

Plastic waste biodegradation and valorization: emerging biotechnological approaches for sustainable waste management

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ABSTRACT

Durability and resistance of various plastic polymers have led to their widespread use, but these same properties make them persistent in the environment and disrupt ecosystems via the food chain. Efficient, cost-effective, and environmentally friendly strategies are therefore needed to treat this plastic waste and mitigate its impact. To enhance mitigation efficiency, modern research relies on advanced microbial technologies including genetic engineering, bioinformatics, and machine learning for producing high-performance plastic-degrading enzymes, discovering novel microbial pathways, and optimizing degradation kinetics across synthetic polymers, respectively. However, because both biotic and abiotic degradation are time-consuming and sometimes ineffective, valorization has emerged as an alternative strategy for plastic waste management. This review goes beyond biodegradation strategies for mitigating plastic waste and comprehensively discusses valorization of recalcitrant plastic waste. Valorization strategies not only decrease the problems associated with plastic waste but simultaneously create employment opportunities and contribute toward global economies. This is a narrative review that focuses on information from theses, research, and review articles published in the English language across various databases from 2000 to 2026. Articles and patents related to microbial degradation, mitigation, and valorization of plastic waste have been summarized to reflect upon the technological advancements and limitations of plastic waste mitigation and valorization. It encourages future research opportunities in sustainable plastic waste management.

1. INTRODUCTION

Bakelite was the first-ever synthetic polymer produced in 1907, marking the emergence of polymer industries and the consequent onset of polymer pollution. Statistical reports indicate that global polymer production rates have increased exponentially after 1950, reaching ~ 460 million tons of annual production [1]. Today, single-use polymers account for 40% of the polymers produced every year. The rise in plastic production from 1.5 million metric tons (MMT) in 1950 to 367 MMT in 2020 is a testament to the global plastic surge [2]. Careless disposal of plastic polymers interrupts the growth of plants, small animals, and aquatic life, thus hindering agricultural yield and posing health hazards to humans. The degraded polymeric forms, or micro-polymers, found in soil contain many toxins that harm humans and other forms of life and can easily enter the food chain in

both terrestrial and aquatic ecosystems. This crisis is faced mainly by developing countries due to low recycling rates [3,4].

Plastic recycling has been considered a management strategy depending on various parameters, especially the benefits that encourage a sustainable lifestyle and reduction in global warming. Recycling also reduces the emergence of further pollution and creates numerous job opportunities. This technique involves the following sequential steps: (1) collection of polymer waste from surrounding areas to a common place; (2) sorting and identification of polymers into their respective categories based on their properties; (3) removal of impurities from polymers for smoother processing; (4) resizing of polymers with shredders, where they are cut into very small fragments; and (5) finally transforming recycled plastics into materials/products, which are then reproduced by the manufacturers [5]. Physical plastic degradation occurs via cracking, embrittlement, and flaking, whereas chemical degradation involves changes at the molecular level, that is, breaking or formation of chemical bonds in the polymeric structure, or oxidation of polymer chains to create new molecules, typically with noticeably shorter chain lengths [4]. The resulting polymers are minuscule but pose considerable environmental risks due to the leaching of small molecules and soluble intermediates of polymer degradation [6].

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The present decade has witnessed the deployment of biological approaches to degrade otherwise recalcitrant plastic polymers and mineralize them without the generation of toxic intermediates. Microbial cells or enzymes extracted from various sources have been found to act on plastic polymers, reducing the complex polymer chains and converting them into simple sources of carbon for utilization by other organisms.

Biological means of plastic degradation have been extensively reviewed in this article by thoroughly searching for studies published in PubMed, Web of Science, Scopus, and Google Scholar from October 2000 to June 2026 using Boolean operators. The search strategy utilized key English terms including microbial/enzymatic degradation, plastic valorization, enzymatic depolymerization, and circular plastic economy to evaluate their suitability for mitigating challenges posed by plastic waste. Apart from degradation, this article also reflects on valorization strategies for plastic waste, leading to robust waste management even in less developed countries where recycling rates are low. Information has been obtained from research articles, published theses, reviews, and patent documents, where relevant studies were screened with respect to their title, abstract, and full text. The information extracted was thematically categorized to state various polymer types, degrading organisms/enzymes, contributing environmental factors, existing limitations, and progress. Valorization technologies and research opportunities in plastic waste management have been detailed. Risk-of-bias assessment was not performed in this narrative review, and only degrading microorganisms have been included.

2. TYPES OF PLASTICS

Polyethylene terephthalate (PET), polyvinyl chloride (PVC), foamed polystyrene (PS), polyurethane, and polymethyl methacrylate are the common types of polymers used. Industrial producers frequently distinguish between “commodity” resins and “specialty” resins when referring to polymers [6,7]. The name “resin” typically refers

to naturally occurring amorphous solids like shellac and rosin and is native to the polymer industry. Polymers, for example, PE, polypropylene (PP), PVC, and PS, known as commodity resins, are produced in large quantities at a low cost for the most popular durable goods and disposable items. Polymers made in small quantities at a higher cost are known as specialty resins because they have qualities suited to certain uses. The so-called engineering polymers, sometimes known as engineering resins, are polymers that may compete with die-cast metals in applications such as plumbing, hardware, and automotive industries [6,7].

Based on their chemical makeup, or the arrangement of carbon atoms in the backbone chain, polymers can also be classified as aliphatic or hetero-chain polymers. The first group includes commodity polymers, for example, PP, which has a pendant methyl group (CH_3) connected to a secondary carbon atom [8]. Hetero-chain polymers contain elements such as oxygen (O), nitrogen (N), or sulfur (S) in their backbone chains, in addition to carbon. Hetero-chain polymers constitute many of the engineering polymers, for example, polycarbonate, which has molecules with two aromatic (benzene) rings. The various types of plastic polymers and their characteristic features are provided in Figure 1.

3. DEGRADATION OF PLASTIC POLYMERS

Thermal degradation, mechano-chemical degradation, photo-oxidative degradation, catalytic degradation, ozone-induced degradation, and biodegradation (including enzyme- or microbe-mediated degradation, depending on the causative agents or location) are various degradation methods of plastic polymers [9]. Physicochemical degradation of plastics involves both physical changes, such as fragmentation and embrittlement, and chemical changes, such as chain scission, oxidation, and cross-linking. Among these, thermal degradation, photodegradation, and biological degradation contribute mainly to the breakdown of plastic polymers in nature and have been discussed here [10].

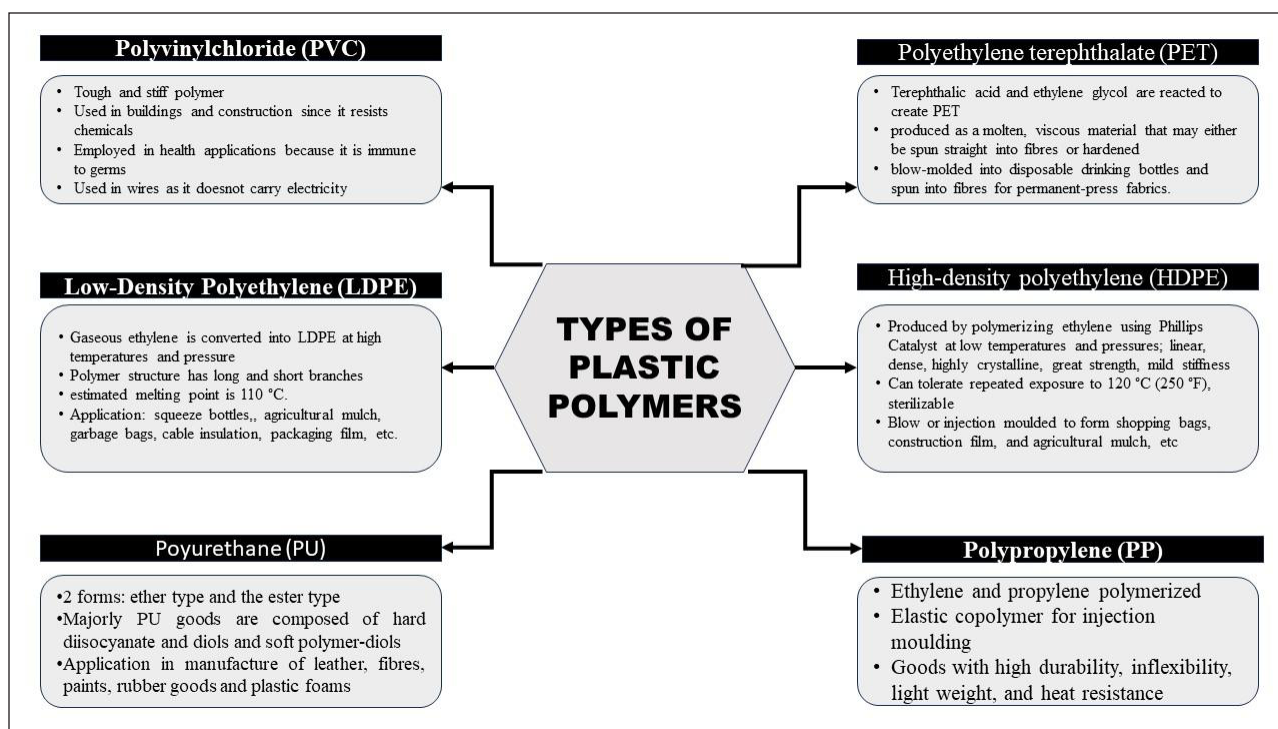


Figure 1. Commonly existing plastic polymers showing some of their composition, properties, and applications.

3.1. Thermal Degradation

The deterioration of plastic materials after exposure to high temperatures causes the molecular chains in plastics to fracture [11], reducing their mechanical properties and changing their aesthetic qualities. Additionally, this event may cause the discharge of flammable compounds and cause the plastic to become more fragile or change color. Selecting plastics with greater heat resistance, avoiding extended or extreme heat exposure, and considering the use of chemicals that increase the plastic's resistance to thermal challenges are a few protective measures to prevent further leaching of plastics into the environment.

3.2. Photodegradation

In the case of photodegradation, photons with greater energy levels can disrupt the molecular structure of plastics, which can have a variety of detrimental effects [10]. Powerful UV photons break the chemical bonds within plastic polymer chains, weaken the structure of the plastic, and reduce its mechanical strength. Additionally, broken polymer chains react with oxygen molecules in the air to form oxygen-containing functional groups on the surface of the plastic. UV light can cause oxidation processes in plastics and increase the plastic's susceptibility to further deterioration, which may result in discoloration, increased brittleness, and decreased functionality [12]. This is especially apparent in outdoor applications such as outdoor furniture, packaging, and signage. Photodegradation and oxidation cause the outer plastic layers to weaken, become fragile, and prone to cracks [10].

Interaction of plastics with oxygen in the presence of heat, light, or certain chemical agents induces a variety of negative changes in their characteristics and usefulness. Heat and light energy serve as the activation energy for oxygen to interact with other oxygen molecules from the environment or those present in the polymeric structure. This interaction kick-starts a chain reaction, forming reactive oxygen species and causing scission of the C–C bonds in the polymer's backbone [8,10]. Chain scission is a phenomenon in which long polymer chains are broken into smaller pieces, lowering the molecular weight of the polymer and decreasing its mechanical strength. Continuous interaction of broken polymeric chains, oxygen-containing functional groups, and molecular oxygen makes the plastic more susceptible to further deterioration [13].

Apart from abiotic factors, mechanical stress factors, including impact and abrasion, lead to the degradation of plastics, for example, structural changes, fractures, and reduced mechanical resilience [14]. The polymer chains can become compromised over time by repeated mechanical stress or abrupt impacts, making the plastic brittle and prone to breaking.

3.3. Biodegradation

Biodegradation of plastic polymers may be mediated mainly by bacteria, fungi, algae, and their metabolites [15]. Bacteria adhere to the surface of polymers, which may already be weakened by environmental factors, and break down the polymeric structure [16]. Microbes degrade polymers in two different ways: internally via metabolic activity or externally via enzymatic secretion. Enzymes can facilitate the transport of materials across the cell membrane by breaking down polymeric chains into smaller molecules (Fig. 2). Different types of synthetic polymers follow different mechanisms of degradation, and each of these classes of polymers is degraded by different microorganisms [17]. For example, enzymes secreted by each microbe differ in nature, and different polymers have different

incubation times for degradation. This process of degradation involves a series of steps: (1) accumulation of microorganisms around the surface of the polymer to be degraded; (2) secretion of degrading enzymes, which get adsorbed on the surface when concentrations are above threshold levels; and (3) surface corrosion and reduction in tensile strength [18]. The reaction occurring between the enzyme and the surface molecule causes the formation of an intermediate molecule, irrespective of the enzyme and substrate, which is easily assimilated by microorganisms as their carbon source [19].

Metagenomics, meta-transcriptomics, metabolomics, and computational biology-based studies have been instrumental in unravelling plastic- and microplastic-degrading microbial communities from various environments [20,21]. These approaches are powerful tools for identifying and selecting potential microbial strains *in situ*. Some of these studies have been elaborated in the following sections and in Table 1.

3.3.1. Organisms involved in polymer biodegradation

(A) Role of bacteria in polymer degradation

For heterotrophs such as fungi and bacteria, synthetic polymers provide nutrients (energy and carbon) in a variety of ways. Synthetic polymers, such as homo- or heteropolymers, may contain the same or distinct types of monomers [22]. Plastic waste is a complex mixture of micro-polymers comprising PET, polyurethane (PU), PS, and low-density polyethylene/high-density polyethylene (LDPE/HDPE), which are ubiquitously distributed in agricultural soils and water bodies. Initially, the carbon–carbon backbone is lysed due to combined abiotic factors, producing shorter polymer fragments or oligomers, which are vulnerable to subsequent microbial attack [15]. Microbes with various bond-cleaving and enzymatic activities attack the plastic on the surface, which may be partially degraded or chemically weakened and is easily susceptible to biodeterioration via microbial extracellular and intracellular depolymerase enzymes, such that polymeric chains become sufficiently small to pass through cell membranes; further metabolism occurs via chain cleavage within the cells [51]. This is followed by enzymatic cleavage within microbial cells, assimilation, and mineralization of the polymeric chains (Fig. 2).

An indirect pathway of biodegradation may be aerobic, anaerobic, or both, as especially seen in composting heaps. CO₂ and H₂O result from aerobic degradation, whereas CO₂, CH₄, and H₂O are products of anaerobic degradation. In nature, fungi and bacteria work together in synergy to degrade plastic polymers, where the enzymatic activity of both species plays significant roles. Following degradation, most polymers are metabolized via the Krebs cycle as the primary core metabolic pathway to produce energy.

Bacillus weihenstephanensis, *Bacillus* spp., *Staphylococcus* spp., *Streptococcus* spp., and *Diplococcus* spp., isolated from garbage soil; *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, and *Acinetobacter ursingii*, isolated from plastic-contaminated soil; and *Trichoderma viride* and *Aspergillus nomius*, isolated from landfill soil, have shown the ability to degrade LDPE, as demonstrated in various studies [52,53].

In the marine environment, the abundantly present plastic polymers, PE and PP, are degraded by various abiotic and biotic factors. Reports show that various types of polymers were degraded upon incubation with certain marine bacterial or fungal strains in the laboratory; however, their exact functioning in the natural marine ecosystem remains undeciphered [54–56]. Some bacteria, such as members of the families Alcanivoraceae, Sphingomonadaceae, and Rhodobacteraceae, have the potential for hydrocarbon degradation and show association with plastic

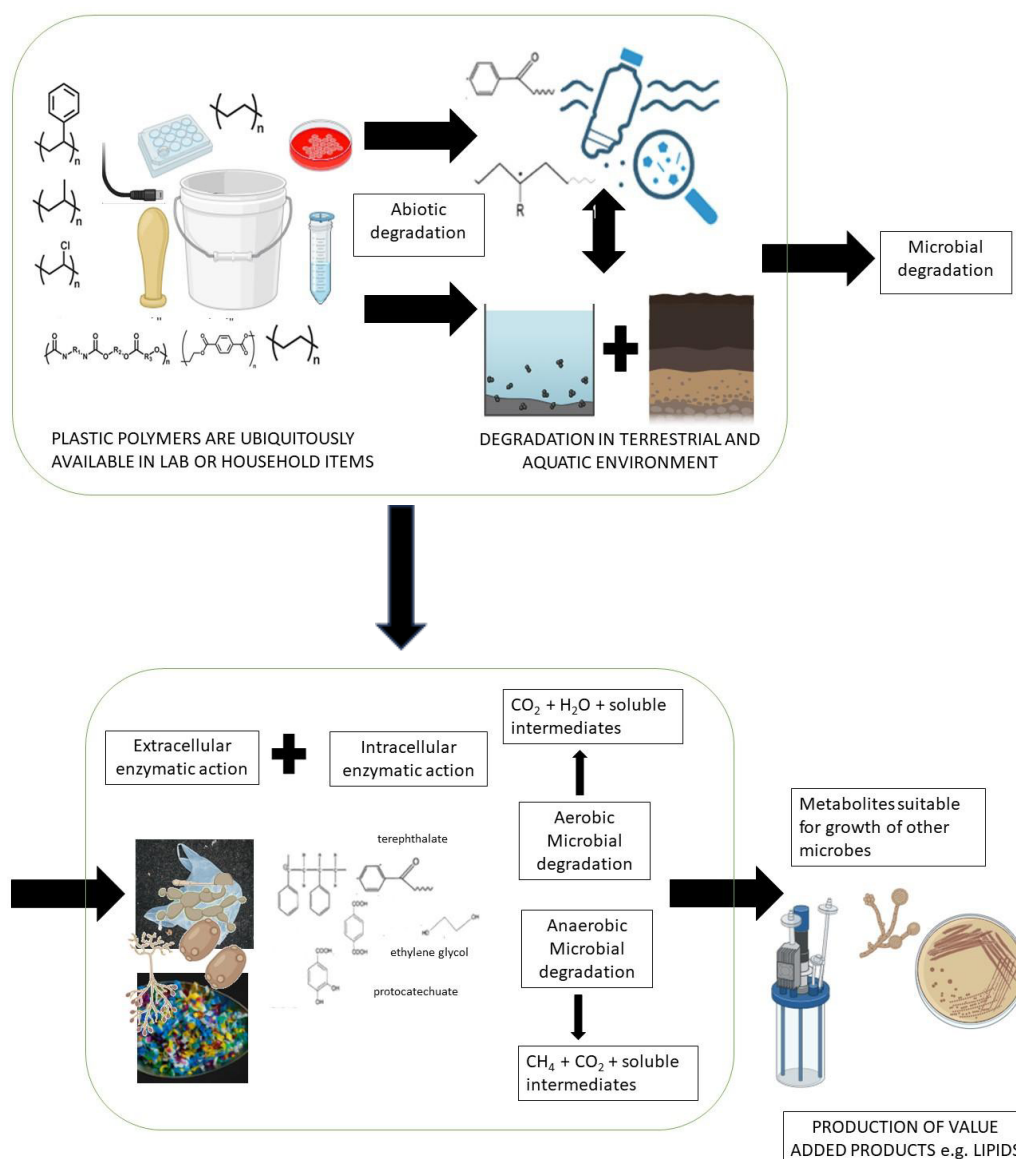


Figure 2. Schematic diagram showing the influence of both abiotic and biotic factors for weathering and subsequent degradation of various types of plastic waste. In the natural environment, various physico-chemical (light, heat, temperature, and radiation) and mechanical (waves, winds, abrasion, etc.) agents result in conformational changes and/or breakdown of the synthetic polymers. Subsequent bacterial and fungal colonization of the deteriorated plastics lead to chain scission of the polymeric structure via extra- or intracellular enzymatic action. These degradation products are shorter C chain intermediates, that may also be used by other microorganisms via optimized fermentation for production of value-added products having industrial importance.

polymeric surfaces [57]. This indicates that the plastic-colonizing ability of such microbial communities might lead to the degradation of plastic polymers and their derivatives. It has been observed that members of the family Alcanivoraceae, which commonly degrade alkanes, could also degrade PET. Microbial communities associated with plastic degradation have been screened in the Baltic Sea and the North Sea, where a common bacterial strain, *Erythrobacter* sp., was found to flourish particularly on PE polymers [57].

(B) Role of fungi in polymer degradation

Bacteria are the initial colonizers of the polymer surface during the fouling process, leading to the subsequent colonization by fungal species that enable further decay. Once degradation rates are

accelerated, metabolic intermediates may be shared between fungal and bacterial strains [58]. Polymer fragments buried in agricultural soil combined with sewage sludge have been reported to be degraded by subsequent fungal attack [53]. A community examination of the polymer surface indicated bacterial and fungal adhesion, suggesting that LDPE was likely used as a nutrient source [16].

The commonly found fungal strains involved in degradation include *Pleurotus tuber-regium*, *Lentinus squarrosulus*, and *Rigidoporus lignosus*, where *P. tuber-regium* was able to reduce the weight of PE by 13.26%. Filamentous fungi, for example, *Aspergillus niger*, *Aspergillus terreus*, *Aureobasidium pullulans*, *Paecilomyces varioti*, *Penicillium funiculosum*, *Penicillium ochrochloron*, *Scopulariopsis brevicaulis*, and *Trichoderma viride*, have also been reported to degrade LDPE [53,59].

Table 1. Microbial potential for breakdown of various plastic polymers.

S. No	Microorganism	Enzyme(s) involved	Isolation source	Incubation time (days)	Material	Weight loss (%)	References
1	<i>Rhodococcus ruber</i> C208	NA	Soil of disposal site	30	Polyolefin	8.0	[22]
2	<i>Bacillus sphericus</i>	Oxidoreductases	Marine water	365	LDPE	2.5–10	[23]
3	<i>Arthrobacter</i> sp. GMB5	NA	Polymer waste dump sites	30	HDPE	12–15	[24]
4	<i>Pseudomonas</i> sp. E4	NA	Soil	80	IMWPE	NA*	[25]
5	<i>Pseudomonas</i> sp. AKS2	Hydroxylase	Waste dumping soil	45	LDPE	5.0	[26]
6	<i>Bacillus subtilis</i> H1584	Oxidoreductases	Pelagic waters	30	LDPE	1.75	[27]
7	<i>Enterobacter asburiae</i> YT1	Laccase	Gut of waxworm	60	LDPE	10.7	[28]
8	<i>Serratia marcescens</i>	NA	Ground soil	70	LLDPE	36.0	[29]
9	<i>Zalerion maritimum</i>	Glycosyl hydrolases	ATCC**	28	PE pellets	NA	[30]
10	<i>Alcanivorax borkumensis</i>	Polyesterases	Mediterranean Sea	80	LDPE	3.5	[31]
11	<i>Phanerochaete chrysosporium</i> NA3	Lignin peroxidase	Garbage disposal soil	84	PS	~20	[32]
12	<i>Xanthomonas</i> sp.; <i>Sphingobacterium</i> sp.	NA	Soil	8	PS film	40–56	[33]
13	<i>Pseudomonas citronellolis</i>	NA	Soil	45	PVC film	13.0	[34]
14	<i>Rhizopus oryzae</i> NA1; <i>Aspergillus terreus</i> NA2	NA	Soil	56	PS film	NA	[35]
15	<i>Phanerochaete chrysosporium</i> NA3	NA	Soil	56	PS film	NA	[35]
16	<i>Exiguobacterium</i> sp. YT2	NA	Mealworm gut	60	PS film	7.5	[36]
17	<i>Acinetobacter radioresistens</i>	NA	NA	60	PS	16.7 ± 0.6	[37]
18	<i>B. flexus</i>	Laccase; other extracellular enzymes	Soil of plastic dumping site	365	PP film	2.5	[38]
19	<i>Brevibacillus</i> sp; <i>Aneurinibacillus</i> sp.	Extracellular enzymes	Landfills and sewage	140	LDPE, HDPE, PP	37.2–58.21	[39]
20	<i>Stenotrophomonas panacihumi</i> PA3-2	Urease	Soil of waste storage yard	90	PP film	~20.3	[40]
21	<i>Thermobifida fusca</i> DSM43793	Hydrolase TfH	NA	21	PET bottles and pellets	22–54.2	[41]
22	<i>Saccharomonospora viridis</i> AHK190	Cut190 (S226P/R228S)	Compost	7.0	Low crystalline PET film	~27	[42]
23	<i>B. subtilis</i> RH11496	TfCut2	NA	5.0	ET packaging	53.8	[43]
24	<i>Exiguobacterium</i> , <i>Arthrobacter</i> , etc.	Laccase, peroxidases, oxidoreductase	Municipal waste dump	90	PVC	~13.32	[44]
25	<i>Purpureocillium lilacinum</i>	Esterase	Soil	21	PBSA film	NA	[45]
26	<i>Alternaria</i> sp. PURDK2	Urethane-bond degrading enzyme	Environment	70	ether-PUR film	27.5	[46]
27	<i>Cladosporium cladosporioides</i> complex	Esterase, protease, urease	Garden soil	14	PUR varnish and foams	87.0	[47]
28	<i>Penicillium</i> sp.	Esterase	PUR waste	60	Impranil DLN; PEE/PES PUR film	8.9	[48]
29	<i>Aspergillus</i> sp. S45	Lipase, esterase	Waste-dumping site	28	Polyester PUR film	15–20	[49]
30	<i>Bacillus</i> sp. strain 27; <i>Rhodococcus</i> sp. strain 36	Extracellular enzymes	Mangrove	40	PP macro-polymer	4–6.4	[50]

ATCC = American Type Culture Collection; DLN = diamond-like nanocomposite; HDPE = high-density polyethylene; IMWPE = ultra-high-molecular-weight polyethylene; LDPE = low-density polyethylene; NA = reports not available; PBSA = polybutylene succinate-co-adipate; PE = polyethylene; PEE = polyether; PES = polyester; PET = polyethylene terephthalate; PP = polypropylene; PS = polystyrene; PUR = polyurethane; PVC = polyvinyl chloride.

Studies on microbial/enzymatic degradation of plastic polymers indicating degradation rates of various polymers. Cumulative weight loss values indicate the primary alterations caused after incubation; however, other confirmatory analytical studies were also conducted. The table indicates qualitative comparison of independently conducted experiments.

Contrary to bacteria, the ability of fungal species to form biofilms on PE has been linked to a gradual decrease in surface hydrophobicity. According to reports, after attachment, *Fusarium* sp. and other fungal species erode the surface [58,60]. However, some strains of *Mucor* and *Aspergillus* are associated with the fouling and deterioration of PE combined with 6% starch [61].

(C) Role of algae in polymer degradation

Many algae, both photosynthetic and heterotrophic, have been reported to contribute substantially to bioremediation, in addition to their numerous industrial applications. They have the capacity to remove both inorganic and organic pollutants from a variety of environments by accumulating, adsorbing, or metabolizing them into relatively harmless substances. A few studies have demonstrated that marine algae can metabolize polymers [62]. Even in terrestrial environments, various polymer surfaces have been found to be colonized by algae, including *Anabaena*, *Chlorella*, *Spirogyra*, *Nostoc*, *Oscillatoria*, and *Spirulina* species. Among these, *A. spiroides* appears to be the most promising, decomposing 8.18% of low-density PE within 30 days. Although *Spirulina* sp. has been shown to biodegrade PET and PP, the rate of degradation was significantly slower than that observed for bacterial and fungal systems after 112 days [63].

These findings are not unexpected, as algae, unlike bacteria, primarily utilize atmospheric CO₂ as their carbon source and sunlight as their main energy source. Their metabolic pathways do not appear to efficiently mineralize microplastics, despite their ability to colonize polymeric surfaces. A recent study has leveraged the remarkable capability of *Phaeodactylum tricornutum* to serve as a genetic host for cloning the well-known PETase enzyme derived from *Ideonella sakaiensis*, enabling the investigation of PET biodegradation [64].

3.3.2. Role of enzymes in polymer degradation

Several types of bacterial enzymes with varying modes of action are involved in the biodegradation of plastics, and they have been classified and discussed below:

(A) Oxidoreductases

Oxidoreductases, such as laccases, tyrosinases, oxygenases, aromatic dioxygenases, and various peroxidases, catalyze redox reactions during the biodegradation of plastics, particularly PE and PS. Laccase, a polycopper monomeric glycoprotein belonging to the blue copper oxidase class, facilitates the reduction of molecular oxygen to water and the oxidation of both phenolic and non-phenolic compounds by utilizing oxygen as an electron acceptor [65–67]. Due to the inability of HDPE molecules to pass through the cell membrane, microbial activity is required to reduce their molecular weight, followed by enzymatic oxidation and subsequent conversion into carboxylic acids, which can then be metabolized via β -oxidation and the Krebs cycle [61].

Hydrophobins are hydrophobic proteins present on fungal surfaces that facilitate hyphal adhesion to plastic substrates and promote surface modification. Similarly, extracellular enzymes such as peroxidases and oxidases accelerate the deterioration of plastic surfaces through oxidative or hydrolytic mechanisms. Several fungal species, including *Phanerochaete chrysosporium*, *Rhizopus oryzae*, *Trametes versicolor*, and *Bjerkandera adusta*, have been reported to degrade PE [68].

Trichoderma harzianum secretes both laccase and manganese peroxidase enzymes; treatment of PE with laccase resulted in a 0.5% reduction, while treatment with peroxidase led to a 0.6% reduction within 10 days. These enzymatic reactions resulted in the formation

of carboxylic acids, aldehydes, aromatics, alcohols, esters, ethers, and alkyl halide groups [69]. Another fungal species, *Aspergillus flavus*, has been implicated in HDPE degradation and can depolymerize long polymer chains into lower molecular weight fragments through the production of laccases and laccase-like multicopper oxidases [70].

Another basidiomycete, *P. chrysosporium*, has been shown to partially degrade PE and significantly reduce its tensile strength in the presence of purified manganese peroxidase [71]. This process requires H₂O₂, as the manganese peroxidase (MnP) system depends on it, even though PE degradation itself does not necessarily require exogenous H₂O₂. *Pleurotus ostreatus*, another basidiomycete, secretes multiple extracellular ligninolytic enzymes, including MnP, laccases, and lignin peroxidases, which contribute to the cleavage of C–C bonds in PE [72].

(B) Lipases and esterases

Lipases are extracellular triacylglycerol hydrolases that cleave the ester bonds of insoluble tri-, di-, and monoglyceride substrates to yield free fatty acids and glycerol [73]. Esterases (hydrolases) produced by bacteria, yeast, and fungi are also involved in plastic degradation. *Comamonas acidovorans* esterase has been shown to support the degradation of PU and polylactic acid polymers of both high and low molecular weights [74].

The lipase (triacylglycerol hydrolase) synthesized by the yeast *Pichia pastoris* alters the surface conformation of polyester fibers at 60°C and within a pH range of 7.5–8.0. *Pichia pastoris* lipase, in combination with fatty alcohol polyoxyethylene ether, has been used to treat PET fibers to increase the number of hydrophilic groups on their surface, thereby facilitating faster degradation [75]. Fungal strains such as *Purpureocillium lilacinum* and *Curvularia senegalensis* have been reported to degrade poly (butylene succinate-co-adipate) and polyurethane, respectively [45,76].

Lipase from *Rhizopus delemar* (endo-cleavage type) degrades polyester-type polyurethanes (ES-PU) composed of diphenylmethane-4,4'-diisocyanate and 1,4-tetramethylenediol, among other components. It has been suggested that the presence of aromatic rings within ES-PU chains influences their biodegradability [68]. Enzymes exhibiting esterase and urethane hydrolase activities from fungi such as *Chaetomium globosum* and *A. terreus* have demonstrated increased esterase activity upon the addition of liquid polyester polyurethanes to the culture medium [77].

As described earlier, lipase from *P. pastoris* promotes the rapid degradation of PET fibers through increased surface hydrophilicity [75]. Additionally, lipase from *Aspergillus oryzae*, induced by bis(2-hydroxyethyl) terephthalate, catalyzes PET hydrolysis. Experimental results have shown that at 55°C, after 24 hours of incubation, PET exhibits altered properties, including slight weight loss, increased hydrophilicity, decreased water contact angle, and reduced half-life [78].

(C) Cutinase

Cutinases are extracellular serine esterases that are classified into one bacterial and two fungal subfamilies [79]. These subfamilies differ in their structural features depending on whether they originate from prokaryotic or eukaryotic organisms [80]. Cutinases are multifunctional enzymes with diverse commercial applications due to their ability to catalyze hydrolysis, esterification, and transesterification reactions. These properties make them useful for modifying synthetic fibers and degrading high-molecular-weight polyesters [81].

Cutinase derived from the thermophilic fungus *Thielavia terrestris* has been reported to lyse polyurethanes, with maximal enzyme activity

observed after 96 hours of cultivation on 2% (w/v) wheat bran as a carbon source, supplemented with 0.1% (w/v) Tween [82].

Extensive studies have been conducted to identify effective strategies for managing plastic waste. However, it remains evident that no single microorganism or enzyme system is capable of completely degrading polyurethanes and other synthetic polymers. Furthermore, the fate of intermediate compounds generated during biodegradation is not fully understood, highlighting the need for deeper insights into the underlying molecular and biochemical pathways, as well as the integration of complementary or disruptive technologies [68].

3.4. Overview of Molecular Degradation

Molecular approaches have been widely applied in biodegradation studies, as they enable direct identification, isolation, and quantification of microorganisms within complex samples. Once biodegradation pathways are well characterized, organisms can be genetically modified to enhance the production and secretion of target enzymes. Genetic engineering can thus reduce the time required for biodegradation or increase the susceptibility of polymers to microbial attack. In addition, degradative enzymes from phylogenetically distant organisms can be combined within a single host through genetic modification, along with adjustments to regulatory mechanisms and enzyme properties. Advances in protein and metabolic engineering have further enabled the development of engineered strains with improved degradation efficiency and broader substrate specificity.

Hydrolysis of PET in natural environments remains challenging due to limited accessibility of its ester bonds. *Ideonella sakaiensis* 201-F6 is known to produce two key enzymes involved in PET degradation: PETase and MHETase [83]. The genes encoding these enzymes have been successfully cloned and expressed in *Escherichia coli* BL21 under the control of a constitutive promoter (J23106), enabling efficient PET degradation. In another approach, the curli system of *E. coli* was engineered to display BIND-PETase on the cell surface. This modified system was able to depolymerize 9.1% of highly crystalline post-consumer PET within 7 days under ambient conditions, demonstrating its potential for environmentally friendly plastic degradation [84].

However, DNA sequence analysis alone is insufficient to fully elucidate undeciphered biodegradation pathways or identify novel enzymes [85]. Complementary approaches such as metagenomics and transcriptomics have contributed significantly to the discovery of genes encoding enzymes with enhanced degradative capabilities. For instance, genome-wide transcriptomic analysis of strain AIIW2 identified genes associated with PET utilization [86]. Comparative analysis of mRNA expression in the presence and absence of PET revealed upregulation of carbon metabolism and cellular transport pathways, indicating active PET hydrolysis and assimilation. The identification of PET degradation products further supported these findings, and the associated genes were subsequently cloned to enhance PET utilization [86].

For large-scale plastic degradation, research must extend beyond individual genes, enzymes, and microbe–polymer interactions. The integration of bioinformatics tools with machine learning has enabled the development of predictive frameworks for identifying microorganisms and enzymes with enhanced degradation potential [87,88]. One such approach, the plastic enzymatic degradation framework, uses machine learning to identify patterns in protein sequences that predict their ability to degrade plastics. In parallel, curated databases have been developed to support biodegradation research. The Plastics Microbial Biodegradation Database (<http://pmbd.genome-mining.cn/home>) compiles information on 79 genes

and 949 microbe–polymer interactions derived from the literature [89]. Similarly, the Plastics-Active Enzyme Database (<https://www.pazy.eu>) contains enzymes with experimentally validated hydrolytic activity toward polymers, providing a reliable resource for biochemical and genetic studies while minimizing errors associated with genome and metagenome annotations [89].

4. EFFECTS OF ENVIRONMENTAL FACTORS ON BIODEGRADATION RATE OF POLYMERS

Polymers undergo physical and chemical changes when exposed to environmental factors such as moisture, heat, light, and microbial activity over extended periods. These processes lead to fragmentation into smaller particles, eventually forming microplastics, as well as cleavage into low-molecular-weight compounds. The rate of degradation depends both on the type of polymer and the surrounding environmental conditions. Therefore, assessing the biodegradability of plastics across different environments is essential.

Studies on petrochemical-based polymers have shown that degradation rates are generally lower in marine environments than in landfills [60,90]. This is often attributed to lower dissolved oxygen levels and reduced ambient temperatures in marine settings. However, some reports suggest that the average degradation rates of HDPE and LDPE may be slightly higher in marine environments than on land, although these differences are often statistically insignificant and subject to considerable uncertainty [91].

On land, exposure to sunlight can result in heat buildup, causing polymers to reach temperatures higher than the surrounding air and thereby accelerating degradation [3,92]. In landfill and industrial composting systems, temperatures can reach 80°C–100°C when sufficient oxygen and moisture are available for thermo-oxidative degradation and hydrolysis, significantly enhancing degradation rates [93]. For example, polylactic acid (PLA) undergoes ester hydrolysis under industrial composting conditions (around 60°C), whereas its degradation is considerably slower at lower temperatures [94]. As a result, under marine conditions where temperatures are much <60°C, PLA exhibits resistance comparable to that of conventional petrochemical-based polymers.

An important drawback of current studies is the assessment of polymer degradation based on percentage weight loss, since observed mass loss is frequently a consequence of leaching plasticizers, loss of micro-fragments, or mechanical degradation to microplastics. Assessments of degradation should be based on changes in percentage weight along with analysis of changes in chemical bonds and product mineralization. These can be studied and confirmed using various analytical techniques, for example, high-temperature gel chromatography, Fourier transform infrared spectroscopy, thermogravimetric analysis, gel permeation chromatography, and gas chromatography-mass spectrometry [32,37,95]. Scanning electron microscopy may be used to reconfirm visual degradation of plastic polymers. Enzyme accessibility, retarded enzyme efficiency, toxicity of additives, and bioavailability of the pollutants/degradation products also affect the outcome of these techniques, warranting further innovations [50,95].

5. VALORIZATION OF PLASTIC WASTE FOR ITS MANAGEMENT AND SOCIETAL WELFARE

The selection of an appropriate plastic valorization process depends on several factors, including the type of plastic, its physical state, the desired end products, and the available infrastructure. Plastic valorization often described as “valuing plastic” involves the responsible management and recycling of plastic waste to maximize

social and environmental benefits. It encompasses strategies aimed at improving resource efficiency, reducing plastic pollution, and supporting sustainable development.

Recycling plastic waste plays a central role in establishing a circular economy, in which new plastic products are generated from existing materials, thereby reducing the demand for virgin polymers. This process involves the collection, sorting, and processing of plastic waste. In addition to mitigating environmental pollution, recycling contributes to resource conservation and job creation through the development of recycling facilities and associated industries.

Educational initiatives are also essential for enhancing public awareness of recycling practices, discouraging the use of single-use plastics, and promoting the benefits of plastic valorization. Such efforts empower communities to make informed decisions and actively participate in reducing plastic waste. Furthermore, increased investment in research and development can support the growth of environmentally sustainable plastic technologies, contributing to long-term economic development.

Support from organizations and institutions is equally important in promoting sustainable practices, generating employment opportunities, and fostering skill development, particularly in underdeveloped communities. These efforts contribute to inclusive local economic growth. However, the effectiveness of such strategies depends on the implementation of robust regulatory frameworks. Strong policies are required to establish standards for eco-friendly packaging, enforce extended producer responsibility programs, and discourage the use of single-use plastics through appropriate taxation measures.

5.1. Plastic Waste to Fuels

Plastic waste can be converted into fuels, offering a dual benefit of reducing environmental pollution while generating value-added energy resources [96–98]. Polyolefins can be transformed into clean fuels such as naphtha, a mixture of hydrocarbons, as well as other useful chemical products [96,97]. Several strategies have been developed for fuel production from plastic waste, including (a) gasification to generate gaseous streams for energy production or chemical synthesis, (b) pyrolysis to produce hydrogen and liquid fuels, and (c) integration of plastic-derived intermediates into existing refinery processes [98].

Waste plastic fuel (WPF) has been successfully produced through the pyrolysis of HDPE. In one study, WPF was blended in different ratios with 10% ethoxy ethyl acetate and 10% ethanol to form quaternary fuel mixtures, which were subsequently evaluated for performance [99]. Advances in such approaches can enable efficient energy recovery from plastic waste and support the use of WPF as an alternative energy source. This has the potential to contribute to future energy demands, reduce carbon emissions, and promote the development of a circular economy.

5.2. Application of Plastic Wastes in Construction Materials

PET, owing to its high tensile strength and low water absorption capacity, can be recycled into fibers for use in construction materials such as concrete and asphalt [100,101]. The production of partition blocks also utilizes waste materials, including PET flakes, tire dust, and bagasse from the sugar industry, representing an effective waste management approach adopted by various industries.

Plastics with high recyclability, such as HDPE and PP, are rigid in nature and are widely used in the manufacture of plastic lumber, tables, chairs, and other furniture. In contrast, LDPE, which is more flexible, is commonly incorporated into bricks and blocks. PS, although hard and brittle, is suitable for producing insulation materials. PVC, due to its hardness and rigidity, is often used as an aggregate in cement-based

composites. PET, being both strong and moderately flexible, finds secondary applications as reinforcing fibers in cementitious materials.

5.3. Depolymerization of Plastics

Depolymerization of plastic waste is an effective valorization strategy for producing reusable chemical building blocks. This process can be achieved through chemolysis, which is often highly selective and requires relatively lower energy input [102]. Depolymerization has emerged as a major area of research, driven by the need for innovative technologies to reduce the economic burden of plastic recycling [103].

Efficient and selective depolymerization requires carefully optimized reaction conditions, with an emphasis on environmentally sustainable (“green”) and cost-effective methodologies. Addressing the inherent chemical inertness of many plastic polymers remains a key challenge. It is also important to note that plastics derived from biomass are not necessarily biodegradable, particularly when their chemical structures resemble those of petroleum-based polymers [104,105]. For effective depolymerization at lower operating temperatures, polymers should ideally undergo low-exergonic polymerization [106]. Consequently, polymers such as polycarbonates and polyesters are more readily depolymerized than polyolefins [107].

5.4. Applications in the Food Industry for Packaging Materials

Materials such as glass, paper, plastics, and metals are widely used in the food packaging industry, where properties such as tensile strength, durability, flexibility, and overall mechanical performance are critical for ensuring food safety and preservation [108]. Synthetic petrochemical-based polymers, including PET, PE, PS, PP, and PVC, are commonly used for packaging applications [109].

These materials are cost-effective and provide excellent barriers against oxygen, thereby preventing rancidity and preserving aroma compounds. They also exhibit high tensile strength, are lightweight, and can be easily molded into various shapes, including transparent or colored forms, making them highly suitable for packaging [110]. However, there is a growing need for improved source-separation technologies to enhance recycling efficiency, along with innovative product design strategies to develop more sustainable packaging solutions.

5.5. Management and Valorization of Non-Homogeneous, Non-Recyclable Plastic Waste

The efficient separation of polymers such as acrylonitrile butadiene styrene, PS, PVC, and PP, particularly when present in complex mixtures, can be improved through advanced technological approaches. For example, the addition of materials such as sawdust to PE waste has been shown to facilitate separation. Similarly, blending waste polyolefins with compatibilizers such as Fusabond and Orevac can significantly improve the mechanical properties of resulting composites.

Mechanical processing often generates substantial quantities of mixed, non-homogeneous plastic waste, commonly referred to as “Plasmix” (notably in Italy), with compositions that vary across regions and municipalities. These heterogeneous materials can be utilized as secondary solid fuels in cement plants or incinerators, or as partial substitutes for coal in cement kilns. However, examples of effective valorization of such mixed waste streams remain limited.

Recent innovations include the production of adhesive materials by combining wood shavings with Plasmix (VGM Patent, 2018), as well as efforts by COREPLA and ENI to generate hydrogen from Plasmix (2019). Additionally, initiatives by companies such as Revet Recycling

and R3direct have explored the potential of converting such materials into feedstock for 3D printing applications.

6. CONCLUSION

Research on the biodegradation of polymers made from petroleum has been a ground-breaking effort to reduce environmental plastic pollution. The microorganisms and enzymes claimed to break down these synthetic polymers have been discussed here. Numerous *Pseudomonas* and *Bacillus* spp. have been shown to partially break down a variety of petroleum-based plastics as well as complicated, resistant substances such as polyaromatic hydrocarbons. Additionally, it has been discovered that the intestinal microorganisms of flies can depolymerize PE, PS, and PVC polymers. While enzymes that efficiently depolymerize the above polymers have not yet been characterized, the enzymes that are directly linked to the depolymerization of PET have been identified and subjected to extensive research. A deeper knowledge of the underlying molecular mechanisms of biodegradation may result from additional studies of the genes and/or gene products (enzymes) that hydrolyze the high molecular weight polymers used for making plastic polymers. Further research on the digestive enzymes found in polymer-degrading invertebrates and their gut microorganisms specifically for persistent non-hydrolysable polymers may be explored for plastic degradation. Based on this information, genetic engineering techniques to produce recombinant microbial strains and/or enzymes may be used as the preferable option to accelerate the biodegradation of synthetic petroleum-based plastic waste. Apart from suitable degradation strategies, optimized recycling and valorization of homogeneous and heterogeneous plastic polymer waste were studied, and innovations have been made in this direction. Novel insights into such strategies may help in suitable management and amelioration of plastic waste.

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8. AUTHOR CONTRIBUTIONS

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This study does not involve experiments on animals or human subjects.

12. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

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14. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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