterization of Polymer Degrading Lipases, LIP1 and LIP2 From Pseudomonas chlororaphis PA23. *Front. Bioeng. Biotechnol.* **2022**, *10*, 854298. [CrossRef]
93. Schwaminger, S.P.; Fehn, S.; Steegmüller, T.; Rauwolf, S.; Löwe, H.; Pflüger-Grau, K.; Berensmeier, S. Immobilization of PETase enzymes on magnetic iron oxide nanoparticles for the decomposition of microplastic PET. *Nanoscale Adv.* **2021**, *3*, 4395–4399. [CrossRef]
94. Rowe, L.; Howard, G.T. Growth of *Bacillus subtilis* on polyurethane and the purification and characterization of a polyurethanase-lipase enzyme. *Int. Biodeterior. Biodegrad.* **2002**, *50*, 33–40. [CrossRef]
95. Yang, S.; Xu, H.; Yan, Q.; Liu, Y.; Zhou, P.; Jiang, Z. A low molecular mass cutinase of *Thielavia terrestris* efficiently hydrolyzes poly(esters). *J. Ind. Microbiol. Biotechnol.* **2013**, *40*, 217–226. [CrossRef]
96. Machado, M.; Vimbela, G.; Silva-Oliveira, T.; Bose, A.; Tripathi, A. The response of *Synechococcus* sp. PCC 7002 to micro−/nano polyethylene particles—Investigation of a key anthropogenic stressor. *PLoS ONE* **2020**, *15*, e0232745. [CrossRef] [PubMed]
97. Barth, M.; Oeser, T.; Wei, R.; Then, J.; Schmidt, J.; Zimmermann, W. Effect of hydrolysis products on the enzymatic degradation of polyethylene terephthalate nanoparticles by a polyester hydrolase from *Thermobifida fusca*. *Biochem. Eng. J.* **2015**, *93*, 222–228. [CrossRef]
98. Li, F.; Wang, S.; Liu, W.; Chen, G. Purification and characterization of poly(L-lactic acid)-degrading enzymes from *Amycolatopsis orientalis* ssp. orientalis. *FEMS Microbiol. Lett.* **2008**, *282*, 52–58. [CrossRef] [PubMed]
99. Harrison, J.P.; Sapp, M.; Schratzberger, M.; Osborn, A.M. Interactions between microorganisms and marine microplastics: A call for research. *Mar. Technol. Soc. J.* **2011**, *45*, 12–20. [CrossRef]
100. Rummel, C.D.; Jahnke, A.; Gorokhova, E.; Kühnel, D.; Schmitt-Jansen, M. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environ. Sci. Technol. Lett.* **2017**, *4*, 258–267. [CrossRef]
101. Wu, R.-T.; Cai, Y.-F.; Chen, Y.-X.; Yang, Y.-W.; Xing, S.-C.; Liao, X.-D. Occurrence of microplastic in livestock and poultry manure in South China. *Environ. Pollut.* **2021**, *277*, 116790. [CrossRef]
102. Hadad, D.; Geresh, S.; Sivan, A. Biodegradation of polyethylene by the thermophilic bacterium *Brevibacillus borstelensis*. *J. Appl. Microbiol.* **2005**, *98*, 1093–1096. [CrossRef] [PubMed]
103. Ganesan, S.; Ruendee, T.; Kimura, S.Y.; Chawengkijwanich, C.; Janjaroen, D. Effect of biofilm formation on different types of plastic shopping bags: Structural and physicochemical properties. *Environ. Res.* **2021**, *206*, 112542. [CrossRef]
104. Faheem, M.; Shabbir, S.; Zhao, J.; Kerr, P.G.; Ali, S.; Sultana, N.; Jia, Z. Multifunctional periphytic biofilms: Polyethylene degradation and Cd^{2+} and Pb^{2+} bioremediation under high methane scenario. *Int. J. Mol. Sci.* **2020**, *21*, 5331. [CrossRef]
105. Richard, H.; Carpenter, E.J.; Komada, T.; Palmer, P.T.; Rochman, C.M. Biofilm facilitates metal accumulation onto microplastics in estuarine waters. *Sci. Total Environ.* **2019**, *683*, 600–608. [CrossRef]
106. Stabnikova, O.; Stabnikov, V.; Marinin, A.; Klavins, M.; Vaseashta, A. The role of microplastics biofilm in accumulation of trace metals in aquatic environments. *World J. Microbiol. Biotechnol.* **2022**, *38*, 117. [CrossRef] [PubMed]
107. Shabbir, S.; Faheem, M.; Ali, N.; Kerr, P.G.; Wang, L.-F.; Kuppusamy, S.; Li, Y. Periphytic biofilm: An innovative approach for biodegradation of microplastics. *Sci. Total Environ.* **2020**, *717*, 137064. [CrossRef] [PubMed]
108. Gilan, I.; Hadar, Y.; Sivan, A. Colonization, biofilm formation and biodegradation of polyethylene by a strain of *Rhodococcus ruber*. *Appl. Microbiol. Biotechnol.* **2004**, *65*, 97–104. [CrossRef]
109. Paço, A.; Duarte, K.; da Costa, J.P.; Santos, P.S.; Pereira, R.; Pereira, M.; Freitas, A.C.; Duarte, A.C.; Rocha-Santos, T.A. Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum*. *Sci. Total Environ.* **2017**, *586*, 10–15. [CrossRef] [PubMed]
110. Howard, G.T.; Norton, W.N.; Burks, T. Growth of Acinetobacter gerneri P7 on polyurethane and the purification and characterization of a polyurethanase enzyme. *Biodegradation* **2012**, *23*, 561–573. [CrossRef]
111. Narciso-Ortiz, L.; Coreño-Alonso, A.; Mendoza-Olivares, D.; Lucho-Constantino, C.A.; Lizardi-Jiménez, M.A. Baseline for plastic and hydrocarbon pollution of rivers, reefs, and sediment on beaches in Veracruz State, México, and a proposal for bioremediation. *Environ. Sci. Pollut. Res.* **2020**, *27*, 23035–23047. [CrossRef]
112. Osman, M.; Satti, S.M.; Luqman, A.; Hasan, F.; Shah, Z.; Shah, A.A. Degradation of polyester polyurethane by *Aspergillus* sp. strain S45 isolated from soil. *J. Polym. Environ.* **2017**, *26*, 301–310. [CrossRef]
113. Magnin, A.; Hoornaert, L.; Pollet, E.; Laurichesse, S.; Phalip, V.; Avérous, L. Isolation and characterization of different promising fungi for biological waste management of polyurethanes. *Microb. Biotechnol.* **2019**, *12*, 544–555. [CrossRef]
114. Vimala, P.P.; Mathew, L. Biodegradation of polyethylene using *Bacillus subtilis*. *Procedia Technol.* **2016**, *24*, 232–239. [CrossRef]

115. Kırbaş, Z.; Keskin, N.E.V.I.N.; Güner, A. Biodegradation of polyvinylchloride (PVC) by white rot fungi. *Bull. Environ. Contam. Toxicol.* **1999**, *63*, 335–342. [CrossRef]
116. Nakamiya, K.; Hashimoto, S.; Ito, H.; Edmonds, J.S.; Yasuhara, A.; Morita, M. Microbial treatment of bis (2-ethylhexyl) phthalate in polyvinyl chloride with isolated bacteria. *J. Biosci. Bioeng.* **2005**, *99*, 115–119. [CrossRef] [PubMed]
117. Atiq, N.; Ahmed, S.; Ali, M.I.; Ahmad, B.; Robson, G. Isolation and identification of polystyrene biodegrading bacteria from soil. *Afr. J. Microbiol. Res.* **2010**, *4*, 1537–1541.
118. Auta, H.; Emenike, C.; Fauziah, S. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environ. Int.* **2017**, *102*, 165–176. [CrossRef] [PubMed]
119. Jeon, H.J.; Kim, M.N. Isolation of mesophilic bacterium for biodegradation of polypropylene. *Int. Biodeterior. Biodegrad.* **2016**, *115*, 244–249. [CrossRef]
120. McGivney, E.; Cederholm, L.; Barth, A.; Hakkarainen, M.; Hamacher-Barth, E.; Ogonowski, M.; Gorokhova, E. Rapid physico-chemical changes in microplastic induced by biofilm formation. *Front. Bioeng. Biotechnol.* **2020**, *8*, 205. [CrossRef] [PubMed]
121. Sun, X.-L.; Xiang, H.; Xiong, H.-Q.; Fang, Y.-C.; Wang, Y. Bioremediation of microplastics in freshwater environments: A systematic review of biofilm culture, degradation mechanisms, and analytical methods. *Sci. Total Environ.* **2023**, *863*, 160953. [CrossRef]
122. Carr, S.A.; Liu, J.; Tesoro, A.G. Transport and fate of microplastic particles in wastewater treatment plants. *Water Res.* **2016**, *91*, 174–182. [CrossRef]
123. Baresel, C.; Ek, M.; Ejhed, H.; Allard, A.-S.; Magnér, J.; Dahlgren, L.; Westling, K.; Wahlberg, C.; Fortkamp, U.; Söhr, S.; et al. Sustainable treatment systems for removal of pharmaceutical residues and other priority persistent substances. *Water Sci. Technol.* **2019**, *79*, 537–543. [CrossRef]
124. Chamas, A.; Moon, H.; Zheng, J.; Qiu, Y.; Tabassum, T.; Jang, J.H.; Abu-Omar, M.; Scott, S.L.; Suh, S. Degradation rates of plastics in the environment. *ACS Sustain. Chem. Eng.* **2020**, *8*, 3494–3511. [CrossRef]
125. Mishra, A.; Kumar, J.; Melo, J.S. Silica based bio-hybrid materials and their relevance to bionanotechnology. *Austin J. Plant Biol.* **2020**, *6*, 1024.
126. Vázquez-Núñez, E.; Molina-Guerrero, C.E.; Peña-Castro, J.M.; Fernández-Luqueño, F.; De La Rosa-Álvarez, M.G. Use of Nanotechnology for the Bioremediation of Contaminants: A Review. *Processes* **2020**, *8*, 826. [CrossRef]
127. Mueller, N.C.; Nowack, B. Nanoparticles for remediation: Solving big problems with little particles. *Elements* **2010**, *6*, 395–400. [CrossRef]
128. Zhu, Y.; Liu, X.; Hu, Y.; Wang, R.; Chen, M.; Wu, J.; Wang, Y.; Kang, S.; Sun, Y.; Zhu, M. Behavior, remediation effect and toxicity of nanomaterials in water environments. *Environ. Res.* **2019**, *174*, 54–60. [CrossRef] [PubMed]
129. Awasthi, A.; Jadhao, P.; Kumari, K. Clay nano-adsorbent: Structures, applications and mechanism for water treatment. *SN Appl. Sci.* **2019**, *1*, 1076. [CrossRef]
130. Jain, K.; Patel, A.S.; Pardhi, V.P.; Flora, S.J.S. Nanotechnology in wastewater management: A new paradigm towards wastewater treatment. *Molecules* **2021**, *26*, 1797. [CrossRef]
131. Tofa, T.S. Degradation of Microplastic Residuals in Water by Visible Light Photocatalysis. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2018.
132. Kiriyanthan, R.M.; Maharajan, T.; Radha, A.; Pandikumar, P. A review on the role of nanotechnology in enhancing environmental sustainability. *Chem. Biol. Interface* **2021**, *11*, 13–33.
133. Baruah, S.; Mahmood, M.A.; Myint, M.T.Z.; Bora, T.; Dutta, J. Enhanced visible light photocatalysis through fast crystallization of zinc oxide nanorods. *Beilstein J. Nanotechnol.* **2010**, *1*, 14–20. [CrossRef]
134. Bolto, B.; Gregory, J. Organic polyelectrolytes in water treatment. *Water Res.* **2007**, *41*, 2301–2324. [CrossRef]
135. Maćczak, P.; Kaczmarek, H.; Ziegler-Borowska, M. Recent Achievements in Polymer Bio-Based Flocculants for Water Treatment. *Materials* **2020**, *13*, 3951. [CrossRef]
136. Jalvo, B.; Aguilar-Sanchez, A.; Ruiz-Caldas, M.X.; Mathew, A.P. Water filtration membranes based on non-woven cellulose fabrics: Effect of nanopolysaccharide coatings on selective particle rejection, antifouling, and antibacterial properties. *Nanomaterials* **2021**, *11*, 1752. [CrossRef]
137. Bahi, A.; Shao, J.; Mohseni, M.; Ko, F.K. Membranes based on electrospun lignin-zeolite composite nanofibers. *Sep. Purif. Technol.* **2017**, *187*, 207–213. [CrossRef]
138. Grbic, J.; Nguyen, B.; Guo, E.; You, J.B.; Sinton, D.; Rochman, C.M. Magnetic extraction of microplastics from environmental samples. *Environ. Sci. Technol. Lett.* **2019**, *6*, 68–72. [CrossRef]
139. Abdullah, M.M.S.; Atta, A.M.; Allohedan, H.A.; Alkhathlan, H.Z.; Khan, M.; Ezzat, A.O. Green synthesis of hydrophobic magnetite nanoparticles coated with plant extract and their application as petroleum oil spill collectors. *Nanomaterials* **2018**, *8*, 855. [CrossRef] [PubMed]
140. Elmaci, G. Microwave-assisted rapid synthesis of C@Fe_3O_4 composite for removal of microplastics from drinking water. *Adıyaman Univ. J. Sci.* **2020**, *10*, 207–217. [CrossRef]
141. Wang, L.; Kaeppler, A.; Fischer, D.; Simmchen, J. Photocatalytic TiO_2 micromotors for removal of microplastics and suspended matter. *ACS Appl. Mater. Interfaces* **2019**, *11*, 32937–32944. [CrossRef]
142. Chellasamy, G.; Kiriyanthan, R.M.; Maharajan, T.; Radha, A.; Yun, K. Remediation of microplastics using bionanomaterials: A review. *Environ. Res.* **2022**, *208*, 112724. [CrossRef]

143. Peydayesh, M.; Suta, T.; Usuelli, M.; Handschin, S.; Canelli, G.; Bagnani, M.; Mezzenga, R. Sustainable removal of microplastics and natural organic matter from water by coagulation–flocculation with protein amyloid fibrils. *Environ. Sci. Technol.* **2021**, *55*, 8848–8858. [CrossRef]
144. Dijkstra, H.; van Beukering, P.; Brouwer, R. Business models and sustainable plastic management: A systematic review of the literature. *J. Clean. Prod.* **2020**, *258*, 120967. [CrossRef]
145. Gharfalkar, M.; Court, R.; Campbell, C.; Ali, Z.; Hillier, G. Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste Manag.* **2015**, *39*, 305–313. [CrossRef]
146. Johansen, M.R.; Christensen, T.B.; Ramos, T.M.; Syberg, K. A review of the plastic value chain from a circular economy perspective. *J. Environ. Manag.* **2021**, *302*, 113975. [CrossRef]
147. Odegard, I.Y.R.; Nusselder, S.; Lindgreen, E.R.; Bergsma, G.C.; de Graaff, L. *Biobased Plastics in a Circular Economy: Policy Suggestions for Biobased and Biobased Biodegradable Plastics*; CE Delft: Delft, The Netherlands, 2017.
148. Solaiman, D.K.Y.; Ashby, R.D.; Foglia, T.A.; Marmer, W.N. Conversion of agricultural feedstock and coproducts into poly(hydroxyalkanoates). *Appl. Microbiol. Biotechnol.* **2006**, *71*, 783–789. [CrossRef] [PubMed]
149. Sheldon, R.A. Green and sustainable manufacture of chemicals from biomass: State of the art. *Green Chem.* **2014**, *16*, 950–963. [CrossRef]
150. Hobbs, C.E. Recent advances in bio-based flame retardant additives for synthetic polymeric materials. *Polymers* **2019**, *11*, 224. [CrossRef]
151. Kwabena, J.; Berko-Boateng, V.N.; Ama, T. Case studies in construction materials use of waste plastic materials for road construction in Ghana. *Case Stud. Constr. Mater.* **2017**, *6*, 1–7.
152. Roy, P.; Mohanty, A.K.; Misra, M. Microplastics in ecosystems: Their implications and mitigation pathways. *Environ. Sci. Adv.* **2022**, *1*, 9–29. [CrossRef]
153. Sun, L.; Li, H.; Dong, L.; Fang, K.; Ren, J.; Geng, Y.; Fujii, M.; Zhang, W.; Zhang, N.; Liu, Z. Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. *Resour. Conserv. Recycl.* **2017**, *119*, 78–88. [CrossRef]
154. Zhu, J.-B.; Watson, E.M.; Tang, J.; Chen, E.Y.-X. A synthetic polymer system with repeatable chemical recyclability. *Science* **2018**, *360*, 398–403. [CrossRef]
155. Brentrup, F.; Küsters, J.; Kuhlmann, H.; Lammel, J. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production. *Eur. J. Agron.* **2004**, *20*, 247–264. [CrossRef]
156. Brand Hijacks Bottles for Refilling to Drastically Reduce Plastic Waste. Available online: https://www.plasticstoday.com/packaging/brand-hijacks-bottles-refilling-drastically-reduce-plastic-waste (accessed on 22 June 2020).
157. Coelho, P.M.; Corona, B.; ten Klooster, R.; Worrell, E. Sustainability of reusable packaging—Current situation and trends. *Resour. Conserv. Recycl. X* **2020**, *6*, 100037. [CrossRef]
158. Briassoulis, D.; Pikasi, A.; Hiskakis, M. End-of-waste life: Inventory of alternative end-of-use recirculation routes of bio-based plastics in the European Union context. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 1835–1892. [CrossRef]
159. Geng, Y.; Tsuyoshi, F.; Chen, X. Evaluation of innovative municipal solid waste management through urban symbiosis: A case study of Kawasaki. *J. Clean. Prod.* **2010**, *18*, 993–1000. [CrossRef]
160. Usman, S.; Razis, A.F.A.; Shaari, K.; Amal, M.N.A.; Saad, M.Z.; Isa, N.M.; Nazarudin, M.F.; Zulkifli, S.Z.; Sutra, J.; Ibrahim, M.A. Microplastics pollution as an invisible potential threat to food safety and security, policy challenges and the way forward. *Int. J. Environ. Res. Public Health* **2020**, *17*, 9591. [CrossRef] [PubMed]
161. Kalantar, Z.N.; Karim, M.R.; Mahrez, A. A review of using waste and virgin polymer in pavement. *Constr. Build. Mater.* **2012**, *33*, 55–62. [CrossRef]
162. Ministry of Environment, Forest and Climate Change. Government Notifies the Plastic Waste Management Amendment Rules, 2021, Prohibiting Identified Single Use Plastic Items by 2022. Available online: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1745433 (accessed on 3 August 2021).
163. Wu, W.-M.; Yang, J.; Criddle, C.S. Microplastics pollution and reduction strategies. *Front. Environ. Sci. Eng.* **2017**, *11*, 6. [CrossRef]