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Review

Biodegradation of Petrochemical Plastics by Microorganisms: Toward Sustainable Solutions for Plastic Pollution

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Abstract

Plastic pollution has emerged as a critical environmental challenge due to the widespread accumulation of petrochemical plastics in natural ecosystems. Conventional waste management strategies, including mechanical recycling and incineration, have demonstrated limited efficiency in addressing the persistence of plastics such as polyethylene, polypropylene, polyethylene terephthalate, and polyvinyl chloride. While incineration eliminates plastic material, it does not promote circularity and may generate toxic emissions. As a sustainable alternative, microbial biodegradation involves bacteria, fungi, and actinomycetes capable of degrading synthetic polymers through enzymatic processes. This review provides a comprehensive overview of microbial degradation of major plastics such as polyethylene, polypropylene, polyethylene terephthalate, and polyvinyl chloride, highlighting key strains, degradation rates, and enzymatic mechanisms. Importantly, biodegradation research also informs the development of in situ remediation technologies and supports new recycling strategies. Advances in protein engineering and synthetic biology are discussed for enhancing degradation efficiency. However, scaling biodegradation to environmental conditions remains challenging due to variable temperature, pH, microbial competition, and potentially toxic intermediates. Despite these limitations, microbial biodegradation represents a promising ecofriendly approach to address plastic waste and promote a biobased circular economy. Future work should integrate microbial processes into existing recycling infrastructure and design robust consortia guided by omics tools.

Keywords: circular bioeconomy; environmental microbiology; genetic engineering; microbial consortia; microbial enzymes; petrochemical plastics; plastic biodegradation; plastic pollution; sustainable bioremediation; synthetic polymers

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1. Introduction

The large scale production of synthetic plastics from petrochemical sources has been regarded as a major industrial achievement that revolutionized modern life. Due to their versatility, low cost, mechanical strength, and chemical resistance, plastics have been

adopted across numerous sectors, including packaging, healthcare, construction, and electronics. Since the 1940s, plastic usage has significantly increased, and more plastic has been produced in the past decade than in the entire 20th century. In 2023 alone, over 423 million tonnes of plastic were manufactured globally [1]. Common plastics derived from petroleum include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), polyacrylates, and low density polyethylene (LDPE) [2]. These materials are typically enhanced with additives such as dyes, fillers, and plasticizers to improve their properties [3]. However, the extensive use and poor management of plastic waste have resulted in widespread environmental contamination. It has been estimated that over 90% of plastic waste persists in the environment for hundreds of years, resisting natural degradation processes [4]. Plastic pollution is now considered a critical global issue, especially in marine and freshwater ecosystems, where plastic debris originating from tourism, industrial discharge, and municipal waste has been widely reported [5]. Mechanical abrasion and photochemical oxidation contribute to the fragmentation of plastics into microplastics, particles measuring less than 5 mm, which are persistent and pervasive in aquatic environments [6]. These microplastics have been detected in marine organisms and food webs, where they pose risks to biodiversity and ecological integrity [7].

The environmental burden is further exacerbated by the incineration and landfilling of plastics, which release hazardous chemicals such as polychlorinated biphenyls (PCBs) and bisphenol derivatives into the air, soil, and water [4,8,9]. In addition to endangering wildlife, such contaminants have raised growing concerns regarding human exposure through inhalation, ingestion, and trophic transfer. Despite increasing efforts to promote plastic reuse, recycling, and conversion into energy (waste-to-energy and waste-to-fuel technologies) [10] or construction materials [11], these approaches have been constrained by high operational costs and limited efficiency. Furthermore, these strategies often require specialized infrastructure for collection, sorting, and processing, which remains insufficient or absent in many regions, particularly in low- and middle-income countries [12]. Thus, plastic pollution is not solely a technological challenge but also a systemic infrastructural issue.

As a result, biological strategies have been explored as ecofriendly alternatives to traditional waste management. Microbial degradation of plastics, particularly those derived from petroleum, has been explored as a potential strategy, especially under controlled conditions such as closed bioreactors, with pretreatment steps and optimized microbial growth. However, its efficiency in natural environments remains limited and challenging, particularly when starting from intact polymeric materials [13]. Several bacterial genera, including *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Nocardia*, as well as fungi such as *Aspergillus*, *Penicillium*, and *Fusarium*, have been found to produce enzymes, such as lipases, esterases, and oxygenases, that facilitate the breakdown of polymer chains [13,14]. This process is often enhanced by prior physicochemical degradation, which shortens polymer length and increases accessibility to microbial enzymes.

Beyond its role in waste treatment, microbial plastic degradation is essential to understanding the environmental fate of synthetic polymers. Insights from microbial metabolism can inform the development of new recycling strategies, in situ remediation approaches, and synthetic biology applications. As such, studying biodegradation contributes to designing circular systems capable of reducing plastic accumulation while recovering value from waste materials.

Hence, microbial biodegradation has been increasingly considered a promising approach to mitigate the persistence and potential toxicity of petrochemical plastics in the environment.

2. The Challenge of Petrochemical Plastics

The term "plastic" refers to a diverse group of synthetic polymers, predominantly derived from petrochemical feedstocks such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) [15]. These polymers have been widely adopted due to their advantageous physicochemical properties, including high tensile strength, resistance to moisture and chemicals, durability, and low manufacturing costs. Such characteristics have made petrochemical plastics ubiquitous in packaging, textiles, consumer products, and numerous industrial applications [15,16] (Figure 1).

Despite their widespread use, these plastics exhibit inherent resistance to degradation in natural environments. Their high molecular weight, hydrophobicity, and stable carbon–carbon backbone structures impede enzymatic and microbial breakdown [15,17]. Unlike condensation polymers such as PET or nylon, which can theoretically be depolymerized into monomers, addition polymers such as PE, PP, and PS lack hydrolyzable functional groups, making them highly recalcitrant to both chemical and biological degradation [13]. This structural robustness contributes to environmental persistence that can span centuries [16]. For instance, PE and PP, the most produced plastics worldwide, are known to remain intact for over 500 years under standard environmental conditions [15,16].

The durability and recalcitrance of petrochemical plastics have resulted in their extensive accumulation in terrestrial and aquatic ecosystems globally. It has been estimated that approximately 70% of produced plastics end up as waste in landfills or the natural environment, where inadequate disposal and recycling systems exacerbate pollution levels. This challenge is further intensified by insufficient infrastructure for collection, sorting, and recycling, especially in regions with limited waste management systems [15].

The fragmentation of larger plastic debris into microplastics, defined as plastic particles smaller than 5 mm, occurs primarily through mechanical abrasion, ultraviolet (UV) radiation, and thermal oxidation [18]. This process does not result in complete mineralization but generates persistent micro- and nanoplastic particles that disperse widely across ecosystems [18,19].

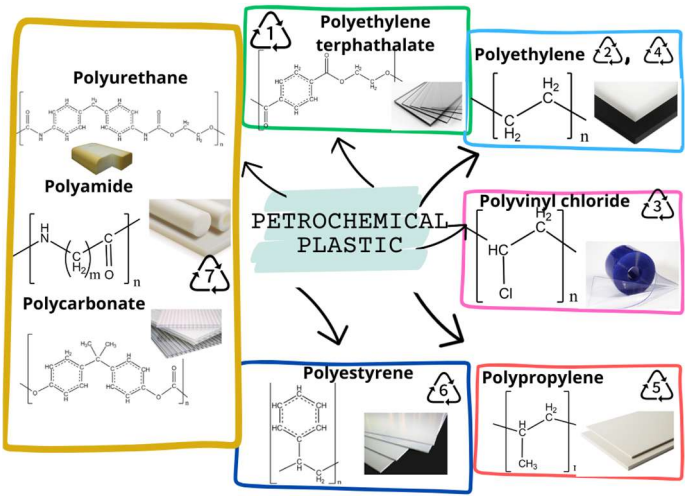

Figure 1. Representative petrochemical-derived plastics along with their chemical structures, recycling symbols, and typical physical appearances. The plastics shown include polyethylene terephthalate (PET, ♳), polyethylene (PE, ♴ and ♵), polyvinyl chloride (PVC, ♶), polypropylene (PP, ♷), polystyrene (PS, ♸), polyamide (PA, ♹), and polycarbonate (PC, ♺). These polymers are widely used in industrial and consumer products. Recycling symbols indicate their classification in plastic waste management systems [20]. The images presented were adapted from publicly available resources provided at https://www.novaplest.fr/en/plastic-materials (accessed on 26 May 2025) and https://webshop.laarmann.eu/featured_item/polyurethane/ (accessed on 2 August 2025).

Microplastics have been detected in diverse environmental matrices, including marine surface waters, deep sea sediments, freshwater bodies, soils, and the atmosphere [18,19]. Their ubiquity has raised considerable concern due to their potential toxicological effects on biota. Microplastics can be ingested by a wide range of organisms, from plankton to fish and marine mammals, leading to physical harm, chemical exposure through adsorbed pollutants, and possible trophic transfer within food webs [19]. Furthermore, microplastics have been identified as vectors for persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), which adsorb onto their surfaces, further magnifying ecological and health risks [21].

The leaching of plastic additives, such as plasticizers (e.g., phthalates), stabilizers, and flame retardants, from polymer matrices into the environment constitutes another critical aspect of plastic pollution [21]. These compounds have been linked to endocrine disruption, carcinogenicity, and other adverse health effects in wildlife and humans [21]. Consequently, the environmental impact of petrochemical plastics extends beyond physical pollution to include chemical toxicity.

The transboundary nature of plastic pollution complicates management efforts. Ocean currents, wind patterns, and river flows facilitate the global distribution of plastic debris, making it a worldwide environmental crisis. Remote and ecologically sensitive regions, such as the Arctic and deep ocean trenches, have been found to contain microplastic contamination, highlighting the pervasive reach of this issue [19].

To date, conventional waste management strategies, including landfilling, incineration, and mechanical recycling, have proven insufficient to address the scale of plastic pollution. Landfilling contributes to long term accumulation and potential soil and groundwater contamination. Incineration, while reducing volume, can release hazardous compounds and does not support resource circularity. Mechanical recycling faces limitations due to polymer heterogeneity, contamination, and degradation of material properties after repeated processing. Moreover, these approaches require coordinated infrastructure and economic incentives, which are not universally available [22].

Given these constraints, innovative and sustainable approaches are urgently required to mitigate the environmental footprint of petrochemical plastics. Among these, biological degradation through microorganisms and enzymes has garnered significant attention due to its ecofriendly potential [15]. Microbial biodegradation may offer a viable pathway to reduce plastic accumulation, complementing waste reduction and recycling initiatives.

3. Treatment of Petrochemical Plastics

Over the past decades, the persistent accumulation of plastic waste has prompted the investigation of more efficient and sustainable degradation and recycling strategies. Among these, physical, chemical, and biological methods have been extensively studied, each offering specific advantages and limitations.

3.1. Physical Methods

Mechanical recycling faces significant limitations due to contamination, degradation of material properties, and the need for precise separation of various polymers. Despite this, it remains the most widely adopted physical method for plastic waste management due to its operational simplicity and cost effectiveness. This process includes washing, grinding, and melting, by which plastic waste is reprocessed into new products. Plastics such as polyethylene terephthalate (PET) and high density polyethylene (HDPE) are commonly recycled through this method, which maintains the polymer backbone and enables their reformation without significant chemical transformation [23].

The standard procedure involves multiple stages, including collection and transportation, cleaning to remove contaminants, mechanical size reduction (shredding or grinding), polymer separation (via flotation or near infrared sorting), and extrusion into pellets [24]. These resins can then be reintroduced into manufacturing chains to produce secondary goods. This approach is favored not only for its compatibility with existing waste infrastructures but also for its lower energy requirements compared to chemical recycling [23].

However, a progressive loss in the mechanical properties of the material has been observed after successive recycling cycles, leading to a decline in the quality of recycled polyethylene terephthalate (PET), which cannot compete with virgin polymer [18]. Such degradation is often due to the thermal and mechanical stress applied during reprocessing, which lowers molecular weight and compromises performance. Moreover, the presence of incompatible polymers, such as PVC in PET streams, can drastically deteriorate product quality, highlighting the need for precise sorting [25].

More advanced physical methods, such as pyrolysis, chemical vapor deposition, and Joule heating, have been explored and, to varying extents, implemented at the industrial scale [26]. These processes result in byproducts that may be repurposed; nevertheless, the generation of secondary toxic waste has also been reported, raising environmental concerns [27]. Although often grouped with physical methods, these strategies are more accurately classified as chemical recycling processes due to the significant molecular transformations involved. They represent promising alternatives but require careful environmental evaluation.

3.2. Chemical Methods

Chemical recycling has been recognized as a promising approach, as it allows polymers to be broken down into their original monomers or other valuable compounds. Unlike mechanical methods, which preserve the polymer backbone, chemical recycling cleaves the molecular structure of plastics, offering the potential for complete material recovery and high purity outputs. This umbrella category includes pyrolysis (thermal decomposition in the absence of oxygen), gasification (conversion to syngas under high temperatures), and solvolysis-based depolymerization (e.g., glycolysis, methanolysis, hydrolysis).

Among these, glycolysis has been widely studied for the depolymerization of PET into bis(2-hydroxyethyl) terephthalate (BHET), which can be directly repolymerized [23,28]. This process allows for the selective recovery of monomers, which can be purified and reused to produce polymers with properties comparable to virgin materials. In addition, methanolysis and hydrolysis also offer viable depolymerization pathways, particularly for polyesters, under optimized conditions [28,29]. These routes are being increasingly investigated as part of circular economic strategies.

Innovative chemical techniques have also emerged, expanding the potential of this recycling category beyond monomer recovery. These include processes designed to convert plastics into fuels or other industrially useful chemicals. Photocatalytic reforming and polystyrene degradation via nitrogen-based catalysts are examples of such processes. Such strategies open avenues for upcycling plastic waste into value-added products, such as hydrogen, alkanes, or specialty chemicals, which can be integrated into energy or chemical supply chains [30,31].

However, despite their versatility, these techniques are often constrained by high energy demands, complex operating conditions, and the generation of hazardous byproducts. This hinders their sustainability and economic feasibility for large-scale deployment. Furthermore, many chemical recycling processes require the use of toxic solvents, expensive catalysts, or high pressure reactors, adding further barriers to scalability and environmental acceptability. As a result, although chemical recycling holds great potential for

improving plastic circularity, its practical implementation remains limited to pilot or early industrial stages.

3.3. Biological Methods

Biological degradation can be implemented in bioreactors for collected waste or applied in situ for contaminated sites. Its success depends on environmental control and strain specificity. In response to the limitations of physical and chemical methods, biological degradation has been proposed as an environmentally friendly alternative. This approach involves the use of microorganisms or specific enzymes to break down plastic polymers, particularly microplastics, through bioremediation [32]. Among the enzymes studied, hydrolases, particularly lipases and cutinases, have been the focus of extensive research. Notable PET hydrolyzing enzymes include TfCut2, Cut190, HiC, and LCC [33].

For instance, the bacterium *Ideonella sakaiensis* has been identified as capable of degrading PET through the enzymatic action of IsPETase and MHETase, providing a novel avenue for biological recycling [34,35]. Fungal species such as *Aspergillus niger* and *Penicillium chrysogenum* have also demonstrated the ability to degrade complex polymers via enzymatic pathways involving cutinases, lipases, and proteases under optimized conditions [35].

Despite considerable progress in the engineering of hydrolase enzymes, industrial-scale applications remain limited by several challenges, including the high cost of enzyme production, the need for costly pretreatments, poor thermal stability, limited catalytic efficiency at operational temperatures, and enzymatic inhibition caused by oligomeric degradation products [36,37]. Furthermore, biological methods are currently most feasible under controlled conditions, such as in bioreactors treating sorted plastic fractions. In contrast, environmental applications (e.g., soil or marine environments) face additional constraints related to microbial survival, substrate availability, and environmental variability.

Nevertheless, the future use of biological degradation is envisioned across several strategies: treatment of pre-collected plastics in industrial facilities, in situ remediation of contaminated environments (e.g., landfills and aquatic systems), and integration into hybrid systems combining abiotic and biotic treatments. With further development, biological degradation may play a pivotal role in circular plastic management.

4. Microorganisms: The Biological Answer

Fortunately, mechanisms for the degradation of these materials have been developed in nature through the action of specialized microorganisms. Various studies have identified bacteria, fungi, and microalgae capable of decomposing petrochemical plastics using enzymes that cleave the chemical bonds in plastic molecules [38]. Microbial plastic degradation is typically an enzymatic process that catalyzes the cleavage of polymeric bonds into monomers [39–41]. Larger polymeric structures are first broken down by secreted exoenzymes into smaller subunits (e.g., multimers and dimers) that can be taken up by microbial cells. Once inside the cells, oligomers or their degradation products are funneled through classical metabolic pathways to produce energy and/or to serve as building blocks for catabolism or anabolism [41,42].

The ability to degrade petrochemical plastics largely depends on the chemical structure of each polymer. Condensation polymers such as polyethylene terephthalate (PET) or polyamides contain hydrolyzable ester or amide bonds and are thus more susceptible to enzymatic cleavage than addition polymers such as polyethylene (PE) and polypropylene (PP), which are composed of chemically inert carbon–carbon backbones and lack functional groups accessible to enzymatic attack [39]. In contrast, most commercial plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are addition polymers with

strong carbon–carbon (C–C) backbones, which are chemically inert and highly resistant to enzymatic depolymerization. As a result, monomer recovery from such plastics is extremely difficult, limiting circular recycling strategies [13,38,41].

An innovative biotechnological strategy has been proposed whereby enzymatic recycling represents a sustainable alternative to traditional recycling methods, which are generally more energy intensive and result in products of inferior quality. Enzymatic recycling offers the possibility of recovering monomers suitable for reintegration into the production chain of bioplastics or other plastic products, without compromising their original properties [43–46].

These microorganisms open new possibilities for the treatment of plastic waste. By integrating principles of applied microbiology with enzyme engineering, this line of research provides a strategic tool for constructing sustainable recycling systems and mitigating the environmental impact of synthetic polymers. The development of artificial microbial consortia has opened new horizons in environmental bioremediation for the removal of recalcitrant compounds. With the help of omics-based tools, microbial communities can now be tailored for synergistic degradation, where different strains or species complement each other's metabolic functions to enhance plastic breakdown under specific environmental conditions [40,47].

Beyond scientific discovery, it is also critical to consider how biological degradation may be applied in practice. Three major approaches have been envisioned: (i) centralized treatment of sorted plastic waste in controlled bioreactors, where optimized microbial consortia operate under defined temperature, pH, and aeration conditions [38,48]; (ii) in situ bioremediation strategies, targeting contaminated terrestrial or aquatic environments, albeit with limited efficiency due to environmental fluctuations and competition with native microbiota [48]; and (iii) integration into hybrid systems that combine abiotic pretreatments (e.g., UV and oxidation) with biological processes to improve substrate accessibility [38].

Nevertheless, challenges persist. Most biodegradation data are derived from laboratory studies under ideal conditions, and their translation to real world environments is hindered by variability in temperature, pH, moisture, nutrient availability, and exposure to toxic compounds. In particular, the breakdown of certain plastics, notably PVC and PS, may result in the release of harmful gases [49] or byproducts that are toxic and potentially carcinogenic, such as vinyl chloride [50] and styrene [51]. These risks underscore the importance of implementing downstream treatment steps, such as the use of detoxifying microbial consortia or coupled bioreactors, to safely manage the resulting intermediates.

Ultimately, while microbial plastic degradation is not a universal solution, it constitutes a vital component of broader circular economic strategies. Its future success will depend on continued advances in enzyme discovery, metabolic engineering, ecological integration, and systems level design.

The most common plastics and their associated degrading microorganisms are detailed below.

4.1. Polyethylene—♳ ♳

Polyethylene (PE), a polymer with the chemical formula $(C_2H_4)_n$, is synthesized from ethylene monomers via addition or radical polymerization processes, often employing Ziegler–Natta catalysts [48,52]. As one of the most abundantly produced synthetic polymers, PE, including both high density polyethylene (HDPE) and low density polyethylene (LDPE), which differ mainly in their degree of branching and resulting physical properties such as crystallinity, density, and mechanical strength, has become a dominant component of microplastic pollution, particularly in marine environments such as the Atlantic Ocean [53].

Although PE is highly resistant to microbial attack due to its linear C–C backbone and high hydrophobicity, certain strategies have been explored to enhance its biodegradability. UV or thermal pretreatments promote surface oxidation and chain scission, introducing carbonyl or hydroxyl groups that increase microbial accessibility. These abiotic steps often precede microbial colonization and facilitate the attachment of biofilms, which is essential for effective degradation [54].

Cyanobacteria and various bacterial and fungal strains have demonstrated PE-degrading capabilities, albeit with low mineralization efficiencies. For example, cyanobacteria such as *Nostoc carneum* and *Phormidium lucidum* achieved surface modification and modest weight loss (~27–30%) over several weeks [55,56], although assimilation of carbon remains limited (<5%) [56]. Insect-based systems, notably larvae of *Tenebrio molitor*, also contribute to PE degradation through gut-associated microbiota, suggesting a synergistic biological mechanism [57].

Further evidence comes from landfill-isolated microbial consortia, including species of *Priestia*, *Klebsiella*, *Pseudomonas*, *Enterobacter*, and *Fusarium*, which have demonstrated significant surface erosion and weight loss of PE films under lab conditions [58]. However, reported degradation efficiencies are inconsistent across studies (ranging from <1% to >60%), depending heavily on plastic form, pretreatment, strain specificity, and incubation conditions (Table 1).

Table 1. Microbial strains involved in the biodegradation of PE (HDPE or LDPE). n.d. Not determined.

Group	Strain	PE Type	Growth Condition	Degradation (%)	Reference
Bacteria	*Bacillus cereus* SHBF2	PE	PE: 2 g/L, 30 °C, 60 days	6.87 ± 0.92	[59]
Bacteria	*Bacillus firmus* NCTC 10335	HDPE	PE: 0.5 g/L, 30 °C, 30 days	15.3	[60]
Bacteria	*Bacillus gottheilii*	PE	PE: 0.5 g/0.27 L, 29 °C, 40 days	6.2	[61]
Bacteria	*Bacillus safensis* BS-10L	LDPE (powder 400 µm)	PE: 1%, 30 °C, 30-90 days	13.40 ± 0.013 to 27.78 ± 0.014	[62]
Bacteria	*Comamonas testosteroni* NCIMB 8955	HDPE	PE: 0.5 g/L, 30 °C, 8 days	12.29	[60]
Bacteria	*Exiguobacterium* sp. HSK30	LDPE	PE: films (2 × 2 cm), 30 °C, 120 days	16.89 ± 1.02	[63]
Bacteria	*Gordonia alkanivorans* PBM1	LDPE	PE: 3 g/L (films 3 × 3 cm), 30 °C, 35 days	0.66 ± 0.508	[64]
Bacteria	*Gordonia alkanivorans* PSW1	LDPE	PE: 3 g/L (films 3 × 3 cm), 30 °C, 35 days	0.88 ± 0.658	[64]
Bacteria	*Micrococcus flavus* RS124	HDPE (sheet; thickness 0.01 mm)	PE: film 1 × 1 cm, 30 °C, 30 days	1.8	[65]
Bacteria	*Morganella morganii* PQ533186	LDPE (from commercial plastic bags)	PE: films 5 × 5 cm, 35 °C, 120 days	42.18	[66]
Bacteria	*Paenibacillus macquariensis* NCTC 10419	HDPE	PE: 0.5 g/L, 30 °C, 30 days	13	[60]
Bacteria	*Phormidium lucidum*	PE (sheet; thickness 20 µm)	PE: films 1 × 1 cm, 24 °C, 42 days	~30	[56]
Bacteria	*Pseudalkalibacillus* sp. MQ-1	PE	PE: 2 × 1.5 cm sheet, 30 °C, 30 days	6.377 ± 1.151	[67]
Bacteria	*Pseudomonas balerica* PDI-17	PE	PE: films 2 × 2 cm, 30 °C, 30 days	4.25–19.9	[54]
Bacteria	*Pseudomonas plecoglossicida* SYp2123	LDPE beads (>500 µm)	PE: 20 g/L, 30 °C, 3 weeks	n.d.	[68]
Bacteria	*Stenotrophomonas* sp.	LDPE	PE: film 3 × 3 cm, 31 °C, 90 days	10.15 ± 1.04	[69]
Consortium of bacteria	*Enterobacter* sp. nov. bt DSCE01 + *Enterobacter cloacae* nov. bt DSCE02 + *Pseudomonas aeruginosa* nov. bt DSCE-CD03	LDPE	PE: film 3 × 3 cm, 37 °C, 160 days	64.25 ± 2	[70]
Cyanobacteria	*Nostoc carneum*	PE (sheet; thickness 20 µm)	PE: films 1 × 1 cm, 24 °C, 6 weeks	27	[44]
Cyanobacteria	*Oscillatoria subbrevis*	PE (sheet; thickness 20 µm)	PE: films 1 × 1 cm, 24 °C, 42 days	~30	[45]
Fungus	*Aspergillus niger*	LDPE	PE: not defined, 35 °C, 48 h	55	[48]
Fungus	*Aspergillus* sp. AQ3A	LDPE microplastics 500–63 µm	PE: 1 g/L, 28 °C, 28 days	47	[49]

Table 1. *Cont.*

Group	Strain	PE Type	Growth Condition	Degradation (%)	Reference
Fungus	*Cladosporium sphaerospermum*	LDPE	PE: film 2 × 2 cm, 35 °C, 7 days	15.23	[55]
Fungus	*Cordyceps* sp. WICC F61	LDPE (sheet; thickness 2.3 mm)	PE: films 1 × 1 cm, 36 °C, 30 days	5.56	[56]
Fungus	*Gongronella* sp. WICC F60	LDPE (sheet; thickness 2.3 mm)	PE: films 1 × 1 cm, 36 °C, 30 days	1.07	[56]
Fungus	*Rhizopus arrhizus* SLNEA1	LDPE (sheets from commercial bags)	PE: 0.2 g/0.15 L (films), 25 °C, 90 days	23.77–29.74	[63]

Despite these advances, real world application remains limited by slow degradation kinetics, incomplete mineralization, and environmental variability. Additionally, incomplete degradation may result in microplastic formation rather than full polymer breakdown, raising further ecological concerns [14,15]. Long term accumulation of degradation byproducts and additives (e.g., antioxidants and plasticizers) is another critical issue that requires further investigation.

4.2. Polypropylene—

Polypropylene (PP) is among the most widely used plastics worldwide due to its favorable mechanical properties, chemical resistance, and low density. Structurally, it is an addition polymer composed of repeating propylene units with a saturated C–C backbone, making it particularly recalcitrant to enzymatic or microbial degradation. Its widespread use in packaging, textiles, and automotive components has contributed significantly to environmental plastic accumulation [71].

Recent studies have demonstrated that certain microorganisms, including bacteria and fungi, can attack PP under specific conditions. Fungal genera such as *Penicillium*, *Aspergillus*, *Talaromyces*, and *Cunninghamella*, isolated from Malaysian soils, were able to grow using PP as a sole carbon source, displaying enzymatic activity of laccase and manganese peroxidase, two oxidative enzymes generally associated with lignin degradation [72]. Similarly, bacterial strains of *Serratia*, *Enterobacter*, and *Pseudomonas*, often recovered from landfills, have shown the ability to alter PP's surface chemistry through oxidation or physical erosion [58].

A notable challenge is the low bioavailability of PP and its high crystallinity, which hinder microbial colonization and enzymatic access [13,73]. However, pretreatments, such as UV exposure or thermal oxidation, can reduce the polymer's molecular weight and increase surface hydrophilicity, thereby enhancing microbial attack. In fact, amorphous or oxidized PP degrades more readily than its crystalline counterpart, particularly when exposed to engineered fungi such as *Aspergillus* or *Engyodontium*, or bacteria such as *Pseudomonas* spp. [74–76].

Metagenomic surveys of PP-contaminated sites have identified key taxa such as *Bacillus*, *Stenotrophomonas*, and *Lysinibacillus*, often associated with stress-tolerant environments [77,78]. Furthermore, marine-derived bacterial consortia and gut microbiota from *Tenebrio molitor* larvae have demonstrated PP degradation confirmed by techniques such as FTIR, GPC, and SEM, offering novel avenues for bioremediation [74].

Nevertheless, degradation rates remain highly variable across studies, ranging from less than 1% to over 70% depending on strain, substrate form, and environmental conditions (Table 2). Incomplete depolymerization, accumulation of oligomeric intermediates, and the release of chemical additives from PP further complicate its environmental fate [7]. While many studies report surface erosion or molecular weight reduction, true mineralization to CO_2 and H_2O remains rare and difficult to demonstrate conclusively [61].

Table 2. Microbial strains involved in the biodegradation of PP.

Group	Strain	PP Type	Growth Condition	Degradation (%)	Reference
Bacterium	*Bacillus cereus*	PP (microparticles)	PP: 1 g/L, 28 days	47.5 ± 0.5/35.5 ± 0.5	[79]
Bacterium	*Bacillus cereus* SHBF2	PP	PP: 2 g/L, 30 °C, 60 days	6.77 ± 0.87	[59]
Bacterium	*Bacillus gottheilii*	PP	PP: 0.5 g/0.27 L, 29 °C, 40 days	3.6	[61]
Bacterium	*Bacillus paramycoides*	PP (<250 nm microplastics)	PP: 0.5 g, 28–30 °C, 21 days	78.99 ± 0.005	[76]
Bacterium	*Bacillus pasteurii*	PP (microplastics)	PP: 1% (*w*/*w*), 30 days	20.95–23.22	[80]
Bacterium	*Bacillus tropicus*	PP (microparticles)	PP: 1 g/L, 28 days	51.5 ± 0.5	[79]
Bacterium	*Brucella pseudintermedia*	PP (microparticles)	PP: 1 g/L, 28 days	28.5 ± 0.5	[79]
Bacterium	*Exiguobacterium marinum* a-1	PP	PP film (2 cm × 1.2 cm, PP30-FM-000125, 0.025 mm in thickness), marine medium, static, 25 °C, 80 days	9.2	[81]
Bacterium	*Lysinibacillus macroides*	PP beads (0.2–0.25 cm) and sheets (0.025 mm)	PP: beads 10% (*w*/*v*), films (2 × 2 cm), 30 °C, 50 days	1.33–2.93	[82]
Bacterium	*Pseudoalteromonas lipolytica* STM3	PP	PP films (1 cm × 1 cm), 28 °C, seawater medium, 30 days	1.3	[83]
Bacterium	*Pseudoalteromonas tetraodonis* SPAM4	PP	PP films (1 cm × 1 cm), 28 °C, seawater medium, 30 days	0.7	[83]
Bacterium	*Pseudomonas aeruginosa*	PP particles (Mn = 4000 ± 500)	PP: 10 g/L, 30 °C, 30 days	9.35 ± 2.22–17.2 ± 1.56	[84]
Bacterium	*Pseudomonas protegens*	PP	PP: 0.92 g cm^{-3}, minimal salt medium, 30 °C, weeks	25.6–32.6	[85]
Bacterium	*Psychrobacillus* sp. LICME-ZWZR-10	PP (particles 850 µm)	PP: 5%, 20 °C, 30 days	9.0 ± 0.40	[86]
Bacterium	*Stenotrophomonas acidaminiphila*	PP (microparticles)	PP: 1 g/L, 28 days	33 ± 1	[79]
Consortium of Bacterium	*Enterobacter* sp. nov. bt DSCE01 + *Enterobacter cloacae* nov. bt DSCE02 + *Pseudomonas aeruginosa* nov. bt DSCE-CD03	PP	PP: film 3 × 3 cm, 37 °C, 160 days	63 ± 2	[70]
Consortium of Fungus	*Aspergillus niger* + *Aspergillus flavus* + *Aspergillus oryzae*	PP	Solid state fermentation, 25–30 °C, 90 days	16.66–23.3	[87]

In practical terms, biological treatment of PP is more viable in engineered systems, such as pretreatment reactor setups or sequential abiotic and biotic degradation chains, rather than uncontrolled environmental contexts. Further research is needed to standardize methodologies, validate degradation endpoints, and assess the toxicity of byproducts.

4.3. Poly(Ethylene Terephthalate)—♺

Polyethylene terephthalate (PET) is a thermoplastic polyester widely used in beverage bottles, textiles, and food packaging due to its excellent mechanical strength, transparency, and chemical resistance [88]. Structurally, PET is a condensation polymer composed of terephthalic acid and ethylene glycol, containing ester bonds that can be hydrolyzed enzymatically, making it more susceptible to biological degradation compared to addition polymers.

Nonetheless, PET's semicrystalline structure, hydrophobic surface, and aromatic backbone contribute to its persistence in natural environments [15]. Upon weathering, PET fragments into microplastics (<5 mm), which are widely detected in aquatic ecosystems and even in human stool samples, raising serious concerns about their long term biological effects [89,90].

In recent years, several bacterial and fungal strains have demonstrated PET degradation capabilities. Notably, *Ideonella sakaiensis* was found to produce PETase and MHETase, two enzymes that sequentially hydrolyze PET into mono(2-hydroxyethyl) terephthalate (MHET) and terephthalic acid (TPA), which are then metabolized [39]. Additionally, bacterial strains from the genera *Bacillus*, *Agromyces*, and *Gordonia*, as well as fungi such as *Aspergillus flavus*, *Aspergillus niger*, and *Trichoderma harzianum*, have shown moderate degradation efficiency, particularly when PET is supplied in low crystallinity or powdered form [88,91–93] (Table 3).

Table 3. Microbial strains involved in the biodegradation of PET, LcPET (low crystallinity), and PcPET(postconsumer PET). n.d. Not determined.

Group	Strain	PET Type	Growth Condition	Degradation (%)	Reference
Bacterium	*Bacillus cereus*	PET granules	PET: 0.5 g/0.27 L, mineral medium, 37 °C, 40 days (mineral)	6.6	[61]
Bacterium	*Bacillus gottheilii*	PET granules	PET: 0.5 g/0.27 L, mineral medium, 29 °C, 40 days (mineral)	3	[61]
Bacterium	*Brucella intermedia* IITR130	PET sheet	PET: (sheet of 0.1 mm thickness), mineral medium, 30 °C, 60 days (mineral)	26	[94]
Bacterium	*Cryptosporangium aurantiacum*	PcPET (powder)	PET: 15 mg/ml; enzymatic degradation, 55 °C, pH 8, 12 h (enzymatic)	94.1	[95]
Bacterium	*Exiguobacterium* sp. (ON627837)	PET (microplastics)	Mineral medium, 37 °C, 30 days (mineral)	4	[96]
Bacterium	*Gordonia* sp. CN2K	PET (microplastic < 5 mm)	Mineral salts medium (MSM), 30 °C, 45 days (mineral)	40.43	[89]
Bacterium	*Piscinibacter sakaiensis*	PET (film)	Mineral medium, 30 °C, 6 weeks (mineral)	n.d.	[39]
Bacterium	*Rhodococcus pyridinivorans* P23	PET	Mineral salts medium, 30 °C, flask culture, 5 weeks (mineral)	4.28	[97]
Bacterium	*Streptomyces* sp.	PET (microparticles 500–212 µm)	Rich medium (LB + 1% PCL), 28 °C, 12 days (rich)	n.d.	[98]
Bacterium	*Thermobifida alba*	PET	Enzymatic degradation (cutinase), PET surface hydrolysis tested (enzymatic)	n.d.	[99]
Bacterium	*Thermobifida fusca*	PET granulate (particle size 4–8 mm)	Enzymatic degradation (purified cutinase TfH), 55 °C, PET with 10% crystallinity, 3 weeks (enzymatic)	50	[100]
Bacterium	*Vibrio* sp. PD6	PET (waste plastic bottles)	Mineral medium, 35 °C, pH 7, 6 weeks (mineral)	35	[93]
Consortium of bacterium	Microbial consortium (*Bacillus cereus* SEHD031MH + *Agromyces mediolanus* PNP3)	PET (microplastics)	Mineral medium, 30 °C, pH 7–7.5, 168 days (mineral)	17	[92]
Consortium of bacterium and fungus	Microbial consortium (Sarcina aurantiaca TB3, *Bacillus subtilis* TB8, *Aspergillus flavus* STF1, *Aspergillus niger* STF2)	PET (packaging plastic)	Mineral medium, 37 °C, 60 days (mineral)	28.78	[91]
Fungus	*Aspergillus fumigatiaffinms*	PcPET	Enzymatic degradation, PET film, 60 °C, 12 days (enzymatic)	n.d.	[101]
Fungus	*Aspergillus niger* and *Trichoderma harzianum*	PET (thickness of 0.3 mm)	Rich medium, room temperature, 30 days (rich)	1.8	[88]
Fungus	*Aspergillus* sp.	PET (waste plastic bottles)	Mineral medium, 35 °C, pH 7, 6 weeks (mineral)	22	[93]
Fungus	*Fusarium solani pisi*	PET (powder)	Enzymatic degradation (cutinase expressed in E. coli BL21), optimized conditions (enzymatic)	n.d.	[102]
Fungus	*Moniliophthora roreri*	PET	Mineral medium, pH 8, 40 °C, 21 days (mineral)	31	[103]
Fungus	*Penicillium funiculosum*	PET water bottles (0.1 mm thickness)	Rich medium, 30 °C, 84 days (rich)	n.d.	[104]
Fungus	*Thermocarpiscus australiensis*	PET	Enzymatic degradation (enzymatic)	n.d.	[105]
Yeast	*Candida antarctica*	PET water bottles (0.1 mm thickness)	Enzymatic degradation, 60 °C, 21 days (enzymatic)	0.4	[104]

Comparative studies of PET hydrolyzing enzymes, including cutinases from *Humicola insolens* (HiC), *Fusarium solani* (FsC), and *Pseudomonas mendocina* (PmC), have shown that enzyme efficiency strongly depends on PET's crystallinity and reaction conditions such as pH and temperature [104]. For instance, enzymatic degradation of postconsumer PET (PcPET) is generally slower than that of low crystallinity PET (LcPET), requiring elevated temperatures (>50 °C) and sometimes auxiliary cofactors to enhance activity.

Despite the promising laboratory results, there are several challenges for real world application. Most enzymatic degradation studies rely on purified enzymes, extended reaction times, and optimized substrates not representative of environmental plastics. Industrial-scale applications are currently limited by high enzyme production costs, incomplete degradation, and accumulation of soluble aromatic intermediates such as TPA, which can exhibit toxicity toward aquatic organisms if not fully metabolized.

Moreover, PET degradation at temperatures over 50 °C releases high amounts of antimony, a catalyst often used during PET synthesis [106], as well as plasticizers (phthalates) [107]. The potential ecotoxicity of these additives and monomers, in conjunction with microplastic fragments generated during partial degradation, must be carefully evaluated before deploying biological treatments in open environments [107].

While biological PET recycling holds great promise for closed-loop systems [95], especially when combined with mechanical sorting and precleaning steps, further optimization is needed to increase degradation rates and ensure safe downstream processing. Enzyme engineering, consortia development, and integrated detoxification modules represent future directions for making PET biodegradation scalable and environmentally viable [102].

4.4. Polyvinyl Chloride—

Polyvinyl chloride (PVC) is one of the most extensively used synthetic polymers, especially in construction materials such as pipes, window frames, and flooring, due to its chemical stability, mechanical strength, and flame retardance [108]. This versatility stems from its chlorinated backbone and the widespread use of additives such as plasticizers, stabilizers, and fillers, which tailor its properties for diverse applications.

However, PVC's recalcitrance to microbial degradation is among the highest of all synthetic plastics. Its polymer backbone, composed of saturated C–C bonds with covalently bound chlorine atoms, is particularly resistant to enzymatic attack [49]. Additionally, chlorine content hinders oxidation and limits microbial colonization due to toxicity [109]. As a result, PVC exhibits extremely slow degradation rates under both natural and controlled conditions [13,49].

Biological degradation of PVC is still in its infancy, with most studies reporting only partial breakdown or surface erosion. Certain bacteria and fungi, including *Aspergillus niger*, *Penicillium funiculosum*, *Phanerochaete chrysosporium*, and *Paecilomyces variotii*, have been shown to colonize PVC surfaces and induce superficial changes, especially when the polymer is pretreated with UV or chemical oxidants [110–112] (Table 4). These pretreatments are believed to increase surface roughness, reduce crystallinity, and introduce polar groups that promote microbial adhesion and potential oxidative degradation.

Table 4. Microbial strains involved in the biodegradation of PVC. n.d. Not determined.

Group	Strain	PVC Type	Growth Conditions	Degradation (%)	References
Fungus	*Aspergillus niger* (ATCC 6275)	PVC thin films (2% *w*/*v*)	Liquid or solid media; ~28–30 °C; 60 days	10	[49,112]
Fungus	*Aureobasidium pullulans*	PVC sheets (0.5 mm thick)	Minimal liquid or solid medium; 25–28 °C, colonization was observed between 25–40 weeks	n.d.	[113]
Fungus	*Chaetomium globosum* (ATCC 16021)	PVC films (40–50 µm)	PDA medium; ~25–30 °C	n.d.	[114]
Fungus	*Cochliobolus* sp	PVC	PVC: 3 g/100 ml, Czapek Dox Agar; 30 °C; solid medium; incubation for weeks to 1 year	n.d.	[115]
Fungus	*Paecilomyces variotii* CBS 62866	PVC	Grown on PDA; ~28–30 °C; weeks	n.d.	[112]
Fungus	*Penicillium funiculosum* ATCC 9644	PVC	Grown on PDA or similar; ~28–30 °C; weeks	n.d.	[112]
Fungus	*Phanerochaete chrysosporium*	PVC thin films (2% *w*/*v*)	High O_2, solid/liquid medium; ~28–30 °C; typical incubation: weeks	n.d.	[49]
Fungus	*Trichoderma viride* ATCC 13631	PVC	Grown on PDA; ~28–30 °C; weeks	n.d.	[112]
Yeast	*Kluyveromyces* sp.	PVC	YPD medium; ~25 °C, colonization was observed after 80 weeks	n.d.	[116]
Yeast	*Rhodotorula aurantiaca*	PVC	Grown on yeast media; ~25 °C, colonization was observed after 80 weeks	n.d.	[116]

Nevertheless, degradation efficiencies reported remain modest, typically under 10%, and are largely limited to surface modifications rather than full depolymerization. In some

cases, long incubation periods, up to 40 weeks, are required to observe colonization, and weight loss measurements often lack confirmation of true mineralization [49,112].

Although the degradation of PVC by physical or chemical methods generates toxic byproducts, microbial degradation, especially when performed by microbial consortia, primarily produces CO_2, N_2, CH_4, and H_2O, which are generally considered nontoxic byproducts [109,117]. However, some studies have revealed the potential formation of toxic degradation byproducts from PVC degradation that may impact organisms both positively and negatively [109]. Furthermore, oxidative depolymerization of PVC can generate hydrochloric acid (HCl) [118], which lowers the pH and may inhibit microbial activity or harm environmental matrices. Microbial catabolism is also associated with chlorine release, raising additional environmental concerns [119]. Further studies using microorganisms or enzymes to degrade PVC, and the detection and quantification of potentially toxic byproducts would be extremely useful in order to develop more efficient strategies.

To address these challenges, future strategies should integrate biological degradation with chemical or catalytic pretreatments under controlled conditions. In particular, co-cultures or consortia engineered to metabolize chlorinated compounds, neutralize acid byproducts, or detoxify vinyl chloride could enhance safety and efficiency. Omics-guided approaches may help identify key metabolic pathways for PVC transformation and support the design of robust microbial systems capable of handling chlorinated substrates [109].

Due to the persistent nature and potential toxicity of PVC degradation byproducts, in situ applications remain highly limited. Instead, treatment should be restricted to closed bioreactors or specialized facilities where emission control, pH buffering, and downstream detoxification can be effectively managed.

4.5. Polystyrene—♺

Polystyrene (PS) is a synthetic aromatic polymer produced from the polymerization of styrene monomers. Due to its low cost, rigidity, and insulating properties, it is widely used in packaging, food containers, disposable utensils, and insulation materials. Its expanded form, known as expanded polystyrene (EPS or Styrofoam), is especially prevalent due to its lightweight and shock-absorbing characteristics [52].

However, PS is considered one of the most environmentally persistent plastics. Its chemical structure, based on a linear hydrocarbon chain with pendant aromatic groups, contributes to its high hydrophobicity and resistance to hydrolysis and enzymatic attack. These characteristics make PS recalcitrant to biodegradation, leading to its accumulation in soils, landfills, and aquatic systems, where it often fragments into microplastics [120,121].

Despite these limitations, certain microbial strains have shown the capacity to degrade PS under specific conditions. Bacterial genera such as *Pseudomonas*, *Rhodococcus*, and *Exiguobacterium* have been reported to form biofilms on PS surfaces, initiate oxidative modifications, and induce moderate depolymerization. Fungi such as *Aspergillus niger* and *Penicillium* spp. have also demonstrated surface erosion and slight weight loss of PS films in laboratory conditions [121]. In marine settings, strains of *Pseudoalteromonas* have shown slow PS film degradation, confirming microbial interaction with this material [83].

Insects such as *Tenebrio molitor* (mealworms) have also been shown to ingest and partially degrade PS, likely with the aid of their gut microbiota. Studies have reported mass loss of PS and detection of styrene oligomers in the gut, supporting microbial involvement. However, these findings raise concerns about the potential accumulation of toxic intermediates such as styrene, a known neurotoxic and potentially carcinogenic compound [57].

Most microbial PS degradation studies report very low degradation rates (often <6%) even after several weeks or months of incubation (Table 5). Furthermore, many experiments

rely on indirect measurements such as surface cracking, FTIR signal shifts, SEM microscopy, or weight loss, which do not confirm mineralization [61]. Few studies trace the complete catabolic pathway or demonstrate conversion to CO_2 or biomass [59].

Table 5. Microbial strains involved in the biodegradation of PS. n.d. Not determined.

Group	Strain	PS Type	Growth Conditions	Degradation (%)	Reference
Bacterium	*Bacillus cereus*	PS granules (250 µm)	37 °C; minimal medium, 40 days	7.4	[61]
Bacterium	*Bacillus cereus* SHBF2	PS microplastic powder (49.67 µm)	Grown in nutrient rich medium; ~30 °C; 30 days	5.94 ± 0.94	[59]
Bacterium	*Bacillus gottheilii*	PS granules (250 µm)	37 °C; minimal medium, 40 days	5.8	[61]
Bacterium	*Geobacillus stearothermophilus* FAFUA011	PS	Thermophilic: 55–65 °C; minimal medium	4.2	[122]
Bacterium	*Pseudoalteromonas lipolytica* STM3	PS films	Marine medium; ~25 °C; 60 days	3.9	[83]
Bacterium	*Pseudoalteromonas tetraodonis* SPAM4	PS films	Marine medium; ~25 °C; 60 days	2.8	[83]
Bacterium	*Rhodococcus ruber* sp. C208	PS	Minimal medium; ~30 °C	n.d.	[121]

Another significant limitation is the potential toxicity of degradation intermediates. In particular, styrene and its derivatives can accumulate in the environment and pose ecological and human health risks [51]. Additionally, flame retardants, colorants, and other additives present in commercial PS products may leach out during degradation, further complicating environmental safety.

To overcome these challenges, future work must prioritize the identification of styrene-metabolizing microorganisms, enzymatic pathways for aromatic ring cleavage, and coupled detoxification systems. Engineered consortia or multistep treatments that integrate abiotic oxidation with biocatalysis may offer better outcomes. Moreover, real world applications must include safeguards to prevent emission of harmful byproducts, especially in open environments [83].

While microbial degradation of PS offers a promising research direction, current results remain restricted to laboratory studies with limited scalability. Effective PS biodegradation will require further development of targeted microbial systems, combined treatment approaches, and rigorous environmental risk assessment.

4.6. Polycarbonate, Polyamide, and Polyurethane—♺

Among synthetic polymers, polycarbonate (PC), polyamide (PA), and polyurethane (PUR) represent a category of durable, high-performance plastics widely used in consumer and industrial applications. PC is commonly used in optical lenses, electronics, and automotive parts; PA (e.g., nylon) in textiles and mechanical components; and PUR in foams, adhesives, coatings, and elastomers. These polymers are characterized by their chemical and thermal resistance, which also contributes to their environmental persistence [123–125].

Compared to polyolefins (polymers derived from ethylene or propylene), PA and PUR contain functional groups such as amide and urethane bonds that, in principle, can be hydrolyzed enzymatically. This structural feature makes them more amenable to microbial attack than PC, which has a rigid aromatic carbonate backbone and is generally considered more resistant to biodegradation [126]. However, degradation efficiencies are highly variable and strongly influenced by the polymer's crystallinity, crosslinking, and additive content.

In the case of PA, several microbial strains, including *Flavobacterium*, *Pseudomonas*, and *Bacillus* spp., have shown the ability to degrade nylon oligomers or depolymerize low molecular weight substrates [127–130]. The activity of enzymes such as nylonases has been demonstrated, but their efficiency on commercial-grade PA remains low. Surface erosion

and chain scission have been observed under laboratory conditions, but full mineralization is rarely achieved [128].

PC degradation has been reported in a limited number of strains, such as *Bacillus* and *Pseudomonas*, with degradation rates of 4–10% over 30–60 days in minimal media [126,131]. Enzymatic activity appears to target the carbonate bonds, but the presence of bisphenol A (BPA), a toxic monomer released during PC degradation, raises significant safety concerns. BPA is a known endocrine disruptor, and its accumulation in aquatic environments poses both ecological and human health risks [132,133].

PUR is structurally diverse and includes both polyether- and polyester-based foams, coatings, and elastomers. Several bacterial genera, including *Pseudomonas*, *Bacillus*, *Comamonas*, and *Corynebacterium*, as well as fungal strains such as *Aspergillus*, *Penicillium*, and *Fusarium*, have shown potential to degrade PUR via esterases, proteases, and urethanases. Some studies report degradation efficiencies exceeding 30–40% over several weeks under optimized conditions, particularly for polyester-based PURs [134–137].

However, significant limitations remain. The degradation of PUR often leads to the release of toxic diisocyanates and aromatic compounds, which may inhibit microbial growth or persist in the environment (Table 6). Moreover, PUR's structural heterogeneity and presence of additives such as flame retardants or crosslinkers complicate standardization and reproducibility across studies.

Table 6. Microbial strains involved in the biodegradation of PUR, PC, and PA. n.d. Not determined.

Group	Strain	Plastic Type	Growth Conditions	Degradation (%)	References
Bacterium	*Flavobacterium* sp.	PA	Minimal medium with polyurea as the sole N source; ~30 °C; 14 days	n.d.	[127,128]
Bacterium	*Pseudomonas* sp.	PA	Minimal medium with polyurea as the N source; ~30 °C; 40 days	n.d.	[127,129,130]
Bacterium	*Bacillus* sp.	PC	Minimal medium; 30–37 °C; 1 month	4–8	[131]
Bacterium	*Pseudomonas* sp.	PC	Minimal medium; 30–37 °C 60 days	5–10	[126]
Fungus	*Penicillium* sp.	PC	Potato Dextrose Broth; ~28 °C, 30 days	9.6	[138]
Bacterium	*Alicycliphilus* sp.	PUR	Minimal medium with PUR 3% (*w*/*v*); ~30 °C; 6 days	n.d.	[134]
Bacterium	*Bacillus amyloliquefaciens* M3	PUR	Grown on PUR foam in liquid medium; ~30 °C; 33 days	30–40	[135]
Bacterium	*Bacillus* sp. (marine)	PUR	Marine broth with PUR; ~25 °C; 4 days	n.d.	[136]
Bacterium	*Comamonas* sp.	PUR	Liquid medium with PUR as a carbon source; ~30 °C, 21 days	n.d.	[139]
Bacterium	*Comamonas acidovorans*	PUR	Minimal medium with PUR and PLA; ~30 °C; 7 days	n.d.	[116]
Bacterium	*Corynebacterium* sp.	PUR	Grown on PUR-containing medium; ~30 °C; 48 h	n.d.	[140]
Bacterium	*Micrococcus* sp.	PUR	Grown on PUR-containing media; ~30 °C, 6 months	n.d.	[135,141]
Bacterium	*Pseudomonas aeruginosa* ATCC 13388	PUR	Liquid medium with PUR film; ~30 °C; 4 weeks	n.d.	[142]
Bacterium	*Pseudomonas* sp. PHC1	PUR	Liquid medium with Impranil or solid PUR; ~28–30 °C; 7 days	n.d.	[143]
Bacterium	*Staphylococcus aureus*	PUR	Minimal medium with PUR; ~30 °C; 45 days	n.d.	[144]
Bacterium	*Staphylococcus warneri*	PUR	Co-culture with PUR and Impranil; ~30 °C; 6 days	n.d.	[145]
Fungus	*Aspergillus niger*	PUR	Solid or liquid media with PUR; ~28–30 °C; >30 days	n.d.	[116,146]
Fungus	*Candida rugosa* and *Candida ethanolica*	PUR	YPD or minimal medium with PUR; ~25–30 °C; 30 days	n.d.	[116]
Fungus	*Cladosporium* sp. P7	PUR	Liquid culture with Impranil; ~28–30 °C; 7 days	94.5	[143]
Fungus	*Embarria clematidis*	PUR	Solid or liquid culture with PUR; ~28–30 °C; 2 weeks	n.d.	[147]
Fungus	*Fusarium solani*	PUR	Minimal medium with PUR foam; ~30 °C. 15 days	36.8	[137]
Fungus	*Pestalotiopsis microspora*	PUR	Grown on PUR as sole C source; aerobic/anaerobic; ~28–30 °C; 2 weeks	n.d.	[148]
Insect + microbiota	*Tenebrio molitor* (larvae)	PUR	Fed with PUR foam; incubation at 25–28 °C; 35 days	67	[141,149]

Overall, the microbial degradation of PC, PA, and PUR is promising but remains constrained by polymer complexity, low degradation rates, and the toxicity of monomeric byproducts such as BPA and isocyanates (Table 6). To improve viability, future research should focus on (i) identifying robust enzymes or consortia capable of operating under environmental stress, (ii) coupling biological treatments with abiotic pretreatments, and (iii) implementing closed bioprocesses with integrated detoxification modules.

5. Genetic and Protein Engineering for Enhanced Biodegradation of Petrochemical Plastics and Its Regulatory Framework

During the search for microorganisms capable of degrading different plastics, numerous genes have been cloned in *Escherichia coli*, providing strains of this species with the ability to catabolize plastics or synthesize enzymes with catalytic activity. Most of the recombinant strains obtained are *E. coli*, used as heterologous expression systems during enzymatic studies. These proteins may or may not be used after purification steps. However, the number of designs focused on endowing new recombinant strains with direct catalytic activities on plastic polymers is limited.

Highlighted examples include the cloning of the alkB gene from *Pseudomonas* sp. E4 in *E. coli* BL12 for polystyrene degradation [150], the Cbotu_EstA protein for PBAT degradation [151], PET-targeted hydrolases from *Thermomonospora curvata* [152], or enzymes from *Piscinibacter sakaiensis* [153], among others mentioned in Table 7. Genetic engineering has not been limited to bacteria. In 2023, Di Rocco et al. [154] described the first recombinant microalgae capable of degrading PET by expressing PETases.

On the other hand, some strategies combine recombinant bacterial strains with other microorganisms capable of degrading the toxic monomers generated during polymer decomposition. This allows a more efficient degradation of the plastic under study [155]. Other approaches involve the complete cloning of catabolic pathways that metabolize these byproducts [156].

The addition of redox mediators such as ABTS and DMP has been shown to facilitate the degradation of recalcitrant polymers such as polypropylene. This has allowed fungal laccases expressed in recombinant strains of *Kluyveromyces lactis* to attack this type of polymer [157]. Likewise, the design of chimeric enzymes has given rise to new proteins capable of degrading ester-like bonds [158]. Also, structural modifications have been made to enzymes capable of degrading plastics such as PET, significantly improving their degradation capacity [159].

These modern biotechnological approaches, coupled with the identification and isolation of strains with degradation potential, reveal enormous potential for addressing the global problem of plastic pollution.

Table 7. List of genetically modified microorganisms with the ability to degrade plastics. The gene or protein used, the donor organism, and the plastic of the study are indicated.

Group	Host	Protein/Gen	Source	Plastic Type	Reference
Bacteria	*Bacillus subtilis*	PETase and MHETase	*Piscinibacter sakaiensis*	PET	[155]
Bacteria	*Clostridium thermocellum*	Cutinasa	Metagenome	PET	[160]
Bacteria	*Escherichia coli*	TfCut2, Tcur1278, Tcur0390	*Thermobifida fusca*, *Thermomonospora curvata*, metagenome (LCC)	Impranil DLN (PUR), Elastollan B85A/C85A	[161]
Bacteria	*Escherichia coli* BL21	*alkB*	*Pseudomonas* sp. E4	Low molecular weight polyethylene (PE)	[150]
Bacteria	*Escherichia coli* BL21 (DE3)	MHETase	*Piscinibacter sakaiensis*	PET	[153]

Table 7. *Cont.*

Group	Host	Protein/Gen	Source	Plastic Type	Reference
Bacteria	*Escherichia coli* BL21-Gold(DE3)	Cbotu_EstA	*Clostridium botulinum*	Poly(butylene adipate-co-butylene terephthalate) (PBAT)	[151]
Bacteria	*Escherichia coli* JM109	*pudA*	*Comamonas acidovorans* TB-35	PUR	[162]
Bacteria	*Escherichia coli* TOP10	Tcur1278 and Tcur0390	*Thermomonospora curvata*	PET	[152]
Fungus	*Kluyveromyces lactis*	Lacasse	*Trametes trogii* (Fungi)	PP	[157]
Fungus	*Pichia pastoris*	Chimeric protein Lip-Cut	*Thermomyces lanuginosus* (Lip) and *Thielavia terrestris* NRRL 8126 (Cut)	Ester bond degradation	[158]
Plant	*Chlamydomonas reinhardtii*	PETase	*Piscinibacter sakaiensis*	PET	[162]

Genetically modified microorganisms (GMMs) have emerged as powerful tools not only for plastic degradation but also for complex pollutants such as hydrocarbons and heavy metals [163,164]. These microorganisms, equipped with new metabolic pathways or new catabolic activities, may represent a breakthrough as alternatives to conventional degradation of plastics and microplastics by physicochemical methods [165]. However, the use of GMMs in open environments is subject to strict regulatory frameworks, especially in the European Union, where current legislation imposes costly and time-consuming approval processes based on precautionary principles [166].

In Europe, Directive 2001/18/EC [167], updated on 27 March 2023, regulates the release of genetically modified organisms (GMOs) into the environment. The ruling of the Court of Justice of the European Union (Case C 528/16, 25 July 2018 [168]) established that GMMs obtained with new tools (CRISP-Cas or targeted mutagenesis) were subject to these directives, with those created by conventional mutagenesis being able to be excluded. Additionally, if a confined use of GMMs is proposed, directive 2009/41/EC [169] is the regulatory framework in these conditions.

In the United States, the use of genetically modified microorganisms (GMMs) is regulated under the Toxic Substances Control Act (TSCA), administered by the Environmental Protection Agency (EPA). TSCA (40 CFR Part 725) [170] requires submitting a Microbial Commercial Activity Notice (MCAN) for commercial applications or a TSCA Experimental Release Application (TERA) for field testing. In order to ensure that GMMs do not have any risk to human health or the environment.

The use of GMMs as main bioremediation agents is a promising tool that is still subject to strict regulation. Regarding the European Union (EU), Wesseler et al. (2022) [166] propose three alternative regulatory models to the current one.

Due to the regulatory framework, alternatives to GMMs have been explored. Not only is genetic engineering a powerful tool, but also enzymes can also be modified to change main properties, such as enhancing catalytic activity and thermal stability, among others. Due to the interest in PET degradation, it is the polymer with the largest number of studies in protein engineering.

TfCut2 is a thermostable cutinase from *Thermobifida fusca* that remains active at temperatures up to 60 °C. Using molecular docking and computer simulations, 22 amino acid variants of TfCut2 were proposed to enhance its activity against PET. Upon testing the purified enzymes, seven variants exhibited increased activity, ranging from 1.3 to 7.2-fold [171]. In a separate study, activity was further enhanced up to 12.7-fold by combining another variant of TfCut2 with a cationic surfactant [172]. Both studies identify the G62A mutation as the most impactful modification, with F209I/A and F249R also contributing significantly to activity enhancement [171,172].

Moreover, fusion protein designs combining PETase and MHETase have demonstrated synergistic effects, facilitating sequential hydrolysis of PET and its intermediate products, increasing degradation efficiency by reducing product inhibition [173]. Similar approaches

have been used for other polymers. In the case of PUR and polyester copolymers, a fusion protein combining a polyamidase from *Nocardia farcinica* with a polymer binding module (PBM) derived from a polyhydroxyalkanoate depolymerase from *Alcaligenes faecalis* showed a 4-fold increase in activity compared to native polyamidase [174]. Similarly, latex-clearing protein (LCp) from *Streptomyces* sp. strain K30 is able to catabolize oxidized PE. Fusion of this protein with a hydrophobic anchoring peptide (LCI) enhanced binding capacity, achieving a 1.15-fold increase in activity [175].

Both conventional mutagenesis techniques and more modern tools have allowed the development of several GMMs with potential application for bioremediation. These microorganisms allow us to alleviate the actual problem with plastics and microplastics. However, due to the precautionary principle, the regulatory frameworks in Europe and the USA are quite strict. With a few exceptions, they cannot be released into the environment and are limited to confined use. The use of enzymes from different microorganisms, as well as variants with improved characteristics, is presented as a complementary alternative. Therefore, we are becoming closer to a more sustainable and ecofriendly circular economy.

6. Conclusions

The global plastic pollution crisis is one of the most pressing environmental challenges of our time. Current recycling systems, while widely implemented, remain insufficient to address the full scale and complexity of plastic waste accumulation. Mechanical methods are dominant but lead to progressive loss of material quality and downcycling, while chemical recycling, though promising, is often constrained by elevated energy requirements, limited scalability, and the risk of generating toxic byproducts.

In this context, microbial biodegradation has been increasingly investigated as a complementary and ecofriendly approach that could contribute to closing the loop in plastic life cycles. Numerous studies have demonstrated the potential of bacteria, fungi, and microbial consortia to degrade a wide range of plastics, from PET to PUR. However, degradation rates are highly variable, often slow, and rarely result in complete mineralization under realistic conditions. Moreover, for many plastics such as PVC or PS, degradation may release hazardous intermediates (e.g., styrene, vinyl chloride, and bisphenol A) that are persistent, bioaccumulative, and may present ecotoxicological risks.

Thus, while biological degradation holds promise, it is not a universal solution and must be applied selectively as part of integrated and modular waste management strategies. A critical evaluation of degradation endpoints, byproduct toxicity, and environmental risks is essential before large-scale deployment. In particular, in situ applications in open or dynamic ecosystems should be approached with caution due to the unpredictable nature of biotic and abiotic interactions, potential dispersal of engineered organisms, and the release of partially degraded toxic compounds.

From a technological perspective, future research should prioritize (i) the discovery and engineering of robust microbial strains and enzymes with higher degradation efficiency and substrate specificity; (ii) the design of coupled systems that integrate abiotic pretreatment (e.g., UV and oxidation) with biological degradation modules; (iii) the incorporation of omics tools to elucidate microbial pathways and optimize consortia; and (iv) the assessment of long term ecological impacts. Furthermore, the regulatory landscape for the application of genetically modified microorganisms (GMMs) in environmental biotechnology must be clearly defined, with adequate biosafety mechanisms and public engagement.

Finally, the environmental and social implications of plastic degradation must not be overlooked. The success of any biodegradation strategy depends on its alignment with circular economy principles public acceptance. In addition, it must be designed to complement, rather than replace, strategies aimed at reducing plastic use at the source, including

redesign, reuse, and prevention policies. Only through coordinated, interdisciplinary, and responsible innovation can microbial biotechnology be transformed into a safe and scalable solution for plastic pollution.

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References

1. Plastic Pollution. Available online: https://ourworldindata.org/plastic-pollution (accessed on 27 May 2025).
2. Yuan, Z.; Nag, R.; Cummins, E. Ranking of potential hazards from microplastics polymers in the marine environment. *J. Hazard. Mater.* **2022**, *429*, 128399. [CrossRef]
3. Impacts of Plastic Pollution. Available online: https://www.epa.gov/plastics/impacts-plastic-pollution (accessed on 27 May 2025).
4. Wang, L.; Li, S.; Ahmad, I.; Zhang, G.; Sun, Y.; Wang, Y.; Sun, C.; Jiang, C.; Cui, P.; Li, D. Global face mask pollution: Threats to the environment and wildlife, and potential solutions. *Sci. Total Environ.* **2023**, *887*, 164055. [CrossRef]
5. Evangeliou, N.; Grythe, H.; Klimont, Z.; Heyes, C.; Eckhardt, S.; Lopez-Aparicio, S.; Stohl, A. Atmospheric transport is a major pathway of microplastics to remote regions. *Nat. Commun.* **2020**, *11*, 3381. [CrossRef] [PubMed]
6. Hermabessiere, L.; Dehaut, A.; Paul-Pont, I.; Lacroix, C.; Jezequel, R.; Soudant, P.; Duflos, G. Occurrence and effects of plastic additives on marine environments and organisms: A review. *Chemosphere* **2017**, *182*, 781–793. [CrossRef] [PubMed]
7. Tuuri, E.; Leterme, S. How plastic debris and associated chemicals impact the marine food web: A review. *Environ. Pollut.* **2023**, *321*, 121156. [CrossRef] [PubMed]
8. Panda, A.; Singh, R.; Mishra, D. Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products-A world prospective. *Renew. Sustain. Energy Rev.* **2010**, *14*, 233–248. [CrossRef]
9. Webb, H.K.; Arnott, J.; Crawford, R.J.; Ivanova, E.P. Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). *Polymers* **2013**, *5*, 1–18. [CrossRef]
10. Tan, A.F.J.; Yu, S.; Wang, C.; Yeoh, G.H.; Teoh, W.Y.; Yip, A.C.K. Reimagining plastics waste as energy solutions: Challenges and opportunities. *npj Mater. Sustain.* **2024**, *2*, 2. [CrossRef]
11. Hasheminezhad, A.; Farina, A.; Yang, B.; Ceylan, H.; Kim, S.; Tutumluer, E.; Cetin, B. The utilization of recycled plastics in the transportation infrastructure systems: A comprehensive review. *Constr. Build. Mater.* **2024**, *411*, 134448. [CrossRef]
12. Singh, N.; Walker, T.R. Plastic recycling: A panacea or environmental pollution problem. *npj Mater. Sustain.* **2024**, *2*, 17. [CrossRef]
13. Cai, Z.; Li, M.; Zhu, Z.; Wang, X.; Huang, Y.; Li, T.; Gong, H.; Yan, M. Biological Degradation of Plastics and Microplastics: A Recent Perspective on Associated Mechanisms and Influencing Factors. *Microorganisms* **2023**, *11*, 1661. [CrossRef]
14. Urbanek, A.; Rymowicz, W.; Mironczuk, A. Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Appl. Microbiol. Biotechnol.* **2018**, *102*, 7669–7678. [CrossRef]
15. Chamas, A.; Moon, H.; Zheng, J.; Qiu, Y.; Tabassum, T.; Jang, J.; Abu-Omar, M.; Scott, S.; Suh, S. Degradation Rates of Plastics in the Environment. *ACS Sustain. Chem. Eng.* **2020**, *8*, 3494–3511. [CrossRef]
16. Sathish, T.; Saravanan, R.; Vijayan, V.; Kumar, S. Investigations on influences of MWCNT composite membranes in oil refineries waste water treatment with Taguchi route. *Chemosphere* **2022**, *298*, 134265. [CrossRef] [PubMed]
17. Bao, C.; Wang, H.; Wang, C.; Zhang, X.; Zhao, X.; Dong, C.; Huang, Y.; Chen, S.; Guo, P.; She, X.; et al. Cooperation of oxygen vacancy and Fe^{III}/Fe^{II} sites in H_2-reduced Fe-MIL-101 for enhanced Fenton-like degradation of organic pollutants. *J. Hazard. Mater.* **2023**, *441*, 129922. [CrossRef]

18. Noël, M.; Wong, C.; Ross, P.; Patankar, S.; Etemadifar, A.; Morales-Caselles, C.; Lyons, S.; Delisle, K. Microplastics distribution in sediment and mussels along the British Columbia Coast, Canada. *Mar. Pollut. Bull.* **2022**, *185*, 114273. [CrossRef] [PubMed]
19. Mato, Y.; Isobe, T.; Takada, H.; Kanehiro, H.; Ohtake, C.; Kaminuma, T. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ. Sci. Technol.* **2001**, *35*, 318–324. [CrossRef]
20. Sintac. Available online: https://sintac.es/en/recycling-symbols-and-their-meanings/ (accessed on 7 June 2025).
21. Sharma, S.; Chatterjee, S. Microplastic pollution, a threat to marine ecosystem and human health: A short review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 21530–21547. [CrossRef]
22. Kibria, M.G.; Masuk, N.I.; Safayet, R.; Nguyen, H.Q.; Mourshed, M. Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management. *Int. J. Environ. Res.* **2023**, *17*, 20. [CrossRef]
23. Killinger, L.; Hanich-Spahn, R.; Flick, K.; Hashmi, A. Lewis-pair-catalytic depolymerization of post-consumer polyethylene terephthalate (PET) waste. *Polym. Degrad. Stab.* **2025**, *233*, 111163. [CrossRef]
24. Kassab, A.; Nabhani, D.A.; Mohanty, P.; Pannier, C.; Ayoub, G.Y. Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. *Polymers* **2023**, *15*, 3881. [CrossRef] [PubMed]
25. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: Challenges and opportunities. *Philos. Trans. R. Soc. B Biol. Sci.* **2009**, *364*, 2115–2126. [CrossRef] [PubMed]
26. Hasan, M.; Haque, R.; Jahirul, M.; Rasul, M. Pyrolysis of plastic waste for sustainable energy Recovery: Technological advancements and environmental impacts. *Energy Convers. Manag.* **2025**, *326*, 119511. [CrossRef]
27. Alaghemandi, M. Sustainable Solutions Through Innovative Plastic Waste Recycling Technologies. *Sustainability* **2024**, *16*, 10401. [CrossRef]
28. Zhao, H.; Ye, Y.; Zhang, Y.; Yang, L.; Du, W.; Wang, S.; Hou, Z. Upcycling of waste polyesters for the development of a circular economy. *Chem. Commun.* **2024**, *60*, 13832–13857. [CrossRef]
29. DesVeaux, J.S.; Uekert, T.; Curley, J.B.; Choi, H.; Liang, Y.; Singh, A.; Mante, O.D.; Beckham, G.T.; Jacobsen, A.J.; Knauer, K.M. Mixed polyester recycling can enable a circular plastic economy with environmental benefits. *One Earth* **2024**, *7*, 2204–2222. [CrossRef]
30. Zhu, C.; Wang, J.; Lv, J.; Zhu, Y.; Huang, Q.; Sun, C. Solar-driven reforming of waste polyester plastics into hydrogen over CdS/NiS catalyst. *Int. J. Hydrog. Energy* **2024**, *51*, 91–103. [CrossRef]
31. Zeng, G.; Su, Y.; Jiang, J.; Huang, Z. Nitrogenative Degradation of Polystyrene Waste. *J. Am. Chem. Soc.* **2025**, *147*, 2737–2746. [CrossRef]
32. Roy, A.; Chakraborty, S. A comprehensive review on sustainable approach for microbial degradation of plastic and it's challenges. *Sustain. Chem. Environ.* **2024**, *7*, 100153. [CrossRef]
33. Nasrabadi, A.; Ramavandi, B.; Bonyadi, Z. Recent progress in biodegradation of microplastics by *Aspergillus* sp. in aquatic environments. *Colloid Interface Sci. Commun.* **2023**, *57*, 100754. [CrossRef]
34. Maity, W.; Maity, S.; Bera, S.; Roy, A. Emerging Roles of PETase and MHETase in the Biodegradation of Plastic Wastes. *Appl. Biochem. Biotechnol.* **2021**, *193*, 2699–2716. [CrossRef]
35. Viel, T.; Manfra, L.; Zupo, V.; Libralato, G.; Cocca, M.; Costantini, M. Biodegradation of Plastics Induced by Marine Organisms: Future Perspectives for Bioremediation Approaches. *Polymers* **2023**, *15*, 2673. [CrossRef]
36. Mican, J.; Jaradat, D.; Liu, W.; Weber, G.; Mazurenko, S.; Bornscheuer, U.; Damborsky, J.; Wei, R.; Bednar, D. Exploring new galaxies: Perspectives on the discovery of novel PET-degrading enzymes. *Appl. Catal. B-Environ. Energy* **2024**, *342*, 123404. [CrossRef]
37. Wei, R.; Zimmermann, W. Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: How far are we? *Microb. Biotechnol.* **2017**, *10*, 1308–1322. [CrossRef] [PubMed]
38. Khurana, S.; Ali, S.; Srivastava, A.; Singh, A.; Agarwal, H.; Chauhan, R.; Joshi, N.; Dufossé, L.; Chauhan, A. Bioremediation of microplastic pollution: A systematic review on mechanism, analytical methods, innovations, and omics approaches. *J. Hazard. Mater. Adv.* **2025**, *19*, 100777. [CrossRef]
39. 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]
40. Gao, R.; Sun, C. A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. *J. Hazard. Mater.* **2021**, *416*, 125928. [CrossRef]
41. Danso, D.; Chow, J.; Streit, W.R. Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. *Appl. Environ. Microbiol.* **2019**, *85*, e01095-19. [CrossRef]
42. Sarvutiene, J.; Prentice, U.; Ramanavicius, S.; Ramanavicius, A. Molecular imprinting technology for biomedical applications. *Biotechnol. Adv.* **2024**, *71*, 108318. [CrossRef]
43. Nasser, R.M.; El Shazly, R.I.; Haseeb, M.E. Depolymerization for a Circular Economy: Sustainable Polymer Waste Management and Resource Recovery. In *Depolymerization: Concepts, Progress, and Challenges Volume 3: Emerging Trends*; ACS Symposium Series; American Chemical Society: Washington, DC, USA, 2025; Volume 1501, pp. 137–168.

44. Chamizo-Ampudia, A.; Alonso, R.M.; Ariza-Carmona, L.; Sanchiz, Á.; San-Martín, M.I. A Review of Bioelectrochemical Strategies for Enhanced Polyhydroxyalkanoate Production. *Bioengineering* **2025**, *12*, 616. [CrossRef]
45. Getino, L.; Martín, J.L.; Chamizo-Ampudia, A.; Getino, L.; Martín, J.L.; Chamizo-Ampudia, A. A Review of Polyhydroxyalkanoates: Characterization, Production, and Application from Waste. *Microorganisms* **2024**, *12*, 2028. [CrossRef]
46. Getino, L.; García, I.; Cornejo, A.; Mateos, R.; Ariza-Carmona, L.M.; Sánchez-Castro, N.; Moran, J.F.; Olivera, E.R.; Chamizo-Ampudia, A. The Effectiveness of Polyhydroxyalkanoate (PHA) Extraction Methods in Gram-Negative *Pseudomonas putida* U. *Polymers* **2025**, *17*, 150. [CrossRef]
47. Yong, C.; Valiyaveettil, S.; Tang, B. Toxicity of Microplastics and Nanoplastics in Mammalian Systems. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1509. [CrossRef]
48. Kong, Y.; Wang, R.; Zhou, Q.; Li, J.; Fan, Y.; Chen, Q. Recent progresses and perspectives of polyethylene biodegradation by bacteria and fungi: A review. *J. Contam. Hydrol.* **2025**, *269*, 104499. [CrossRef]
49. Ali, M.; Ahmed, S.; Robson, G.; Javed, I.; Ali, N.; Atiq, N.; Hameed, A. Isolation and molecular characterization of polyvinyl chloride (PVC) plastic degrading fungal isolates. *J. Basic Microbiol.* **2014**, *54*, 18–27. [CrossRef] [PubMed]
50. Zarus, G.M.; Muianga, C.; Brenner, S.; Stallings, K.; Casillas, G.; Pohl, H.R.; Mumtaz, M.M.; Gehle, K. Worker studies suggest unique liver carcinogenicity potential of polyvinyl chloride microplastics. *Am. J. Ind. Med.* **2023**, *66*, 1033–1047. [CrossRef] [PubMed]
51. Vodicka, P.; Koskinen, M.; Naccarati, A.; Oesch-Bartlomowicz, B.; Vodickova, L.; Hemminki, K.; Oesch, F. Styrene Metabolism, Genotoxicity, and Potential Carcinogenicity. *Drug Metab. Rev.* **2006**, *38*, 805–853. [CrossRef] [PubMed]
52. Zaman, I.; Turjya, R.; Shakil, M.; Al Shahariar, M.; Emu, M.; Ahmed, A.; Hossain, M. Biodegradation of polyethylene and polystyrene by *Zophobas atratus* larvae from Bangladeshi source and isolation of two plastic-degrading gut bacteria. *Environ. Pollut.* **2024**, *345*, 123446. [CrossRef]
53. Pabortsava, K.; Lampitt, R. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. *Nat. Commun.* **2020**, *11*, 4073. [CrossRef]
54. Nedi, E.; Ebu, S.; Somboo, M. Identification and molecular characterization of Polyethylene degrading bacteria from garbage dump sites in Adama, Ethiopia. *Environ. Technol. Innov.* **2024**, *33*, 103441. [CrossRef]
55. Sarmah, P.; Rout, J. Cyanobacterial degradation of low-density polyethylene (LDPE) by *Nostoc carneum* isolated from submerged polyethylene surface in domestic sewage water. *Energy Ecol. Environ.* **2019**, *4*, 240–252. [CrossRef]
56. 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]
57. Wang, Q.; Chen, H.; Gu, W.; Wang, S.; Li, Y. Biodegradation of aged polyethylene (PE) and polystyrene (PS) microplastics by yellow mealworms (*Tenebrio molitor* larvae). *Sci. Total Environ.* **2024**, *927*, 172243. [CrossRef] [PubMed]
58. Wróbel, M.; Szymanska, S.; Kowalkowski, T.; Hrynkiewicz, K. Selection of microorganisms capable of polyethylene (PE) and polypropylene (PP) degradation. *Microbiol. Res.* **2023**, *267*, 127251. [CrossRef] [PubMed]
59. Hossain, S.; Shukri, Z.N.A.; Waiho, K.; Ibrahim, Y.S.; Kamaruzzan, A.S.; Rahim, A.I.A.; Draman, A.S.; Wahab, W.; Khatoon, H.; Kasan, N.A. Biodegradation of polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics by floc-forming bacteria, *Bacillus cereus* strain SHBF2, isolated from a commercial aquafarm. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 32225–32245. [CrossRef]
60. Newrick, B.; Valdés, D.; Laca, A.; Laca, A.; Díaz, M. Enhanced biodegradation of high-density polyethylene microplastics: Study of bacterial efficiency and process parameters. *J. Hazard. Mater.* **2025**, *485*, 136822. [CrossRef]
61. Auta, H.; Emenike, C.; Fauziah, S. Screening of *Bacillus* strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. *Environ. Pollut.* **2017**, *231*, 1552–1559. [CrossRef]
62. Ji, S.H.; Yoo, S.; Park, S.; Lee, M.J. Biodegradation of low-density polyethylene by plasma-activated *Bacillus* strain. *Chemosphere* **2024**, *349*, 140763. [CrossRef]
63. Sharma, H.; Neelam, D. Biodegradation efficacy of *Exiguobacterium* sp. HSK30 towards vegetable packaging LDPE film. *Biologia* **2025**, *80*, 1469–1482. [CrossRef]
64. Wafaa, D.; Sadik, M.; Eissa, H.; Tonbol, K. Biodegradation of low-density polyethylene LDPE by marine bacterial strains *Gordonia alkanivorans* PBM1 and PSW1 isolated from Mediterranean Sea, Alexandria, Egypt. *Sci. Rep.* **2025**, *15*, 16769. [CrossRef]
65. Sardar, R. Identification and biodegradation characterization of high-density polyethylene using marine bacteria isolated from the coastal region of the Arabian Sea, at Gujarat, India. *World J. Microbiol. Biotechnol.* **2025**, *41*, 74. [CrossRef]
66. Uddin, M.; Venkatesan, S.; Pal, S.; Vinu, R.; Sekar, K.; Kandasamy, R. Accelerating biodegradation efficiency of low-density polyethylene and its hazardous dissolved organic matter using unexplored polyolefin-respiring bacteria: New insights on degradation characterization, biomolecule influence and biotransformation pathways. *J. Hazard. Mater.* **2025**, *492*, 138144. [CrossRef]
67. Meng, Q.; Yi, X.; Zhou, H.; Song, H.; Liu, Y.; Zhan, J.; Pan, H. Isolation of marine polyethylene (PE)-degrading bacteria and its potential degradation mechanisms. *Mar. Pollut. Bull.* **2024**, *207*, 116875. [CrossRef]

68. Kim, Y.; Kim, Y.; Shin, Y.; Choi, S.; Park, J.; Kim, H.; Lim, K.; Ha, S. Efficient biodegradation of low-density polyethylene by *Pseudomonas plecoglossicida* SYp2123 was observed through FT-IR and FE-SEM analysis. *Biotechnol. Bioprocess Eng.* **2024**, *29*, 743–750. [CrossRef]
69. Mazaheri, H.; Nazeri, S. Biodegradation and Detoxification of Low-Density Polyethylene (LDPE) by *Stenotrophomonas* sp. and *Alcaligenaceae bacterium*. *Bull. Environ. Contam. Toxicol.* **2024**, *112*, 19. [CrossRef] [PubMed]
70. Skariyachan, S.; Taskeen, N.; Kishore, A.; Krishna, B.; Naidu, G. Novel consortia of *Enterobacter* and *Pseudomonas* formulated from cow dung exhibited enhanced biodegradation of polyethylene and polypropylene. *J. Environ. Manag.* **2021**, *284*, 112030. [CrossRef] [PubMed]
71. Alsabri, A.; Tahir, F.; Al-Ghamdi, S. Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region. *Mater. Today Proc.* **2022**, *56*, 2245–2251. [CrossRef]
72. Hock, O.; Kee, W.; Ahmed, R.; Ying, J.; Rui, W.; Er, L.; Tanee, T. Degradation of Polypropylene Using Fungal Enzyme As A Sustainable Approach To Management Plastic Waste. *Malays. Appl. Biol.* **2024**, *53*, 93–100. [CrossRef]
73. Lomwongsopon, P.; Martínez, B.M.; Jiménez, A.B.; Bardenstein, A.L.; Kusano, Y.; Christiansen, J.d.C.; Varrone, C. Enhancing biodegradation of polyolefins and real mixed plastic waste by combination of pretreatment and mixed microbial consortia. *Chemosphere* **2025**, *373*, 144151. [CrossRef]
74. Xian, Z.; Yin, C.; Zheng, L.; Zhou, N.; Xu, Y. Biodegradation of additive-free polypropylene by bacterial consortia enriched from the ocean and from the gut of *Tenebrio molitor* larvae. *Sci. Total Environ.* **2023**, *892*, 164721. [CrossRef]
75. Samat, A.; Carter, D.; Abbas, A. Biodeterioration of pre-treated polypropylene by *Aspergillus terreus* and *Engyodontium album*. *npj Mater. Degrad.* **2023**, *7*, 28. [CrossRef]
76. Devi, K.; Raju, P.; Santhanam, P.; Kumar, S.; Krishnaveni, N.; Roopavathy, J.; Perumal, P. Biodegradation of low-density polyethylene and polypropylene by microbes isolated from Vaigai River, Madurai, India. *Arch. Microbiol.* **2021**, *203*, 6253–6265. [CrossRef] [PubMed]
77. Wijayanti, C.; Sanjaya, E.H.; Wahab, R.A.; Susanti, E. Exploration of the polypropylene degrading bacteria candidates from the passive zone of the Supit Urang landfill in Malang city by using the next generation sequencing (NGS) method. *Highlights Biosci.* **2024**, *7*, bs202402. [CrossRef]
78. Denaro, M.A.; Olivelli, M.; Bernabeu, P.R. Biodegradation of polypropylene in presence of chromium mediated by *Stenotrophomonas* sp. and *Lysinibacillus* sp. isolated from wetland sediments. *Curr. Microbiol.* **2025**, *82*, 369. [CrossRef]
79. Jeyavani, J.; Al-Ghanim, K.; Govindarajan, M.; Nicoletti, M.; Malafaia, G.; Vaseeharan, B. Bacterial screening in Indian coastal regions for efficient polypropylene microplastics biodegradation. *Sci. Total Environ.* **2024**, *918*, 170499. [CrossRef]
80. Wang, Z.; Li, Y.; Bai, L.; Hou, C.; Zheng, C.; Li, W. Biodegradation of polypropylene microplastics by *Bacillus pasteurii* isolated from a gold mine tailing. *Emerg. Contam.* **2025**, *11*, 100397. [CrossRef]
81. Sun, Y.; Zhang, Y.; Hao, X.; Zhang, X.; Ma, Y.; Niu, Z. A novel marine bacterium *Exiguobacterium marinum* a-1 isolated from in situ plastisphere for degradation of additive-free polypropylene. *Environ. Pollut.* **2023**, *336*, 122390. [CrossRef]
82. Andriani, D.; Apriana, A.Y.; Srikandace, Y.; Ratnaningrum, D.; Endah, E.S. Polypropylene film and beads biodegradation by *Lysinibacillus macroides* isolated from coastal area of Muara Angke in Jakarta-Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1017*, 012019.
83. Lv, S.; Wang, Q.; Li, Y.; Gu, L.; Hu, R.; Chen, Z.; Shao, Z. Biodegradation of polystyrene (PS) and polypropylene (PP) by deep-sea psychrophilic bacteria of *Pseudoalteromonas* in accompany with simultaneous release of microplastics and nanoplastics. *Sci. Total Environ.* **2024**, *948*, 174857. [CrossRef]
84. Wang, P.; Zhao, J.; Ruan, Y.; Cai, X.; Li, J.; Zhang, L.; Huang, H. Degradation of Polypropylene by the *Pseudomonas aeruginosa* Strains LICME WZH-4 and WGH-6. *J. Polym. Environ.* **2022**, *30*, 3949–3958. [CrossRef]
85. Tabatabaei, F.; Mafigholami, R.; Moghimi, H.; Khoramipoor, S. Investigating biodegradation of polyethylene and polypropylene microplastics in Tehran DWTPs. *Water Sci. Technol.* **2023**, *88*, 2996–3008. [CrossRef]
86. Li, Y.; Zhao, J.; Wang, P.; Zhang, Z.; Zhang, L. A Polypropylene-Degrading *Psychrobacillus* Strain Isolated From a Landfill. *J. Environ. Eng. Landsc. Manag.* **2024**, *32*, 85–92. [CrossRef]
87. Alshammari, A.M.; Virk, P.; Elsayim, R.; Al-Otaibi, N.R.; Al Sudairi, A.T.; Awad, M.; Al-Odayni, A.-B.M.; Fouad, D. A Consortium of Aspergillus Species Biodegrades Polypropylene Plastic. Available online: https://www.researchgate.net/publication/391377289_A_Consortium_of_Aspergillus_Species_Biodegrades_Polypropylene_Plastic (accessed on 19 May 2025).
88. Tegariyanto, M.; Titah, H.; Pratikno, H. Biodegradation of polyethylene terephthalate (PET) plastics using a combination of *Aspergillus niger* and *Trichoderma harzianum*. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1414*, 012028. [CrossRef]
89. Swamy, T.; Nagarathna, S.; Reddy, P.; Nayak, A. Efficient biodegradation of Polyethylene terephthalate (PET) plastic by *Gordonia* sp. CN2K isolated from plastic contaminated environment. *Ecotoxicol. Environ. Saf.* **2024**, *281*, 116635. [CrossRef]
90. Zhang, N.; Li, Y.; He, H.; Zhang, J.; Ma, G. You are what you eat: Microplastics in the feces of young men living in Beijing. *Sci. Total Environ.* **2021**, *767*, 144345. [CrossRef]

91. Maheswaran, B.; Al-Ansari, M.; Al-Humaid, L.; Raj, J.; Kim, W.; Karmegam, N.; Rafi, K. In vivo degradation of polyethylene terephthalate using microbial isolates from plastic polluted environment. *Chemosphere* **2023**, *310*, 136757. [CrossRef]
92. Torena, P.; Alvarez-Cuenca, M.; Reza, M. Biodegradation of polyethylene terephthalate microplastics by bacterial communities from activated sludge. *Can. J. Chem. Eng.* **2021**, *99*, S69–S82. [CrossRef]
93. Sarkhel, R.; Sengupta, S.; Das, P.; Bhowal, A. Comparative biodegradation study of polymer from plastic bottle waste using novel isolated bacteria and fungi from marine source. *J. Polym. Res.* **2020**, *27*, 16. [CrossRef]
94. Srivastava, P.; Saji, J.; Manickam, N. Biodegradation of polyethylene terephthalate (PET) by *Brucella intermedia* IITR130 and its proposed metabolic pathway. *Biodegradation* **2024**, *35*, 671–685. [CrossRef] [PubMed]
95. Hong, H.; Ki, D.; Seo, H.; Park, J.; Jang, J.; Kim, K. Discovery and rational engineering of PET hydrolase with both mesophilic and thermophilic PET hydrolase properties. *Nat. Commun.* **2023**, *14*, 4556. [CrossRef]
96. Tripathy, B.; Sahoo, P.; Sundaray, H.; Das, A. In-vitro biodegradation of discarded marine microplastics across the eastern coast of the Bay of Bengal, India using *Exiguobacterium* sp. *Environ. Chem. Ecotoxicol.* **2024**, *6*, 236–247. [CrossRef]
97. Guo, W.; Duan, J.; Shi, Z.; Yu, X.; Shao, Z. Biodegradation of PET by the membrane-anchored PET esterase from the marine bacterium *Rhodococcus pyridinivorans* P23. *Commun. Biol.* **2023**, *6*, 1090. [CrossRef]
98. Farzi, A.; Dehnad, A.; Fotouhi, A.F. Biodegradation of polyethylene terephthalate waste using *Streptomyces* species and kinetic modeling of the process. *Biocatal. Agric. Biotechnol.* **2019**, *17*, 25–31. [CrossRef]
99. Ribitsch, D.; Acero, E.; Greimel, K.; Eiteljoerg, I.; Trotscha, E.; Freddi, G.; Schwab, H.; Guebitz, G. Characterization of a new cutinase from *Thermobifida alba* for PET-surface hydrolysis. *Biocatal. Biotransform.* **2012**, *30*, 2–9. [CrossRef]
100. Billig, S.; Oeser, T.; Birkemeyer, C.; Zimmermann, W. Hydrolysis of cyclic poly(ethylene terephthalate) trimers by a carboxylesterase from *Thermobifida fusca* KW3. *Appl. Microbiol. Biotechnol.* **2010**, *87*, 1753–1764. [CrossRef]
101. Lee, S.; Kim, M.; Seo, H.; Hong, H.; Park, J.; Ki, D.; Kim, K. Characterization and Engineering of a Fungal Poly(ethylene terephthalate) Hydrolyzing Enzyme from *Aspergillus fumigatiaffinis*. *ACS Catal.* **2024**, *14*, 4108–4116. [CrossRef]
102. Santos-Beneit, F.; Chen, L.; Bordel, S.; de la Flor, R.; García-Depraect, O.; Lebrero, R.; Rodriguez-Vega, S.; Muñoz, R.; Börner, R.; Börner, T. Screening Enzymes That Can Depolymerize Commercial Biodegradable Polymers: Heterologous Expression of *Fusarium solani* Cutinase in *Escherichia coli*. *Microorganisms* **2023**, *11*, 328. [CrossRef]
103. Vázquez-Alcántara, L.; Oliart-Ros, R.; García-Bórquez, A.; Peña-Montes, C. Expression of a Cutinase of *Moniliophthora roreri* with Polyester and PET-Plastic Residues Degradation Activity. *Microbiol. Spectr.* **2021**, *9*, e0097621. [CrossRef]
104. Carniel, A.; Valoni, É.; Nicomedes, J.; Gomes, A.; de Castro, A. 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]
105. Brinch-Pedersen, W.; Keller, M.; Dorau, R.; Paul, B.; Jensen, K.; Borch, K.; Westh, P. Discovery and Surface Charge Engineering of Fungal Cutinases for Enhanced Activity on Poly(ethylene terephthalate). *ACS Sustain. Chem. Eng.* **2024**, *12*, 7329–7337. [CrossRef]
106. Allafi, A.R. The effect of temperature and storage time on the migration of antimony from polyethylene terephthalate (PET) into commercial bottled water in Kuwait. *Acta Biomed. Atenei Parm.* **2020**, *91*, e2020105. [CrossRef]
107. Dhaka, V.; Singh, S.; Anil, A.G.; Sunil Kumar Naik, T.S.; 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]
108. Havaei, M.; Akin, O.; Locaspi, A.; Varghese, R.; Minette, F.; Romers, E.; De Meester, S.; Van Geem, K. Beyond the Landfill: A critical review of techniques for End-of-Life Polyvinyl chloride (PVC) valorization. *Waste Manag.* **2025**, *193*, 105–134. [CrossRef] [PubMed]
109. Jaiswal, S.; Sharma, B.; Shukla, P. Integrated approaches in microbial degradation of plastics. *Environ. Technol. Innov.* **2020**, *17*, 100567. [CrossRef]
110. Veronelli, M.; Mauro, M.; Bresadola, S. Influence of thermal dehydrochlorination on the photooxidation kinetics of PVC samples. *Polym. Degrad. Stab.* **1999**, *66*, 349–357. [CrossRef]
111. Kamo, T.; Kondo, Y.; Kodera, Y.; Sato, Y.; Kushiyama, S. Effects of solvent on degradation of poly(vinyl chloride). *Polym. Degrad. Stab.* **2003**, *81*, 187–196. [CrossRef]
112. Whitney, P. A comparison of two methods for testing defined formulations of PVC for resistance to fungal colonisation with two methods for the assessment of their biodegradation. *Int. Biodeterior. Biodegrad.* **1996**, *37*, 205–213. [CrossRef]
113. Webb, J.; Nixon, M.; Eastwood, I.; Greenhalgh, M.; Robson, G.; Handley, P. Fungal colonization and biodeterioration of plasticized polyvinyl chloride. *Appl. Environ. Microbiol.* **2000**, *66*, 3194–3200. [CrossRef]
114. Vivi, V.; Martins-Franchetti, S.; Attili-Angelis, D. Biodegradation of PCL and PVC: *Chaetomium globosum* (ATCC 16021) activity. *Folia Microbiol.* **2019**, *64*, 1–7. [CrossRef]
115. Sumathi, T.; Viswanath, B.; Sri Lakshmi, A.; SaiGopal, D.V.R. Production of Laccase by *Cochliobolus* sp. Isolated from Plastic Dumped Soils and Their Ability to Degrade Low Molecular Weight PVC. *Biochem. Res. Int.* **2016**, *2016*, 9519527. [CrossRef]
116. Srikanth, M.; Sandeep, T.; Sucharitha, K.; Godi, S. Biodegradation of plastic polymers by fungi: A brief review. *Bioresour. Bioprocess.* **2022**, *9*, 42. [CrossRef] [PubMed]

117. Amobonye, A.E.; Bhagwat, P.; Singh, S.; Pillai, S. Chapter 10—Biodegradability of Polyvinyl chloride. In *Biodegradability of Conventional Plastics*; Sarkar, A., Sharma, B., Shekhar, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 201–220. [CrossRef]
118. Arraq, R.R.; Hadi, A.G.; Ahmed, D.S.; El-Hiti, G.A.; Kariuki, B.M.; Husain, A.A.; Bufaroosha, M.; Yousif, E. Enhancement of Photostabilization of Poly(Vinyl Chloride) in the Presence of Tin–Cephalexin Complexes. *Polymers* **2023**, *15*, 550. [CrossRef] [PubMed]
119. Peng, B.-Y.; Chen, Z.; Chen, J.; Yu, H.; Zhou, X.; Criddle, C.S.; Wu, W.-M.; Zhang, Y. Biodegradation of Polyvinyl Chloride (PVC) in *Tenebrio molitor* (Coleoptera: Tenebrionidae) larvae. *Environ. Int.* **2020**, *145*, 106106. [CrossRef] [PubMed]
120. Bakir, A.; Rowland, S.; Thompson, R. Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. *Environ. Pollut.* **2014**, *185*, 16–23. [CrossRef]
121. Sun, Y.; Hu, J.; Yusuf, A.; Wang, Y.; Jin, H.; Zhang, X.; Liu, Y.; Wang, Y.; Yang, G.; He, J. A critical review on microbial degradation of petroleum-based plastics: Quantitatively effects of chemical addition in cultivation media on biodegradation efficiency. *Biodegradation* **2022**, *33*, 1–16. [CrossRef]
122. Xing, R.-Z.; Zhao, Z.-Q.; Zhao, W.-Q.; Chen, Z.; Chen, J.-F.; Zhou, S.-G. Biodegradation of Polystyrene by *Geobacillus stearothermophilus*. *Huan Jing Ke Xue* **2021**, *42*, 3056–3062. [CrossRef]
123. Sushmita, K.; Madras, G.; Bose, S. The journey of polycarbonate-based composites towards suppressing electromagnetic radiation. *Funct. Compos. Mater.* **2021**, *2*, 13. [CrossRef]
124. Kumar Maurya, A.; Kumar, S.; Singh, M.; Manik, G. Polyamide fiber reinforced polymeric composites: A short review. *Mater. Today Proc.* **2023**, *80*, 98–103. [CrossRef]
125. Karrech, A.; Zhou, H. A systematic review on the recycling of polyurethane products from offshore applications. *Circ. Econ.* **2025**, *4*, 100129. [CrossRef]
126. Shah, A.; Hasan, F.; Hameed, A.; Ahmed, S. Biological degradation of plastics: A comprehensive review. *Biotechnol. Adv.* **2008**, *26*, 246–265. [CrossRef]
127. Tsuchiya, K.; Fukuyama, S.; Kanzaki, N.; Kanagawa, K.; Negoro, S.; Okada, H. High homology between 6-aminohexanoate-cyclic-dimer hydrolases of *Flavobacterium* and *Pseudomonas* strains. *J. Bacteriol.* **1989**, *171*, 3187–3191. [CrossRef]
128. Negoro, S.; Kakudo, S.; Urabe, I.; Okada, H. A New nylon oligomer degradation gene (nylc) on plasmid *pOAD2* from a *Flavobacterium* sp. *J. Bacteriol.* **1992**, *174*, 7948–7953. [CrossRef]
129. Kanagawa, K.; Negoro, S.; Takada, N.; Okada, H. Plasmid dependence of *Pseudomonas* sp. strain NK87 enzymes that degrade 6-aminohexanoate-cyclic dimer. *J. Bacteriol.* **1989**, *171*, 3181–3186. [CrossRef]
130. Gatz-Schrupp, J.; Deckard, P.; Hufford, B.; Ly, S.; Tupa, P.; Masuda, H. Isolation and genomic analysis of 11-aminoundecanoic acid-degrading bacterium *Pseudomonas* sp. JG-B from nylon 11 enrichment culture. *J. Genom.* **2020**, *8*, 16–20. [CrossRef]
131. Arefian, M.; Tahmourespour, A.; Zia, M. Polycarbonate biodegradation by newly isolated *Bacillus* strains. *Arch. Environ. Prot.* **2020**, *46*, 14–20. [CrossRef]
132. Antonakou, E.V.; Achilias, D.S.; Antonakou, E.V.; Achilias, D.S. Recent Advances in Polycarbonate Recycling: A Review of Degradation Methods and Their Mechanisms. *Waste Biomass Valorization* **2012**, *4*, 9–21. [CrossRef]
133. Siddiqui, M.N.; Redhwi, H.H.; Antonakou, E.V.; Achilias, D.S. Pyrolysis mechanism and thermal degradation kinetics of poly(bisphenol A carbonate)-based polymers originating in waste electric and electronic equipment. *J. Anal. Appl. Pyrolysis* **2018**, *132*, 123–133. [CrossRef]
134. Pérez-Lara, L.; Vargas-Suárez, M.; López-Castillo, N.; Cruz-Gómez, M.; Loza-Tavera, H. Preliminary study on the biodegradation of adipate/phthalate polyester polyurethanes of commercial-type by *Alicycliphilus* sp BQ8. *J. Appl. Polym. Sci.* **2016**, *133*. [CrossRef]
135. Rafiemanzelat, F.; Jafari, M.; Emtiazi, G. Study of Biological Degradation of New Poly(Ether-Urethane-Urea)s Containing Cyclopeptide Moiety and PEG by *Bacillus amyloliquefaciens* Isolated from Soil. *Appl. Biochem. Biotechnol.* **2015**, *177*, 842–860. [CrossRef]
136. Gui, Z.; Liu, G.; Liu, X.; Cai, R.; Liu, R.; Sun, C. A Deep-Sea Bacterium Is Capable of Degrading Polyurethane. *Microbiol. Spectr.* **2023**, *11*, e0007323. [CrossRef]
137. Maestri, C.; Plancher, L.; Duthoit, A.; Hebert, R.; Di Martino, P. Fungal Biodegradation of Polyurethanes. *J. Fungi* **2023**, *9*, 760. [CrossRef]
138. Ciuffi, B.; Fratini, E.; Rosi, L. Plastic pretreatment: The key for efficient enzymatic and biodegradation processes. *Polym. Degrad. Stab.* **2024**, *222*, 110698. [CrossRef]
139. Vargas-Suárez, M.; Savín-Gámez, A.; Domínguez-Malfavón, L.; Sánchez-Reyes, A.; Quirasco-Baruch, M.; Loza-Tavera, H. Exploring the polyurethanolytic activity and microbial composition of landfill microbial communities. *Appl. Microbiol. Biotechnol.* **2021**, *105*, 7969–7980. [CrossRef]
140. Shah, A.; Hasan, F.; Akhter, J.; Hameed, A.; Ahmed, S. Degradation of polyurethane by novel bacterial consortium isolated from soil. *Ann. Microbiol.* **2008**, *58*, 381–386. [CrossRef]

141. Vargas-Suárez, M.; Fernández-Cruz, V.; Loza-Tavera, H. Biodegradation of polyacrylic and polyester polyurethane coatings by enriched microbial communities. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 3225–3236. [CrossRef]
142. Shah, Z.; Hasan, F.; Krumholz, L.; Aktas, D.; Shah, A. Degradation of polyester polyurethane by newly isolated *Pseudomonas aeruginosa* strain MZA-85 and analysis of degradation products by GC MS. *Int. Biodeterior. Biodegrad.* **2013**, *77*, 114–122. [CrossRef]
143. Park, W.; Hwangbo, M.; Chu, K. Plastisphere and microorganisms involved in polyurethane biodegradation. *Sci. Total Environ.* **2023**, *886*, 163932. [CrossRef]
144. Curia, R.; Milani, M.; Didenko, L.; Avtandilov, G.; Shevlyagina, N.; Smirnova, T. Beyond the biodestruction of polyurethane: *S. aureus* uptake of nanoparticles is a challenge for toxicology. *Microsc. Adv. Sci. Res. Educ.* **2014**, *1*, 16–23.
145. Salgado, C.A.; Pereira Vidigal, P.M.; Dantas Vanetti, M.C. Biodegradation of polyurethanes by *Staphylococcus warneri* and by microbial co-culture. *Chemosphere* **2024**, *359*, 142169. [CrossRef]
146. Najam, M.; Javaid, S.; Iram, S.; Pasertsakoun, K.; Oláh, M.; Székacs, A.; Aleksza, L. Microbial Biodegradation of Synthetic Polyethylene and Polyurethane Polymers by Pedospheric Microbes: Towards Sustainable Environmental Management. *Polymers* **2025**, *17*, 169. [CrossRef]
147. Khruengsai, S.; Sripahco, T.; Pripdeevech, P. Biodegradation of Polyester Polyurethane by *Embarria clematidis*. *Front. Microbiol.* **2022**, *13*, 874842. [CrossRef]
148. Russell, J.; Huang, J.; Anand, P.; Kucera, K.; Sandoval, A.; Dantzler, K.; Hickman, D.; Jee, J.; Kimovec, F.; Koppstein, D.; et al. Biodegradation of Polyester Polyurethane by Endophytic Fungi. *Appl. Environ. Microbiol.* **2011**, *77*, 6076–6084. [CrossRef]
149. Liu, J.; Liu, J.; Xu, B.; Xu, A.; Cao, S.; Wei, R.; Zhou, J.; Jiang, M.; Dong, W. Biodegradation of polyether-polyurethane foam in yellow mealworms (*Tenebrio molitor*) and effects on the gut microbiome. *Chemosphere* **2022**, *304*, 135263. [CrossRef]
150. Yoon, M.G.; Jeon, H.J.; Kim, M.N. Biodegradation of polyethylene by a soil bacterium and AlkB cloned recombinant cell. *J. Bioremed. Biodegrad.* **2012**, *3*, 1–8.
151. Perz, V.; Baumschlager, A.; Bleymaier, K.; Zitzenbacher, S.; Hromic, A.; Steinkellner, G.; Pairitsch, A.; Lyskowski, A.; Gruber, K.; Sinkel, C.; et al. Hydrolysis of synthetic polyesters by *Clostridium botulinum* esterases. *Biotechnol. Bioeng.* **2016**, *113*, 1024–1034. [CrossRef]
152. Wei, R.; Oeser, T.; Then, J.; Kühn, N.; Barth, M.; Schmidt, J.; Zimmermann, W. Functional characterization and structural modeling of synthetic polyester-degrading hydrolases from *Thermomonospora curvata*. *AMB Express* **2014**, *4*, 44. [CrossRef]
153. Janatunaim, R.Z.; Fibriani, A. Construction and Cloning of Plastic-degrading Recombinant Enzymes (MHETase). *Recent Pat. Biotechnol.* **2020**, *14*, 229–234. [CrossRef]
154. Di Rocco, G.; Taunt, H.; Berto, M.; Jackson, H.; Piccinini, D.; Carletti, A.; Scurani, G.; Braidi, N.; Purton, S. A PETase enzyme synthesised in the chloroplast of the microalga *Chlamydomonas reinhardtii* is active against post-consumer plastics. *Sci. Rep.* **2023**, *13*, 10028. [CrossRef]
155. 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]
156. Brandenberg, O.; Schubert, O.; Kruglyak, L. Towards synthetic PETtrophy: Engineering *Pseudomonas putida* for concurrent polyethylene terephthalate (PET) monomer metabolism and PET hydrolase expression. *Microb. Cell Factories* **2022**, *21*, 119. [CrossRef]
157. Sabellico, G.; Baggetta, A.; Sandrucci, E.; Zanellato, G.; Martinelli, A.; Montanari, A.; Bianchi, M. Oxidative deterioration of polypropylene by redox mediators and yeast expressing a fungal recombinant laccase. *Int. Biodeterior. Biodegrad.* **2025**, *196*, 105947. [CrossRef]
158. Liu, M.; Yang, S.; Long, L.; Cao, Y.; Ding, S. Engineering a Chimeric Lipase-cutinase (Lip-Cut) for Efficient Enzymatic Deinking of Waste Paper. *Bioresources* **2018**, *13*, 981–996. [CrossRef]
159. Blasberg, A.; Christian, B.; Goyal, A.; Vacca, J.; Wells, J. Inserting *Ideonella sakaiensis* genes into chassis *Comamonas testosteroni* to create bacterial super-degrader for plastic waste reduction. *BioTreks* **2024**, *9*, 249–259. Available online: https://biotreks.org/wp-content/uploads/2024/10/e202426.pdf (accessed on 12 May 2025).
160. Yan, F.; Wei, R.; Cui, Q.; Bornscheuer, U.; Liu, Y. Thermophilic whole-cell degradation of polyethylene terephthalate using engineered *Clostridium thermocellum*. *Microb. Biotechnol.* **2021**, *14*, 374–385. [CrossRef]
161. Schmidt, J.; Wei, R.; Oeser, T.; Silva, L.; Breite, D.; Schulze, A.; Zimmermann, W. Degradation of Polyester Polyurethane by Bacterial Polyester Hydrolases. *Polymers* **2017**, *9*, 65. [CrossRef]
162. Nomura, N.; Shigeno-Akutsu, Y.; Nakajima-Kambe, T.; Nakahara, T. Cloning and sequence analysis of a polyurethane esterase of *Comamonas acidovorans* TB-35. *J. Ferment. Bioeng.* **1998**, *86*, 339–345. [CrossRef]
163. Sharma, S.; Pathania, S.; Bhagta, S.; Kaushal, N.; Bhardwaj, S.; Bhatia, R.K.; Walia, A. Microbial remediation of polluted environment by using recombinant *E. coli*: A review. *Biotechnol. Environ.* **2024**, *1*, 8. [CrossRef]
164. Rafeeq, H.; Afsheen, N.; Rafique, S.; Arshad, A.; Intisar, M.; Hussain, A.; Bilal, M.; Iqbal, H.M.N. Genetically engineered microorganisms for environmental remediation. *Chemosphere* **2023**, *310*, 136751. [CrossRef]

165. Ngaba, M.J.Y.; Rennenberg, H.; Hu, B. Insights Into the Efficiency and Health Impacts of Emerging Microplastic Bioremediation Approaches. *Glob. Chang. Biol.* **2025**, *31*, e70226. [CrossRef]
166. Wesseler, J.; Kleter, G.; Meulenbroek, M.; Purnhagen, K.P. EU regulation of genetically modified microorganisms in light of new policy developments: Possible implications for EU bioeconomy investments. *Appl. Econ. Perspect. Policy* **2023**, *45*, 839–859. [CrossRef]
167. European Parliament and of the Council. Directive 2001/18/EC on the Deliberate Release into the Environment of Genetically Modified Organisms and Repealing Council Directive 90/220/EEC. 2001, pp. 1–39. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32001L0018 (accessed on 20 July 2025).
168. Judgment of the Court in Case C-528/16 *EUR-Lex*. 25 July 2018. Available online: https://curia.europa.eu/juris/document/document.jsf?text=&docid=204387&pageIndex=0&doclang=EN&mode=lst&dir=&occ=first&part=1&cid=116151 (accessed on 20 July 2025).
169. European Parliament and of the Council. Directive 2009/41/EC of the European Parliament and of the Council of 6 May 2009 on the Contained Use of Genetically Modified Micro-Organisms. 2009. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0041 (accessed on 20 July 2025).
170. Toxic Substances Control Act (TSCA). Biotechnology Regulations, 40 CFR Part 725. 1997. Available online: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-R/part-725 (accessed on 20 July 2025).
171. Mrigwani, A.; Pitaliya, M.; Kaur, H.; Kasilingam, B.; Thakur, B.; Guptasarma, P. Rational mutagenesis of *Thermobifida fusca* cutinase to modulate the enzymatic degradation of polyethylene terephthalate. *Biotechnol. Bioeng.* **2022**, *120*, 674–686. [CrossRef] [PubMed]
172. 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*, 674–686. [CrossRef] [PubMed]
173. 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]
174. Gamerith, C.; Acero, E.H.; Pellis, A.; Ortner, A.; Vielnascher, R.; Luschnig, D.; Zartl, B.; Haernvall, K.; Zitzenbacher, S.; Strohmeier, G.; et al. Improving enzymatic polyurethane hydrolysis by tuning enzyme sorption. *Polym. Degrad. Stab.* **2016**, *132*, 69–77. [CrossRef]
175. Kong, D.; Zhang, H.; Yuan, Y.; Wu, J.; Liu, Z.; Chen, S.; Zhang, F.; Wang, L. Enhanced biodegradation activity toward polyethylene by fusion protein of anchor peptide and *Streptomyces* sp. strain K30 latex clearing protein. *Int. J. Biol. Macromol.* **2024**, *264*, 130378. [CrossRef] [PubMed]