fermentation

MDPI

Review

Microbial Degradation of (Micro)plastics: Mechanisms, Enhancements, and Future Directions

Wei Gao, Mingxuan Xu, Wanqi Zhao, Xiaorui Yang, Fengxue Xin, Weiliang Dong, Honghua Jia and Xiayuan Wu *

College of Biotechnology and Pharmaceutical Engineering, Nanjing Tech University, Nanjing 211816, China; gwww@njtech.edu.cn (W.G.); xmx@njtech.edu.cn (M.X.); zwq1006@njtech.edu.cn (W.Z.); yangxiaorui@njtech.edu.cn (X.Y.); xinfengxue@njtech.edu.cn (F.X.); dwl@njtech.edu.cn (W.D.); hhjia@njtech.edu.cn (H.J.)

* Correspondence: wuxiayuan@njtech.edu.cn

Abstract: Plastic wastes, widely distributed in the environment, can be transformed into microplastics, posing a huge threat to ecosystems and human health due to their stability and adsorbability to other toxic pollutants (e.g., heavy metals and antibiotics). Recently, microbial degradation of (micro)plastics has gained widespread attention because of its green and sustainable properties. Microbial degradation of (micro)plastics is based on the cascade effects of various enzymes secreted by microorganisms, which can convert (micro)plastics into oligomers and monomers, or even mineralize them into CO_2 and H_2O. The microbial degradation of (micro)plastics is affected by multiple factors, such as microbial species, plastic properties, and environmental conditions. Currently, limited efficient plastic-degrading microorganisms have been discovered, and their degradation mechanisms are still unclear. Furthermore, the efficiency of microbial degradation needs to be improved for future application. Therefore, this review systematically summarizes the sources and properties of existing plastics, identifies pure cultures and mixed cultures for plastic degradation, and examines their influencing factors. In particular, the microbial degradation behaviors of (micro)plastics, including relevant enzymes, degradation efficiency, and degradation mechanisms, were thoroughly discussed. Additionally, the augmentation technologies coupling with microbial degradation, such as advanced oxidation, electrochemical, and genetic engineering technologies, were introduced and highlighted for their potential prospects. This review provides a reference for future research and development of (micro)plastic biodegradation technology.

Keywords: microplastic; microbial degradation; advanced oxidation; bioelectrochemical system; synthetic biology

Citation: Gao, W.; Xu, M.; Zhao, W.; Yang, X.; Xin, F.; Dong, W.; Jia, H.; Wu, X. Microbial Degradation of (Micro)plastics: Mechanisms, Enhancements, and Future Directions. *Fermentation* **2024**, *10*, 441. https://doi.org/10.3390/fermentation10090441

Academic Editors: Konstantinos G. Kalogiannis, Diomi Mamma, Alessio Siciliano and Xiaoqing Lin

Received: 29 July 2024
Revised: 21 August 2024
Accepted: 22 August 2024
Published: 23 August 2024

1. Introduction

Plastic is a significant material widely applied in various fields, and its production is increasing along with the rapid development of the global economy. The global production of plastics reached 345 million tons in 2017 and increased to approximately 400 million tons by 2022, with China accounting for about one-third of the total [1–3]. Moreover, around 93% of discarded plastics are not recycled and are mainly converted into microplastics that are widely distributed in nature. There are about 24.4 trillion microplastic particles in the global oceans, and high concentrations of microplastic particles are also found in freshwater systems; additionally, soil systems contain about 4 to 23 times more microplastic particles than aquatic systems [4,5]. The durability, adsorption capacity, cytotoxicity, and reproductive toxicity of microplastics in the environment pose a huge threat to the ecosystem. Therefore, efficient technologies for (micro)plastic degradation or recycling are essential for the sustainable development of society [6–9].

Currently, the common techniques for (micro)plastic degradation are chemical and thermal degradation. However, these methods have several disadvantages, including high cost, low efficiency, and the production of toxic by-products [10–12]. Biodegradation by

microorganisms, such as bacteria, fungi, and microalgae, mainly involves the enzymatic cleavage of plastic polymer chains, leading to the breakdown of the polymer into smaller molecules (e.g., oligomers, dimers, and monomers) and even CO_2 and H_2O [13]. Some microorganisms can achieve high-value conversion of degraded monomers while degrading plastics [14]. Compared to physical and chemical degradation, microbial degradation offers the advantages of being cost-effective, environmentally friendly, and sustainable. In the current context of economic development, with a focus on "green" initiatives, it holds great potential for widespread application [15,16]. However, the (micro)plastic biodegradation technology is still in its infancy, and only a few plastic-degrading microorganisms and enzymes have been discovered. There are few comprehensive reviews that provide systematic information for researchers in this field.

Hence, this review systematically summarizes the sources and properties of different types of plastics, identifies pure and mixed cultures for plastic biodegradation, and examines the corresponding influencing factors. It particularly focuses on the microbial degradation behaviors of (micro)plastics, including relevant enzymes, degradation efficiency, and degradation mechanisms. Additionally, the application of coupled enhancement technologies for microbial degradation, such as advanced oxidation, electrochemical, and genetic engineering technologies, is introduced, with the technologies' future development potential highlighted.

2. Sources and Properties of (Micro)plastics

Plastic is a synthetic polymeric material composed of various elements such as carbon, hydrogen, oxygen, nitrogen, silicon, and chlorine, typically derived from natural gas, oil, coal, and their derivatives [17,18]. The overwhelming majority of plastics enter the environment after human use and are transformed into microplastics, measuring less than 5 mm, through natural processes such as solar radiation, weathering, and enzyme action, which presents a significant threat to ecosystems and human health [19,20]. Based on differences in chemical structure, plastics are primarily classified into three categories. The first category is polyester plastics, which contain ester bonds. These are more prone to degradation by microorganisms due to the ease of hydrolysis of the ester bonds. Examples include polyethylene terephthalate (PET), polylactic acid (PLA), and polyurethane (PU). The second category is polyolefin plastics, characterized by the stability of the C-C bond as well as their high hydrophobicity and crystallinity, which make them resistant to microbial degradation [21]. Examples include polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP). The third category is polyamide plastics, represented by polyamides (PA), which have strong polar amide groups that make them highly crystalline and challenging to biodegrade. The physical and chemical properties of these three types of plastics are presented in Table 1.

Table 1. Types and properties of common plastics.

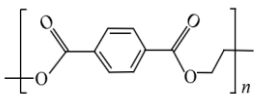
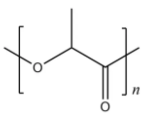
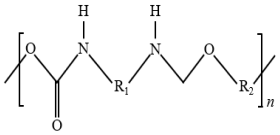
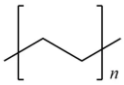
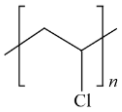
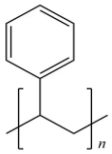
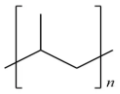
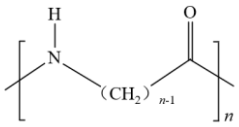
Plastic Category	Plastic Name	Structural Formula	Density (g/cm^3)	Crystallinity	Glass Transition Temperature (T_g) (°C)	Molecular Polarity	Reference
Polyester	Polyethylene terephthalate (PET)		1.33–1.35	Semi-crystalline	73–78	Polar	[22]
	Polylactic acid (PLA)		1.25–1.28	Semi-crystalline	60–65	Polar	[23]
	Polyurethane (PU)		1.15–1.3	Semi-crystalline	−62	Polar	[24]

Table 1. *Cont.*

Plastic Category	Plastic Name	Structural Formula	Density (g/cm^3)	Crystallinity	Glass Transition Temperature (T_g) (°C)	Molecular Polarity	Reference
Polyolefin	Polyethylene (PE)		0.92–0.97	Semi-crystalline	−110	Non-polar	[25]
	Polyvinyl chloride (PVC)		1.15–1.70	Amorphous	60–100	Non-polar	[26,27]
	Polystyrene (PS)		1.04–1.06	Amorphous	90	Non-polar	[28,29]
	Polypropylene (PP)		0.89–0.91	Semi-crystalline	(−20)–0	Non-polar	[30]
Polyamide	Polyamides (PA)		1.02–1.05	Semi-crystalline	−60	Polar	[31]

3. Microbial Degradation of (Micro)plastics

3.1. Pure Cultures for (Micro)plastic Degradation

3.1.1. Bacteria

Currently, there is substantial research on the bacterial degradation of (micro)plastics, and significant progress has been made in elucidating the molecular mechanisms underlying the partial bacterial degradation. Bacteria such as *Acinetobacter*, *Bacillus*, *Pseudomonas*, and *Klebsiella* have been gradually isolated through enrichment and culture from plastic waste, sludge, and wastewater. Furthermore, a wide range of genes and enzymes involved in plastic degradation have been continuously identified (Table 2) [32–35].

For polyester plastics, in 2016, Yoshida et al. [36] first isolated a strain of *Ideonella sakaiensis* that was able to completely degrade PET within six weeks. This bacterium produces two hydrolytic enzymes, PETase and MHETase, which catalyze the degradation of PET into monomers, facilitating further catabolism. This represents the shortest and most efficient bacterial degradation of PET reported to date. Subsequently, Seongjoon et al. [37] proposed a detailed process for the degradation of PET into bis(2-hydroxyethyl) terephthalate (BHET), monohydroxyethyl terephthalate (MHET), terephthalate (TPA), and ethylene glycol (EG) based on structural and site-directed mutagenesis experiments. PETase secreted by *I. sakaiensis* first binds to the PET surface using its flat hydrophobic surface that has a substrate binding cleft. It then undergoes further degradation through a nick generation step and terminal digestion step, leading to the accumulation of four molecules: BHET, MHET, TPA, and EG. BHET can be further degraded into MHET and EG (Figure 1).

For polyolefin plastics, in 2023, Zhang et al. [38] isolated a PVC-degrading strain of *Klebsiella* sp. EMBL-1 from the intestines of insect larvae. The average weight loss of PVC films reached 19.57% over 90 days. The degradation genes of PVC identified were *KatG*, *lccA*, *ladA*, *ENO*, *dhaA*, and *ilvD*, and the degradation enzymes included catalase, dehalogenase, laccase, esterase, enolase, aldehyde dehydrogenase, and oxygenase. The degradation pathway of PVC was hypothesized to be as follows: PVC is first dechlorinated and depolymerized into oligomers under the action of extracellular peroxidases and dehalogenases. The oligomers are further oxidized by laccase, esterase, enolase, aldehyde dehydrogenase, and oxygenase into small molecules of alcohols, organic acids, and fatty acids, which then

enter the cell. The fatty acids enter the tricarboxylic acid cycle after β-oxidation and are finally mineralized into CO_2 and H_2O (Figure 1). In 2024, Lina et al. [39] isolated a deep-sea *Acinetobacter venetianus* F1 strain that degraded PE by 12.2% within 56 days. Multi-omics analysis identified the key degradation enzymes, including hydroxylase, monooxygenase, alcohol dehydrogenase, aldehyde dehydrogenase, esterase, and lipase. The pathway for PE degradation involves the initial depolymerization of oligomers and alkanes into cells under the effect of peroxidase, followed by oxidation into alcohol via hydroxylase and monooxygenase. Subsequently, the alcohol is further oxidized into aldehyde and ketone by alcohol dehydrogenase and aldehyde dehydrogenase. Ketones are then converted to esters through Baeyer–Villiger oxidation before being cleaved by esterases and lipases to form corresponding alcohols and fatty acids. These compounds undergo β-oxidation before entering the tricarboxylic acid cycle for mineralization to CO_2 and H_2O.

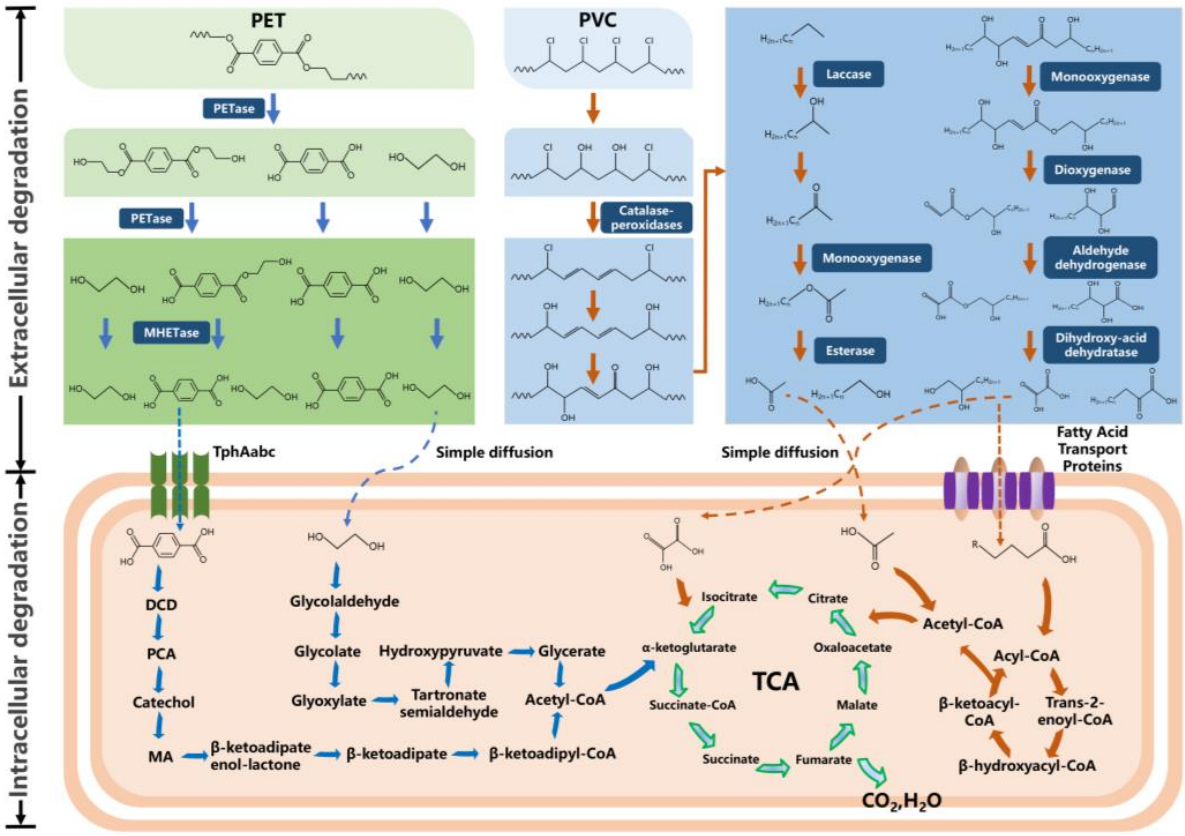


Figure 1. Bacteria-mediated degradation pathways of PET and PVC.

3.1.2. Fungi

Fungi capable of degrading (micro)plastics primarily include *Aspergillus*, *Dendrosporum*, *Fusarium*, *Penicillium*, and *Xanthosporea pinnatifida* (Table 2). Their mycelial structures can effectively penetrate the surface of the polymer material and reach the interior, thereby maximizing the degradation of (micro)plastics. Additionally, fungi can generate biosurfactants and various oxidative enzymes, demonstrating outstanding performance in degrading (micro)plastics [40].

The rate of (micro)plastic degradation by fungi also depends on the type of plastic [41]. Polyester and polyamide plastics contain readily hydrolyzable functional groups, which can be directly attacked by fungal hydrolases such as esterases, keratases, lipases, and proteases released by mycelium, hydrolyzing the plastic polymers into small carbon chains for metabolism. Khan et al. [42] initially isolated *Aspergillus tubingensis*, a PUR-degrading fungus, from the soil. This biodegradation process is divided into three steps: *Aspergillus tubingensis* initially adheres to the surface of the PUR membrane, where its mycelium grows

and reproduces. Ultimately, it secretes esterase and lipase to degrade PUR. For polyolefin plastics, most research typically begins with pretreatment using ultraviolet light or chemical oxidants, which induce these polymers to generate carbonyl and ester functional groups that can serve as target sites for fungal peroxidases, oxidases, hydrolases, keratases, and lipases. Zhang et al. [43] isolated a strain of *Aspergillus flavus* PEDX3 from the intestinal tract of the wax borer and discovered that the fungus exhibited strong degradation of HDPE, with potentially efficient degradation enzymes identified as laccase multicopper oxidases (LMCOs). Gao et al. [44] successfully isolated a strain of marine fungus *Alternaria alternata* FB1 that could effectively colonize and degrade PE film, with a degradation rate of up to 95% after 120 days. The main degradation product was diglycolamine, and the primary degradation enzymes were peroxidase and laccase. In conclusion, the specific molecular mechanisms of (micro)plastic degradation by fungi have not yet been fully elucidated, and there is considerable research space for isolating fungi with the ability to degrade (micro)plastics from the environment.

3.1.3. Microalgae

Microalgae possess excellent application prospects for degrading marine (micro)plastic pollution due to their superior adaptation to the ocean compared to bacteria and fungi, as well as their capacity for photosynthesis and autotrophic nutrition [45]. Microalgae found to be capable of degrading (micro)plastics mainly include cyanobacteria, green algae, and diatoms (Table 2) [46]. In the process of microalgal-mediated (micro)plastic degradation, the adhesion of various microalgae is frequently the initial step. When microalgae adhere to plastic surfaces, they generate ligninolytic enzymes and extracellular polysaccharidases, which play a crucial role in plastic degradation and contribute to reducing the activation energy necessary for breaking the chemical bonds of polymers [47]. Sarmah et al. [48] isolated two strains of fast-growing cyanobacteria, *Phormidium lucidum* and *Oscillatoria subbrevis*, which were capable of colonizing PE effectively and degrading LDPE by up to 30% after 42 days without any pretreatment with oxidants. Gowthami et al. [49] screened and identified a strain of green alga, *Picochlorum maculatum*, which was able to degrade LDPE efficiently, by up to 20% after 45 days, through the generation of extracellular polymers that adhered to LDPE and subsequently degraded it. Currently, there are relatively fewer studies on the degradation of (micro)plastics by microalgae, but considering the high economic recycling value of microalgae, it is worthy of further investigation.

Table 2. Pure microbial degradation of (micro)plastics.

Microorganism Category	Plastic	Microorganism and Source	Key Enzyme	Degradation Condition	Plastic Weight Loss	Reference
Bacteria	PET	*Ideonella sakaiensis*/Soil	PETase, MHETase.	30 °C, 300 strokes/min, aerobic	100%/42 d	[36]
	PVC	*Klebsiella* sp. EMBL-1/Larval gut	Catalase-peroxidase, Dehalogenases, Enolase, Aldehyde dehydrogenase, Oxygenase.	30 °C, 150 rpm/min, aerobic	19.57%/90 d	[38]
	PE	*Acinetobacter venetianus* F1/Sediments from the Haima cold seeps	Monooxygenase, Oxygenase, Dehydrogenase, Esterase, Lipase, Hydrolases, Reductases.	28 °C, 160 rpm/min, aerobic	12.2%/56 d	[39]

Table 2. *Cont.*

Microorganism Category	Plastic	Microorganism and Source	Key Enzyme	Degradation Condition	Plastic Weight Loss	Reference
Fungi	PUR	*Aspergillus tubingensis*/Soil	Esterase, Lipase.	37 °C, 150 rpm/min, aerobic	90%/60 d	[42]
	PVC	*Phanerocheate chrysosporium*/Laboratory	Lignin peroxidase.	25 °C, pH = 5, aerobic	31%/28 d	[50]
	PE	*Alternaria alternata*/Plastic debris in coastal areas	Laccase, Peroxidase, Oxidoreductase.	25 °C, alkali, aerobic	Not available	[44]
Microalgae	LDPE	*Phormidium lucidum*/Domestic sewage	Laccase, Peroxidase.	aerobic	30%/42 d	[48]
	LDPE	*Oscillatoria subbrevis*/Domestic sewage	Laccase, Peroxidase.	aerobic	30%/42 d	[48]

3.2. Mixed Cultures for (Micro)plastic Degradation

3.2.1. Natural Mixed Cultures

Currently, there are fewer studies on the degradation of (micro)plastics by natural mixed cultures compared to pure bacterial cultures (Table 3). Researchers have found that by enriching natural mixed cultures from waste, they were able to degrade PE to varying degrees, with the dominant genera identified mainly as *Bacillus* sp., *Paenibacillus* sp., and *Pseudomonas* sp. [33,51,52]. Additionally, recent research has discovered that certain insects can survive by consuming different plastic films, revealing that the gut flora of these insects has significant degrading effects on plastics. For instance, Xu et al. [53] enriched a natural mixed bacterial consortium, EF1, from the gut of *Tenebrio molitor* larvae and identified *Stenotrophomonas*, *Enterococcus*, and *Acinetobacter* as the dominant genera. This resulted in a degradation rate of 6.13% for PVC film after 30 days of treatment with EF1.

Table 3. Natural mixed bacterial degradation of (micro)plastics.

Plastic	Dominant Bacteria	Culture Source	Degradation Condition	Plastic Weight Loss	Reference
HDPE	*Bacillus* sp., *Pseudomonas* sp.	Discarded refuse	30 °C, aerobic	23.14%/4 weeks	[51]
PVC	*Stenotrophomonas*, *Enterococcus*, *Acinetobacter*	Larval gut	30 °C, 180 rpm/min, aerobic	6.13%/30 d	[53]
PE	*Bacillus* sp., *Paenibacillus* sp.	Landfill	30 °C, aerobic	14.7%/60 d	[33]
PE	*Betaproteobacteria*, *Alphaproteobacteria*, *Gamma-proteobacteria*	Discarded refuse	25 °C, 120 rpm/min, aerobic	19%/6 months	[52]

3.2.2. Artificial Mixed Cultures

Most artificial mixed-bacterial systems for degrading (micro)plastics are typically composed of *Bacillus* sp. and *Pseudomonas* sp. as the core strains, with additional strains added (Table 4). Both *Bacillus* sp. and *Pseudomonas* sp. have individual capabilities for degrading plastics, and when interacting with other microorganisms, they can mitigate the effects of toxic products on a single degrading bacterium, thereby promoting effective plastic degradation.

For polyester plastics, in 2021, Gao et al. [54] utilized thousands of plastic waste samples collected in Huiquan Bay as bacterial sources. They isolated three strains of PET-degrading bacteria, including *Exiguobacterium* sp., *Halomonas* sp., and *Ochrobactrum* sp., then combined them in a ratio of OD_{600} of 1:1:1. This artificial bacterial system degraded the PET film into small pieces after 2 weeks. The treated PET film exhibited a notable trend towards depolymerization, and the primary degradation products were identified as TPA and MHET. Qi et al. [55] developed an artificial hybrid bacterial system consisting of *Rhodococcus jostii* and two metabolically engineered *Bacillus subtilis* strains; initially, they constructed a *Bacillus* system with two engineered *Bacillus subtilis* strains that secreted PETase and MHETase, leading to the degradation of PET film up to 13.6% after 7 days; subsequently, *Rhodococcus jostii* was added to this system for further degradation of the intermediate product TPA. As a result, the weight loss of PET film reached 31.2% after 7 days, representing an increase in mass loss of about 17.6% compared to the *Bacillus* system alone.

For polyolefin plastics, in 2023, Wang et al. [56] isolated three strains of *Rhodopseudomonas* sp. P1, *Rhodanobacter* sp. Rs, and *Microbacterium* sp. M1 from bacterial sources obtained in soil ecosystems for polyethylene mulch film (PMFs) degradation. These strains were then combined with *Bacillus aryabhattai* 5-3, a typical PMF-degrading bacterium, to form a mixed culture system using PMFs as the sole carbon source. Based on the property changes of the PMFs (roughness, chemical functional groups, and hydrophobicity), the most effective combination was finally found to be the two-bacteria system of *Rhodanobacter* sp. Rs and *Bacillus aryabhattai* 5-3. Xiang et al. [57] isolated three predominant PS-degrading bacteria, *Stenotrophomonas maltophilia*, *Bacillus velezensis*, and *Acinetobacter radioresistance*, from soil and river sediments. Among them, the co-culture of *Stenotrophomonas maltophilia* and *Bacillus veleziensis* achieved a 43.5% weight loss of PS after 60 days, which was significantly higher than that achieved by either bacterium alone.

Table 4. Artificial mixed bacterial degradation of (micro)plastics.

Plastic	Microbial Community Construction	Culture Source	Degradation Condition	Plastic Weight Loss	Reference
PET	*Rhodococcus jostii*, *Bacillus subtilis*	Laboratory	30 °C, aerobic	31.2%/60 d	[55]
PET	*Exiguobacterium* sp., *Halomonas* sp., *Ochrobactrum* sp.	Surface sedimentary samples	Culture for four weeks, aerobic	Not available	[54]
PE	*Rhodopseudomonas* sp. P1, *Rhodanobacter* sp. Rs, *Microbacterium* sp. M1, *Bacillus aryabhattai* 5-3	Soil	28 °C, 180 rpm for 60 d, aerobic	Not available	[56]
PE	*Acinetobacter* sp. NyZ450, *Bacillus* sp. NyZ451	Larval gut	23 °C, 180 rpm/min, aerobic	18%/30 d	[58]
PS	*Stenotrophomonas*, *maltophilia*, *Bacillus velezensis*	Soil and river sediments	30 °C, 110 rpm/min, aerobic	43.5%/60 d	[57]

3.3. Factors Impacting Microbial Degradation of (Micro)plastics

The efficiency of microbial degradation of (micro)plastics is influenced by three primary factors: the specific microbial species involved, the properties of the plastic, and the prevailing environmental conditions. Variations in the degradation capacity of different microorganisms towards plastics are primarily attributed to differences in substrate specificity exhibited by their secreted degradation enzymes. Fungi demonstrate superior degradation potential compared to other microorganisms due to their robust adsorption, colonization, survival abilities, and capability to produce a diverse array of specific degradation enzymes. Polyester plastics exhibit greater susceptibility to microbial degradation than other types due to the presence of easily hydrolyzable ester bonds. Environmental factors, such as tem-

perature, humidity, pH, light exposure, and oxygen level, can influence plastic degradation by impacting both the growth and metabolism of microorganisms and altering functional group structures on the plastic surface. Specifically, optimal humidity, temperature, and pH levels are helpful to promote the proliferation and metabolic activity of microorganisms. In this context, increased production and activity of enzymes can catalyze the breakdown of plastic polymers into simpler polymers and low-molecular-weight organic acids. In natural settings, light and oxygen can catalyze the generation of numerous reactive oxygen species (ROS) on (micro)plastic surfaces, thereby accelerating their aging processes. Chen et al. [59] investigated PS degradation in situ within intertidal sediments and sediment column samples. They observed that anaerobic–aerobic alternating conditions led to an increase in the weight loss rate for PS over 60 days by a factor ranging from 0.7 to 5.8 compared to static anaerobic or aerobic conditions. Therefore, the meticulous regulation of environmental parameters is essential to increase the rate of plastic biodegradation. This highlights the importance of the combination of controlled environmental conditions and plastic properties for advancing plastic waste management and treatment through sustainable biotechnology.

4. Coupled Enhanced Technologies

4.1. Advanced Oxidation Technology

Advanced oxidation technologies (AOPs) utilize strong oxidants or physical processes such as light and electricity to produce reactive oxygen species (ROS), thereby achieving efficient degradation of organic pollutants [60–62]. The primary AOP technologies for enhancing the degradation of (micro)plastics through indirect or direct coupling with microbial degradation are photocatalysis and Fenton reactions (Figure 2). Indirect coupling involves the pre-application of AOP technology to modify the surface structure of (micro)plastics, making them more susceptible to microbial degradation. For instance, Montazer et al. [63] conducted UV pretreatment on PE and then identified a PE-degrading bacterium IRN19, resulting in a weight loss of 26.8 ± 3.04% within 28 days. Similarly, Tribedi et al. [64] compared the degradation of PE in soil with and without UV pretreatment and found that the degree of PE degradation in the pretreated group was nearly double that of the untreated group, with a weight loss rate of 6% within 28 days. Direct coupling involves utilizing microorganisms and AOP technology simultaneously to more efficiently degrade (micro)plastics. Xing et al. [65] discovered that thermophilic iron-reducing bacteria in thermophilic compost could facilitate the production of ·OH in compost through Fe^{2+} generation, thereby synergizing with microbial degradation to expedite the decomposition of (micro)plastics. Furthermore, Yang et al. [66] utilized *Shewanella putrefaciens* 200 to construct a microbial-driven Fenton reaction under alternating anaerobic-aerobic incubation conditions for enhancing PS degradation, resulting in a weight loss rate of 6.1 ± 0.6% within just 14 days—a significant improvement compared to microbial degradation alone by a factor of 11.5.

4.2. Electrochemical Technology

The bioelectrochemical system (BES) is a technology for treating pollutants that combines microbial metabolism and electrochemical reactions [67]. Microbial metabolic activity plays a crucial role in determining the degradation of (micro)plastics. Therefore, integrating the redox properties of BES with microbial degradation to enhance microbial activity represents an effective approach for promoting the degradation of (micro)plastics (Figure 2). Research on the degradation of (micro)plastics by BES is still in its early stages, with limited relevant literature reports. Wang et al. [68,69] investigated the impact of PE microplastics on BES wastewater treatment and observed that PE reduced methane production in the electrochemical anaerobic digestion of wastewater and the electrochemical activity of BES. This reduction was attributed to decreased microbial activity and diversity, extracellular electron transport, and the abundance of methanogenic genes; the degradation of PE in BES within wastewater has not yet been studied. The degradation of microplastics PVC, PE, and PLA

in soil using BES has been examined, and the results indicated that the closed-circuit group achieved a decrease percentage of 8.94% in PLA weight after 120 days, which increased by 3.01–3.54 times compared to that from the open-circuit group. Partial degradation of PE was also observed, while PVC degradation was not significant. This suggests that PLA and PE could serve as potential carbon sources to enhance electricity production from soil-based BES systems, whereas PVC may inhibit electricity generation; electrical stimulation enhances the enrichment of bacteria responsible for degrading microplastic surfaces, thereby improving the abundance of genes related to microbial degradation and metabolism while reducing chemical stability [70]. BES involves the direct coupling of microorganisms and electrochemistry. Considering the impact of electrochemical catalysis on the degradation and high-value conversion of plastics, an alternative direction for future research could be to explore the indirect coupling of electrochemical catalysis as a front-end pretreatment or terminal high-value conversion method for microbial degradation of (micro)plastics [71,72].

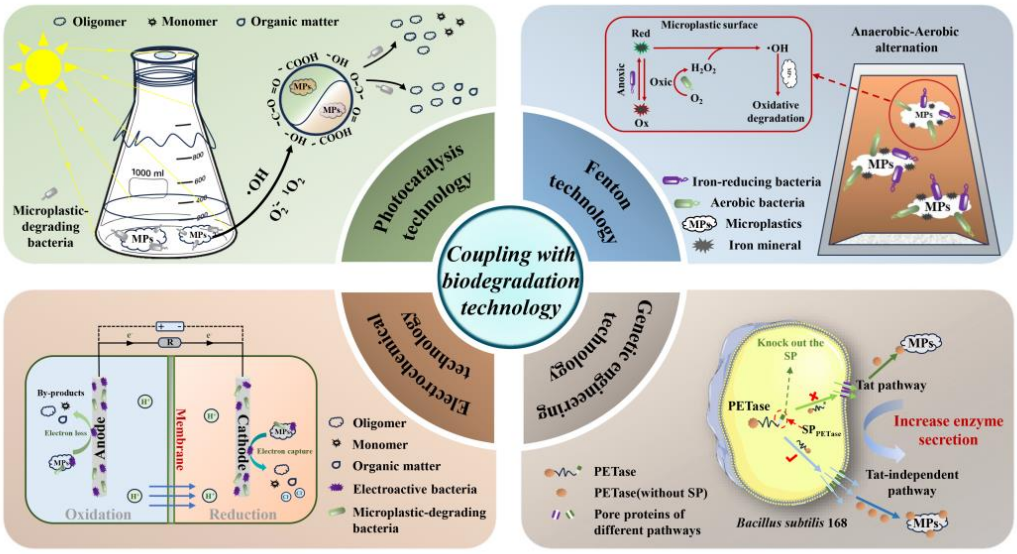


Figure 2. Coupled enhanced technologies for biodegradation.

4.3. Genetic Engineering Technology

Genetic engineering technology is a method used to artificially manipulate the genetic information of microorganisms in a targeted manner, aiming to optimize their initial performance or impart specific functions. Microorganisms primarily degrade (micro)plastics by secreting extracellular enzymes, and one effective way to enhance the degradation of (micro)plastics is through genetic engineering to improve the immobilization, functionalization, and activity of plastic-degrading enzymes (Figure 2) [73]. Huang et al. [74] utilized *Bacillus subtilis*-168 as a chassis microorganism and regulated PETase secretion by constructing strains with different Tat proteins (TatAd, TatCd, TatAy, TatCy, and TatAc) deficient strains. They found that PETase secretion was maximized when all five Tat proteins were knocked out, resulting in a 3.8-fold increase compared with the original strain. Yan et al. [75] developed a thermotolerant degrading engineered bacterium using a strong promoter strategy with *Clostridium thermocellum*. This led to high levels of expression of thermophilic cutinase (LCC), resulting in a 62% weight loss of PET film at 60 °C for 14 days, significantly better than previously reported thermophilic or microalgae-engineered microbial systems. However, it has been suggested that building synthetic microbial communities holds more promise than engineering modifications of single bacteria, as it can help promote depolymerization and upcycling of plastics through the synergy of different microbial metabolic pathways [76]. Bao et al. [14] developed a two-bacterial system comprising two engineered soil *Pseudomonas putida* strains, Pp-T and Pp-E: Pp-T was created by deleting *ped* operon and expressing *tpaAa*, *tpaAb*, *tpaB*, *tpaC*, and *tpaK* genes constitutively to specifically degrade TPA. By contrast, Pp-E promotes gene expression of *gcl*, *glxR*, *hyi*, *ttuD*, and *pykA*

by knocking out the *gclR* gene and specifically degrades EG by replacing the native promoter of the *glcDEF* operon with a strong constitutive promoter (Ptac). This two-bacterial system demonstrated its capability to completely consume PET hydrolyzing monomer while converting it into medium chain length polyhydroxyalkanoates (mcl-PHA) as well as *cis-cis* muconate (MA) through the introduction of two different biosynthetic pathways.

5. Conclusions

Plastic products bring convenience to our daily lives, but they also cause severe pollution to the environment. Microbial degradation is a kind of green and sustainable method for (micro)plastic waste treatment, which meets the needs of low-carbon development in current society. Novel plastic-degrading microorganisms have recently been found in a wide variety of environments. However, microbial degradation of (micro)plastics still suffers from the problems of low efficiency, slow rate, and the tendency to produce smaller plastics with stronger toxicity, such as nanoplastics. Hence, future research should improve the (micro)plastic removal and achieve the upgraded recycling of plastic wastes, such as screening efficient plastic-degrading microorganisms, developing genetic engineering modification strategies based on the in-depth elucidation of biodegradation mechanisms, constructing stable and controllable artificial microbial communities, and combining biodegradation with physicochemical technologies. In addition, most of the existing studies conducted (micro)plastic biodegradation and microorganism screening under aerobic conditions. However, based on the diversity of environments containing (micro)plastic pollution, researchers should pay more attention to the microorganisms degrading (micro)plastics under anaerobic conditions.

Funding: This work was financially supported by the National Key Research and Development Program of China (2021YFC2103600), the Natural Science Foundation of Jiangsu Province of China for Excellent Young Scholars (BK20211591), the National Natural Science Foundation of China (22478184), the Jiangsu Synergetic Innovation Center for Advanced Bio-Manufacture (XTD2209), and the National Students' Platform for Innovation and Entrepreneurship Training Program (202410291043Z).

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

References

1. Plastics Europe. Available online: https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023 (accessed on 22 May 2024).
2. Shi, J.; Zhang, C.; Chen, W.-Q. The expansion and shrinkage of the international trade network of plastic wastes affected by China's waste management policies. *Sustain. Prod. Consum.* **2021**, *25*, 187–197. [CrossRef]
3. Van Oosterhout, L.; Dijkstra, H.; Borst, D.; Duijndam, S.; Rehdanz, K.; Van Beukering, P. Triggering sustainable plastics consumption behavior: Identifying consumer profiles across Europe and designing strategies to engage them. *Sustain. Prod. Consum.* **2023**, *36*, 148–160. [CrossRef]
4. Isobe, A.; Azuma, T.; Cordova, M.R.; Cózar, A.; Galgani, F.; Hagita, R.; Kanhai, L.D.; Imai, K.; Iwasaki, S.; Kako, S.I.; et al. A multilevel dataset of microplastic abundance in the world's upper ocean and the Laurentian Great Lakes. *Micropl. Nanopl.* **2021**, *1*, 16. [CrossRef]
5. Nizzetto, L.; Futter, M.; Langaas, S. Are Agricultural Soils Dumps for Microplastics of Urban Origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779. [CrossRef] [PubMed]
6. Behera, S.; Das, S. Environmental impacts of microplastic and role of plastisphere microbes in the biodegradation and upcycling of microplastic. *Chemosphere* **2023**, *334*, 138928. [CrossRef]
7. Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L. Plastic waste inputs from land into the ocean. *Science* **2015**, *347*, 768–771. [CrossRef]
8. Rochman, C.M.; Browne, M.A.; Halpern, B.S.; Hentschel, B.T.; Hoh, E.; Karapanagioti, H.K.; Rios-Mendoza, L.M.; Takada, H.; Teh, S.; Thompson, R.C. Classify plastic waste as hazardous. *Nature* **2013**, *494*, 169–171. [CrossRef]
9. Maity, S.; Biswas, C.; Banerjee, S.; Guchhait, R.; Adhikari, M.; Chatterjee, A.; Pramanick, K. Interaction of plastic particles with heavy metals and the resulting toxicological impacts: A review. *Environ. Sci. Pollut. Res.* **2021**, *28*, 60291–60307. [CrossRef] [PubMed]
10. Liu, S.; Chen, Q.; Ding, H.; Song, Y.; Pan, Q.; Deng, H.; Zeng, E.Y. Differences of microplastics and nanoplastics in urban waters: Environmental behaviors, hazards, and removal. *Water Res.* **2024**, *260*, 121895. [CrossRef]

11. Guo, S.; Feng, D.; Li, Y.; Liu, L.; Tang, J. Innovations in chemical degradation technologies for the removal of micro/nano-plastics in water: A comprehensive review. *Ecotoxicol. Environ. Saf.* **2024**, *271*, 115979. [CrossRef]
12. Xu, Z.; Bai, X. Microplastic Degradation in Sewage Sludge by Hydrothermal Carbonization: Efficiency and Mechanisms. *Chemosphere* **2022**, *297*, 134203. [CrossRef] [PubMed]
13. Chattopadhyay, I. Role of microbiome and biofilm in environmental plastic degradation. *Biocatal. Agric. Biotechnol.* **2022**, *39*, 102263. [CrossRef]
14. Bao, T.; Qian, Y.; Xin, Y.; Collins, J.J.; Lu, T. Engineering microbial division of labor for plastic upcycling. *Nat. Commun.* **2023**, *14*, 5712. [CrossRef]
15. He, W.; Li, Y.; Ni, L.; Zhu, W. Effect of stabilizer EDTA on the thermal hazard of green synthesis process of adipic acid and development of microchannel continuous flow process. *Emerg. Manag. Sci. Technol.* **2023**, *3*, 22. [CrossRef]
16. Wang, M.; Wang, Y.; Liu, J.; Yu, H.; Liu, P.; Yang, Y.; Sun, D.; Kang, H.; Wang, Y.; Tang, J.; et al. Integration of advanced biotechnology for green carbon. *Green Carbon* **2024**, *2*, 164–175. [CrossRef]
17. Ogunbayo, A.O.; Olanipekun, O.O.; Adamu, I.A. Preliminary Studies on the Microbial Degradation of Plastic Waste Using *Aspergillus niger* and *Pseudomonas* sp. *J. Environ. Prot. Ecol.* **2019**, *10*, 625–631. [CrossRef]
18. Rios, L.M.; Jones, P.R.; Moore, C.; Narayan, U.V. Quantitation of persistent organic pollutants adsorbed on plastic debris from the Northern Pacific Gyre's "eastern garbage patch". *J. Environ. Monitor.* **2010**, *12*, 2226–2236. [CrossRef]
19. Sorasan, C.; Edo, C.; González-Pleiter, M.; Fernández-Pinas, F.; Leganés, F.; Rodríguez, A.; Rosal, R. Ageing and fragmentation of marine microplastics. *Sci. Total Environ.* **2022**, *827*, 154438. [CrossRef]
20. Rillig, M.C. Microplastic in terrestrial ecosystems and the soil? *Environ. Sci. Technol.* **2012**, *46*, 6453–6454. [CrossRef]
21. Zhang, Y.; Pedersen, J.N.; Eser, B.E.; Guo, Z. Biodegradation of polyethylene and polystyrene: From microbial deterioration to enzyme discovery. *Biotechnol. Adv.* **2022**, *60*, 107991. [CrossRef]
22. Dhaka, V.; Singh, S.; Anil, A.G.; Naik, T.S.S.K.; Garg, S.; Samuel, J.; Kumar, M.; Ramamurthy, P.C.; Singh, J. Occurrence, toxicity and remediation of polyethylene terephthalate plastics. A review. *Environ. Chem. Lett.* **2022**, *20*, 1777–1800. [CrossRef] [PubMed]
23. Scaffaro, R.; Maio, A.; Nostro, A. Poly(lactic acid)/carvacrol-based materials: Preparation, physicochemical properties, and antimicrobial activity. *Appl. Microbiol. Biotechnol.* **2020**, *104*, 1823–1835. [CrossRef] [PubMed]
24. Pfohl, P.; Bahl, D.; Rückel, M.; Wagner, M.; Meyer, L.; Bolduan, P.; Battagliarin, G.; Hüffer, T.; Zumstein, M.; Hofmann, T.; et al. Effect of Polymer Properties on the Biodegradation of Polyurethane Microplastics. *Environ. Sci. Technol.* **2022**, *56*, 16873–16884. [CrossRef]
25. Yang, S.-S.; Ding, M.-Q.; Ren, X.-R.; Zhang, Z.-R.; Li, M.-X.; Zhang, L.-L.; Pang, J.-W.; Chen, C.-X.; Zhao, L.; Xing, D.-F.; et al. Impacts of physical-chemical property of polyethylene on depolymerization and biodegradation in yellow and dark mealworms with high purity microplastics. *Sci. Total Environ.* **2022**, *828*, 154458. [CrossRef]
26. Ouyang, Z.; Zhang, Z.; Jing, Y.; Bai, L.; Zhao, M.; Hao, X.; Li, X.; Guo, X. The photo-aging of polyvinyl chloride microplastics under different UV irradiations. *Gondwana Res.* **2022**, *108*, 72–80. [CrossRef]
27. Endo, K. Synthesis and structure of poly(vinyl chloride). *Prog. Polym. Sci.* **2002**, *27*, 2021–2054. [CrossRef]
28. Zhou, D.; Wu, B.-H.; Yang, W.-W.; Li, X.; Zhu, L.-W.; Xu, Z.-K.; Wan, L.-S. Effect of polar groups of polystyrenes on the self-assembly of breath figure arrays. *J. Polym. Sci.* **2022**, *60*, 2371–2382. [CrossRef]
29. Du, T.; Shao, S.; Qian, L.; Meng, R.; Li, T.; Wu, L.; Li, Y. Effects of photochlorination on the physicochemical transformation of polystyrene nanoplastics: Mechanism and environmental fate. *Water Res.* **2023**, *243*, 120367. [CrossRef] [PubMed]
30. Mahato, B.; Babarinde, V.O.; Abaimov, S.G.; Lomov, S.V.; Akhatov, I. Interface strength of glass fibers in polypropylene: Dependence on the cooling rate and the degree of crystallinity. *Polym. Compos.* **2020**, *41*, 1310–1322. [CrossRef]
31. Zhang, Y.; Wang, M.; Zhang, D.; Wang, Y.; Wang, L.; Qiu, Y.; Wang, L.; Chen, T.; Zhao, L. Crystallization and Performance of Polyamide Blends Comprising Polyamide 4, Polyamide 6, and Their Copolymers. *Polymers* **2023**, *15*, 3399. [CrossRef]
32. Hou, L.; Xi, J.; Liu, J.; Wang, P.; Xu, T.; Liu, T.; Qu, W.; Lin, Y.B. Biodegradability of polyethylene mulching film by two Pseudomonas bacteria and their potential degradation mechanism. *Chemosphere* **2022**, *286*, 131758. [CrossRef]
33. Park, S.Y.; Kim, C.G. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. *Chemosphere* **2019**, *222*, 527–533. [CrossRef] [PubMed]
34. Kim, H.R.; Lee, H.M.; Yu, H.C.; Jeon, E.; Lee, S.; Li, J.; Kim, D.H. Biodegradation of Polystyrene by *Pseudomonas* sp. Isolated from the Gut of Superworms (Larvae of *Zophobas atratus*). *Environ. Sci. Technol.* **2020**, *54*, 6987–6996. [CrossRef]
35. Auta, H.S.; Emenike, C.U.; Jayanthi, B.; Fauziah, S.H. Growth kinetics and biodeterioration of polypropylene microplastics by *Bacillus* sp. and *Rhodococcus* sp. isolated from mangrove sediment. *Mar. Pollut. Bull.* **2018**, *127*, 15–21. [CrossRef] [PubMed]
36. 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]
37. Joo, S.; Cho, I.J.; Seo, H.; Son, H.F.; Sagong, H.Y.; 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]
38. Zhang, Z.; Peng, H.; Yang, D.; Zhang, G.; Zhang, J.; Ju, F. Polyvinyl chloride degradation by a bacterium isolated from the gut of insect larvae. *Nat. Commun.* **2022**, *13*, 5360. [CrossRef]
39. Lyu, L.; Fang, K.; Huang, X.; Tian, X.; Zhang, S. Polyethylene is degraded by the deep-sea *Acinetobacter venetianus* bacterium. *Environ. Chem. Lett.* **2024**, *22*, 1591–1597. [CrossRef]

40. Sanchez, C. Fungal potential for the degradation of petroleum-based polymers: An overview of macro- and microplastics biodegradation. *Biotechnol. Adv.* **2020**, *40*, 107501. [CrossRef]
41. Ahmed, T.; Shahid, M.; Azeem, F.; Rasul, I.; Shah, A.A.; Noman, M.; Hameed, A.; Manzoor, N.; Manzoor, I.; Muhammad, S. Biodegradation of plastics: Current scenario and future prospects for environmental safety. *Environ. Sci. Pollut. Res.* **2018**, *25*, 7287–7298. [CrossRef]
42. Khan, S.; Nadir, S.; Shah, Z.U.; Shah, A.A.; Karunarathna, S.C.; Xu, J.; Khan, A.; Munir, S.; Hasan, F. Biodegradation of polyester polyurethane by *Aspergillus tubingensis*. *Environ. Pollut.* **2017**, *225*, 469–480. [CrossRef] [PubMed]
43. 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]
44. Gao, R.; Liu, R.; Sun, C. A marine fungus *Alternaria alternata* FB1 efficiently degrades polyethylene. *J. Hazard. Mater.* **2022**, *431*, 128617. [CrossRef] [PubMed]
45. Yan, N.; Fan, C.; Chen, Y.; Hu, Z. The Potential for Microalgae as Bioreactors to Produce Pharmaceuticals. *Int. J. Mol. Sci.* **2016**, *17*, 962. [CrossRef] [PubMed]
46. Vimal Kumar, R.; Kanna, G.R.; Elumalai, S. Biodegradation of Polyethylene by Green Photosynthetic Microalgae. *J. Bioremediat. Biodegrad.* **2017**, *2017*, 1000381. [CrossRef]
47. Chia, W.Y.; Tang, D.Y.Y.; Khoo, K.S.; Lup, A.N.L.; Chew, K.W. Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. *Environ. Sci. Ecotechnol.* **2020**, *4*, 100065. [CrossRef]
48. Sarmah, P.; Rout, J. Efficient biodegradation of low-density polyethylene by cyanobacteria isolated from submerged polyethylene surface in domestic sewage water. *Environ. Sci. Pollut. Res.* **2018**, *25*, 33508–33520. [CrossRef]
49. Gowthami, A.; Marjuk, M.S.; Raju, P.; Devi, K.N.; Santhanam, P.; Kumar, S.D.; Perumal, P. Biodegradation efficacy of selected marine microalgae against Low-Density Polyethylene (LDPE): An environment friendly green approach. *Mar. Pollut. Bull.* **2023**, *190*, 114889. [CrossRef]
50. Khatoon, N.; Jamal, A.; Ali, M.I. Lignin peroxidase isoenzyme: A novel approach to biodegrade the toxic synthetic polymer waste. *Environ. Technol.* **2019**, *40*, 1366–1375. [CrossRef]
51. Devi, R.S.; Ramya, R.; Kannan, K.; Antony, A.R.; Kannan, V.R. Investigation of biodegradation potentials of high density polyethylene degrading marine bacteria isolated from the coastal regions of Tamil Nadu, India. *Mar. Pollut. Bull.* **2019**, *138*, 549–560. [CrossRef]
52. Syranidou, E.; Karkanorachaki, K.; Amorotti, F.; Repouskou, E.; Kroll, K.; Kolvenbach, B.; Corvini, P.F.; Fava, F.; Kalogerakis, N. Development of tailored indigenous marine consortia for the degradation of naturally weathered polyethylene films. *PLoS ONE* **2017**, *12*, e0183984. [CrossRef]
53. Xu, Y.; Xian, Z.N.; Yue, W.; Yin, C.F.; Zhou, N.Y. Degradation of polyvinyl chloride by a bacterial consortium enriched from the gut of *Tenebrio molitor* larvae. *Chemosphere* **2023**, *318*, 137944. [CrossRef] [PubMed]
54. Gao, R.; Sun, C. A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. *J. Hazard. Mater.* **2021**, *416*, 125928. [CrossRef] [PubMed]
55. Qi, X.; Ma, Y.; Chang, H.; Li, B.; Ding, M.; Yuan, Y. Evaluation of PET Degradation Using Artificial Microbial Consortia. *Front. Microbiol.* **2021**, *12*, 778828. [CrossRef]
56. Wang, P.; Liu, J.; Han, S.; Wang, Y.; Duan, Y.; Liu, T.; Hou, L.; Zhang, Z.; Li, L.; Lin, Y. Polyethylene mulching film degrading bacteria within the plastisphere: Co-culture of plastic degrading strains screened by bacterial community succession. *J. Hazard. Mater.* **2023**, *442*, 130045. [CrossRef]
57. Xiang, P.; Zhang, Y.; Zhang, T.; Wu, Q.; Zhao, C.; Li, Q. A novel bacterial combination for efficient degradation of polystyrene microplastics. *J. Hazard. Mater.* **2023**, *458*, 131856. [CrossRef] [PubMed]
58. Yin, C.-F.; Xu, Y.; Zhou, N.-Y. Biodegradation of polyethylene mulching films by a co-culture of *Acinetobacter* sp. strain NyZ450 and *Bacillus* sp. strain NyZ451 isolated from *Tenebrio molitor* larvae. *Int. Biodeter. Biodegr.* **2020**, *155*, 105089. [CrossRef]
59. Chen, S.; Yang, Y.; Jing, X.; Zhang, L.; Chen, J.; Rensing, C.; Luan, T.; Zhou, S. Enhanced aging of polystyrene microplastics in sediments under alternating anoxic-oxic conditions. *Water Res.* **2021**, *207*, 117782. [CrossRef]
60. Ortiz, D.; Munoz, M.; Nieto-Sandoval, J.; Romera-Castillo, C.; de Pedro, Z.M.; Casas, J.A. Insights into the degradation of microplastics by Fenton oxidation: From surface modification to mineralization. *Chemosphere* **2022**, *309*, 136809. [CrossRef]
61. Xu, Q.; Huang, Q.-S.; Luo, T.-Y.; Wu, R.-L.; Wei, W.; Ni, B.-J. Coagulation removal and photocatalytic degradation of microplastics in urban waters. *Chem. Eng. J.* **2021**, *416*, 129123. [CrossRef]
62. Pang, W.; Li, B.; Wu, Y.; Zeng, Q.; Yang, J.; Zhang, Y.; Tian, S. Upgraded recycling of biodegradable PBAT plastic: Efficient hydrolysis and electrocatalytic conversion. *Chem. Eng. J.* **2024**, *486*, 150342. [CrossRef]
63. Montazer, Z.; Habibi-Najafi, M.B.; Mohebbi, M.; Oromiehei, A. Microbial Degradation of UV-Pretreated Low-Density Polyethylene Films by Novel Polyethylene-Degrading Bacteria Isolated from Plastic-Dump Soil. *J. Polym. Environ.* **2018**, *26*, 3613–3625. [CrossRef]
64. Tribedi, P.; Dey, S. Pre-oxidation of low-density polyethylene (LDPE) by ultraviolet light (UV) promotes enhanced degradation of LDPE in soil. *Environ. Monit. Assess.* **2017**, *189*, 624. [CrossRef]
65. Xing, R.; Sun, H.; Du, X.; Lin, H.; Qin, S.; Chen, Z.; Zhou, S. Enhanced degradation of microplastics during sludge composting via microbially-driven Fenton reaction. *J. Hazard. Mater.* **2023**, *449*, 131031. [CrossRef]

66. Yang, Y.; Chen, J.; Chen, Z.; Yu, Z.; Xue, J.; Luan, T.; Chen, S.; Zhou, S. Mechanisms of polystyrene microplastic degradation by the microbially driven Fenton reaction. *Water Res.* **2022**, *223*, 118979. [CrossRef]
67. Wang, H.; Zhou, Q. Bioelectrochemical systems—A potentially effective technology for mitigating microplastic contamination in wastewater. *J. Clean. Prod.* **2024**, *450*, 141931. [CrossRef]
68. Wang, S.; Wang, X.; Fessler, M.; Jin, B.; Su, Y.; Zhang, Y. Insights into the impact of polyethylene microplastics on methane recovery from wastewater via bioelectrochemical anaerobic digestion. *Water Res.* **2022**, *221*, 118844. [CrossRef] [PubMed]
69. Wang, S.; Xu, M.; Jin, B.; Wünsch, U.J.; Su, Y.; Zhang, Y. Electrochemical and microbiological response of exoelectrogenic biofilm to polyethylene microplastics in water. *Water Res.* **2022**, *211*, 118046. [CrossRef]
70. Wang, K.; Yang, S.; Yu, X.; Bai, M.; Ye, H.; Xu, Y.; Zhao, L.; Wu, D.; Li, X.; Weng, L.; et al. Microplastics degradation stimulated by in-situ bioelectric field in agricultural soils. *Environ. Int.* **2023**, *177*, 108035. [CrossRef]
71. Zhou, H.; Ren, Y.; Li, Z.; Xu, M.; Wang, Y.; Ge, R.; Kong, X.; Zheng, L.; Duan, H. Electrocatalytic upcycling of polyethylene terephthalate to commodity chemicals and H_2 fuel. *Nat. Commun.* **2021**, *12*, 4679. [CrossRef]
72. Zheng, W.; Liu, Z.; Wang, B.; Tao, M.; Ji, H.; Xiang, X.; Fu, Z.; Liao, L.; Liao, P.; Chen, R. Effective degradation of polystyrene microplastics by Ti/La/Co-Sb-SnO_2 anodes: Enhanced electrocatalytic stability and electrode lifespan. *Sci. Total Environ.* **2024**, *922*, 171002. [CrossRef]
73. Rahmati, F.; Sethi, D.; Shu, W.; Asgari Lajayer, B.; Mosaferi, M.; Thomson, A.; Price, G.W. Advances in microbial exoenzymes bioengineering for improvement of bioplastics degradation. *Chemosphere* **2024**, *355*, 141749. [CrossRef] [PubMed]
74. Huang, X.; Cao, L.; Qin, Z.; Li, S.; Kong, W.; Liu, Y. Tat-Independent secretion of polyethylene terephthalate hydrolase PETase in *Bacillus subtilis* 168 mediated by Its native signal peptide. *J. Agric. Food Chem.* **2018**, *66*, 13217–13227. [CrossRef] [PubMed]
75. Yan, F.; Wei, R.; Cui, Q.; Bornscheuer, U.T.; Liu, Y.J. Thermophilic whole-cell degradation of polyethylene terephthalate using engineered Clostridium thermocellum. *Microb. Biotechnol.* **2021**, *14*, 374–385. [CrossRef] [PubMed]
76. Jimenez, D.J.; Sanchez, A.; Dini-Andreote, F. Engineering microbiomes to transform plastics. *Trends Biotechnol.* **2024**, *42*, 265–268. [CrossRef]