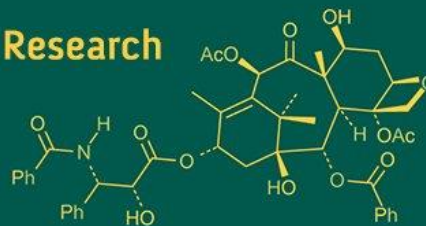


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Bacterial biodegradation of plastics: Current advances, mechanisms and future prospects

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Abstract

The increasing accumulation of plastic waste has become a major global environmental concern due to the widespread use of synthetic polymers and their resistance to natural degradation processes. Various conventional plastics remain in ecosystems for long periods, causing harmful effects on environment quality and human health. In response to this challenge, bacterial biodegradation has emerged as a sustainable and environment friendly approach for plastic waste remediation. This review discusses the key stages of bacterial plastic degradation, including mechanism of surface colonization, biofilm formation, polymer degradation, assimilation of degradation products and final mineralization into simpler compounds. Numerous bacterial and fungal genera have shown the ability to degrade different plastic materials by producing specific extracellular enzymes. Notably, the discovery of *Ideonella sakaiensis* and its PET-degrading enzymes, PETase and MHETase, has marked a significant advance in the biological recycling of polyethylene terephthalate (PET). Furthermore, developments in genomics, metagenomics, protein engineering, synthetic biology and engineered microbial consortia have improved the efficiency of microbial plastic degradation. However, several factors still limit degradation efficiency on commercial scale. Therefore, future research should focus on bacterial biodegradation as it offers great potential for managing plastic waste and minimizing its environmental impact.

Keywords: Synthetic plastics, bacterial biodegradation, plastic pollution

Introduction

Plastics are among the most widely used materials in modern society because of their versatility and numerous practical applications. Their affordability, durability, lightweight properties, mechanical strength and water resistance have contributed to their diverse use across industries. Nevertheless, rapid increase in plastic production and consumption has led to severe environmental pollution in both natural and anthropogenic ecosystems. The accumulation of plastic waste poses significant threats to environmental sustainability and human health [2, 54, 48, 26]. The widespread presence of these polymers in aquatic systems, agricultural soils and waste disposal sites has become a growing global concern. Although plastics offer many advantages over conventional materials, their resistance to degradation remains a major environmental challenge, as their long-chain polymeric structures can remain in the environment for hundreds of years before breaking down naturally [17].

Plastics as a global threat

Plastic waste has emerged as one of the most concerned environmental issues worldwide, driven by the continuous increase in plastic production. Global plastic production was estimated at around 311 million tonnes in 2014 [44]. Approximately 80% of the plastics consumed globally consist of synthetic polymers such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU) and PET. In addition, some less commonly used polymers, including polyethylene succinate (PES), polyethylene glycol (PEG), and polyvinyl alcohol (PVA), contain comparatively more hydrolysable functional groups. Among these materials, PET is particularly resistant to biodegradation and may remain in the environment for extended periods before being completely degraded by microorganisms. As a result, PET waste is accumulating at an alarming rate and increasingly posing threat to ecosystems worldwide [50].

While synthetic polymers and PET are often considered relatively non-toxic, their fragmented forms, including microplastics and larger plastic particles, are highly durable and widely found in both terrestrial and aquatic habitats. These particles can accumulate in living organisms and may carry potentially harmful additives, pigments and other chemical contaminants. Plastic pollution has become especially serious in marine environments, where plastics are easily transported and incorporated into food system. The movement of these materials into animal and human food chain has been linked to several adverse health outcomes, including immune-related disorders, congenital abnormalities and an elevated risk of cancer [39].

Degradation of Plastic Wastes

Plastic waste can be degraded through a combination of abiotic (physicochemical) and biotic (microbial) processes. The degradation pathway typically begins with the physical breakdown of plastic materials into smaller fragments [20, 29, 6, 10]. Researchers have identified four principal mechanisms involved in plastic degradation i.e., photodegradation, hydrolysis, thermo-oxidative degradation and biodegradation. In natural environments, plastics such as high-density polyethylene (HDPE), low-density polyethylene (LDPE) and PP initially undergo degradation due to exposure to ultraviolet (UV) radiation, followed by thermo-oxidative and hydrolytic reactions. These processes reduce the molecular weight of the polymers and produce smaller fragments that are more susceptible to microbial colonization and degradation. However, despite the occurrence of these degradation mechanisms, the complete mineralization of conventional plastics are extremely slow and can take several decades under natural environmental conditions [10, 59].

Factors affecting the degradation rate of plastics

Degradation of synthetic plastic polymers are controlled by the polymer's characteristic features and exposure to various abiotic and biotic factors [11], as shown in Fig. 1.

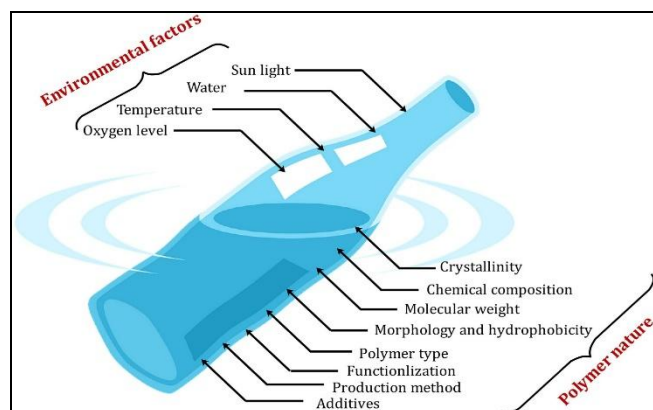


Fig 1: Factors affecting degradation of plastics [67].

Biodegradation

The biodegradation of complex, natural and synthetic substances is typically achieved more effectively by microbial consortia than by individual microbial strains, largely due to the restricted metabolic capabilities of single microorganisms. Consequently, microbial communities are considered as potential agents for the degradation of plastic waste, which represents one of the major concerned environmental challenges of modern times. Although the

application of microbial consortia in plastic degradation has received relatively limited attention, their effectiveness in the biodegradation of hydrocarbons and other xenobiotic compounds has been well documented. Yu *et al.*, reported that microorganisms operating within a consortium often exhibit superior biodegradation performance compared to individual strains, either through direct participation in degradation processes or by detoxifying harmful intermediate products formed during degradation [63]. Moreover, interactions among consortium members, such as metabolic cross-feeding and the production of metabolites that support co-metabolic degradation, can further improve the overall efficacy of biodegradation [23].

Plastic biodegradation primarily involves conversion of polymeric materials into biogas and biomass, in the absence of air, by anaerobic microbes that can efficiently utilize polymers as a carbon source for their growth and multiplication [3, 4, 33, 45]. Various synthetic polymers, including PE, PP, PS, PVC, PU and PET, have been widely used as an important commodity for human life. However, the intrinsic properties of plastics as well as their unique physicochemical properties limit their biodegradability, making them a weak growth substrate for microbes [6, 16]. In terms of plastic biodegradation, several studies have mainly focused on the isolation of individual microorganisms with degradative capability; however, they indicate that bacterial and fungal consortia have great potential in plastic waste biodegradation and bioremediation. The biodegradation of polyester polyurethane (PSPU) and polyacrylic polymers is more efficient in the presence of microbial communities than by single strains or individual community members [56]. Similarly, Gaytán *et al.*, reported the effectiveness of bacterial consortium for the degradation of a PU-acrylate copolymer. On the other hand, the deterioration of PSPU coupons by fungal compost consortia was also reported significant [19, 64]. However, it remains unclear whether the fungal strains perform the degradation individually or as a part of fungal consortium. Moreover, microbial consortia from various environments for plastic degradation, such as PE, PP, PS, polycaprolactone (PCL) and weathered polyethylene (WPE) have been investigated [6, 37, 49, 52, 53].

Plastic waste biodegradation initiates via the enzymatic fractionation of the polymeric chain into low-MW compounds such as oligomers, dimers, and monomers, which takes place by enzyme binding to the polymer and catalysis of its hydrolytic cleavage. The process finally progresses to the mineralization of these low-MW compounds into CO₂ and H₂O. Bacteria, fungi and algae have been reported as effective polymer-degrading microbes and are capable of degrading polymers, such as PE + and PU [6].

Role of microbes in plastic degradation

Numerous microorganisms have been reported for their plastic biodegradation potential. Some of these strains include *Aspergillus*, *Streptococcus*, *Bacillus*, *Penicillium*, *Staphylococcus*, *Pseudomonas*, *Streptomyces* and *Moraxella* [1]. Our literature survey has indeed shown that bacterial strains such as *Pseudomonas* spp., *Bacillus* spp. and *Streptomyces* spp. have exhibited high degradation efficiency against various plastic polymers [30, 34]. The available evidence suggests that the contribution of bacteria to plastic biodegradation require further investigations,

particularly to identify promising bacterial species and to evaluate the effectiveness of microbial consortia in degrading plastic waste. While fungal strains have been shown to exhibit greater plastic degradation, efficiencies compared to bacteria [35], bacterial systems offer several practical advantages. Bacteria are generally easier to culture, adapt more readily to diverse environmental conditions and are capable of degrading a variety of polymeric substrates. In contrast, fungal degradation processes often depend on more stable environmental conditions [14].

Recently, the strain of the microorganism *Ideonella sakaiensis* 201-F6 was discovered, which grows on low-crystallinity PET films [39]. *I. sakaiensis* produces particular enzymes, including mono (2-hydroxyethyl) terephthalic acid hydrolase (MHETase) and PET hydrolase (PETase) to

hydrolyze PET into ethylene glycol (EG) and terephthalic acid (TPA) monomers, which are then further metabolized. These enzymes have drawn international interest because they can be used for the bioconversion of PET. For constructing PETase and MHETase strains, a targeted gene disruption system has been developing *Ideonella*. Disrupting growth revealed that for the degradation of PET, PETase is the single enzyme for degradation in the bacteria, while MHETase and PETase play important roles in the assimilation of PET. *Ideonella sakaiensis* is a non-spore-forming, gram-negative, rod-shaped, aerobic bacterium that belongs to the class Betaproteobacteria. The optimal growth conditions are a pH 7 to 7.5 and temperature 30 to 37 °C. As *I. sakaiensis* grows only under mild conditions, the stability of *I. sakaiensis* PETase (IsPETase) is relatively low [25].

Table 1: Bacterial Degradation Efficiency on Different Synthetic Plastic Polymers

Bacterial Species	Plastic Polymer	Isolation Source	Incubation Time	Degradation Efficiency/Remarks	Reference
<i>Arthrobacter</i> sp. GMB5	Polyethylene (PE)	Dumpsites	30 days	12-15% reduction in plastic weight	Balasubramanian <i>et al.</i> (2010) [15]
<i>Pseudomonas</i> sp. GMB7	Polyethylene (PE)	Dumpsites	30 days	12-15% reduction in plastic weight	Balasubramanian <i>et al.</i> (2010) [15]
<i>Serratia marcescens</i>	Polyethylene (PE)	Soil	70 days	36% weight loss of PE	Azeko <i>et al.</i> (2015) [13]
<i>Streptomyces</i> spp.	Polyethylene (PE)	Soil	180 days	46.7% reduction in PE weight	Deepika and Jaya (2015) [18]
<i>Pseudomonas</i> spp.	Polyethylene (PE)	Soil	180 days	24.2% reduction in PE weight	Deepika and Jaya (2015) [18]
<i>Enterobacter</i> sp.	LDPE	Soil	120 days	Up to 81% reduction in weight	Skariyachan <i>et al.</i> (2018) [49]
<i>Pantoea</i> sp.	LDPE	Soil	120 days	Up to 38% reduction in weight	Skariyachan <i>et al.</i> (2018) [49]
<i>Pseudomonas</i> spp.	Polyethylene (PE)	Water and Soil	90 days	35-40% weight reduction; extracellular lipase production	Skariyachan <i>et al.</i> (2018) [49]
<i>Brevibacillus borstelensis</i>	Polyethylene (PE)	Coastal regions	30 days	11.4% weight reduction	Mohanrasu <i>et al.</i> (2018) [36]
<i>Microbulbifer hydrolyticus</i> IRE-31	Polyethylene (PE)	Marine pulp mill wastes	30 days	Surface morphological changes and ketone group formation	Li <i>et al.</i> (2020) [30]
<i>Bacillus subtilis</i>	Polyurethane (PU)	Soil	20 days	60.6% weight reduction; esterase activity detected	Shah <i>et al.</i> (2016) [46]
<i>Pseudomonas aeruginosa</i>	Polyurethane (PU)	Soil	20 days	Significant PU degradation and esterase production	Shah <i>et al.</i> (2016) [46]
<i>Brevibacillus</i> spp.	Polyurethane (PU)	Sewage treatment plants and landfills	140 days	37.2-45.7% weight loss	Skariyachan <i>et al.</i> (2018) [49]
<i>Aneurinibacillus</i> spp.	Polyurethane (PU)	Sewage treatment plants and landfills	140 days	37.2-45.7% weight loss	Skariyachan <i>et al.</i> (2018) [49]
<i>Bacillus</i> sp.	Polyurethane (PU)	Soil	28 days	Hydrolysis zones and CO ₂ release observed	Shah <i>et al.</i> (2008) [45]
<i>Pseudomonas</i> sp.	Polyurethane (PU)	Soil	28 days	Hydrolysis zones and CO ₂ release observed	Shah <i>et al.</i> (2008) [45]
<i>Micrococcus</i> sp.	Polyurethane (PU)	Soil	28 days	Hydrolysis activity observed	Shah <i>et al.</i> (2008) [45]
<i>Arthrobacter</i> sp.	Polyurethane (PU)	Soil	28 days	Hydrolysis activity observed	Shah <i>et al.</i> (2008) [45]
<i>Corynebacterium</i> sp.	Polyurethane (PU)	Soil	28 days	Hydrolysis activity observed	Shah <i>et al.</i> (2008) [45]
<i>Corynebacterium</i> sp. B12	Polyurethane (PU)	Soil	84 days	1.2-17.7% weight loss	Kay <i>et al.</i> (1991) [28]
<i>Pseudomonas aeruginosa</i>	Polyurethane (PU)	Soil	84 days	1.2-17.7% weight loss	Kay <i>et al.</i> (1991) [28]
<i>Pseudomonas denitrificans</i>	Polyurethane (PU)	Soil	150 days	Poly(ether urethane) degradation	Stepien <i>et al.</i> (2017) [51]
<i>Pseudomonas fluorescens</i>	Polyurethane (PU)	Soil	150 days	High degradative activity	Stepien <i>et al.</i> (2017) [51]
<i>Bacillus subtilis</i>	Polyurethane (PU)	Soil	150 days	Highest degradative activity	Stepien <i>et al.</i> (2017) [51]
<i>Saccharomonospora viridis</i>	PET	NA	3 days	Cut190 enzyme degraded 27% PET	Kawai <i>et al.</i> (2014) [27]
<i>Thermobifida fusca</i>	PET	NA	5 days	TfCut2 cutinase degraded 97% PET	Wei <i>et al.</i> (2019a) [58]
<i>Ideonella sakaiensis</i>	PET	Standard strain	18 h	PETase and MHETase degraded PET into monomers	Yoshida <i>et al.</i> (2016) [60]
<i>Ideonella sakaiensis</i>	PET	NA	1 day	PETase caused 1% PET weight loss	Wei <i>et al.</i> (2019a, b) [58, 59]
<i>Vibrio</i> sp.	PET	Seawater	42 days	35% reduction in PET weight	Sarkhel <i>et al.</i> (2020) [42]
<i>Thermobifida fusca</i>	PET	Soil	55 °C Temp.	50% decrease in average mol. weight of polymer for 3 weeks	Atanasova <i>et al.</i> (2021) [12]
<i>Arthrobacter</i> sp. GMB5	Polyethylene (PE)	Dumpsites	30 days	12-15% reduction in plastic weight	Balasubramanian <i>et al.</i> (2010) [15]
<i>Pseudomonas</i> sp. GMB7	Polyethylene (PE)	Dumpsites	30 days	12-15% reduction in plastic weight	Balasubramanian <i>et al.</i> (2010) [15]
<i>Serratia marcescens</i>	Polyethylene (PE)	Soil	70 days	36% weight loss of PE	Azeko <i>et al.</i> (2015) [13]
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Biodegradation mechanism of synthetic plastic polymers

Microbial degradation of plastics proceeds through four main stages: colonization, bio fragmentation, assimilation and mineralization. The first stage, colonization, involves the attachment of microorganisms, either individually or as part of a microbial consortium, to the plastic surface, leading to biofilm formation and the initiation of polymer deterioration ^[41]. This process can be examined using various microscopic techniques, including electron, photonic and polarization microscopy. Microbial attachment is supported by the secretion of extracellular substances such as polysaccharides and hydrophobin proteins, which help in the establishment of microbial communities on plastic surfaces ^[43].

Following colonization, these extracellular compounds enter the polymer matrix, change pore structures and modify the surface morphology of the plastic material ^[21]. Such changes decrease the stability and durability of the polymer while increasing the surface available for microbial activity. The extracellular slime produced by microorganisms also

encourages the accumulation of nutrients and pollutants, thereby supporting microbial growth and speeding up the biodeterioration process ^[65]. This emphasizes the important role of extracellular enzymes and microbial secretions in facilitating plastic biodegradation.

Furthermore, chemoorganotrophic microorganisms contribute to biodeterioration by secreting organic acids such as oxalic, gluconic, citric and glyoxylic acids ^[24]. Similarly, chemo lithotrophic bacteria, including *Nitrobacter* spp. and *Thiobacillus* spp., produce strong compounds such as nitric acid and sulfuric acid, which further promote polymer deterioration ^[38]. These metabolic activities can change the pH of the surrounding environment, increasing surface erosion and promoting degradation ^[32]. Consequently, microbial consortia are generally considered more effective in promoting biodeterioration than individual microbial species due to their broader metabolic capabilities and synergistic interactions.

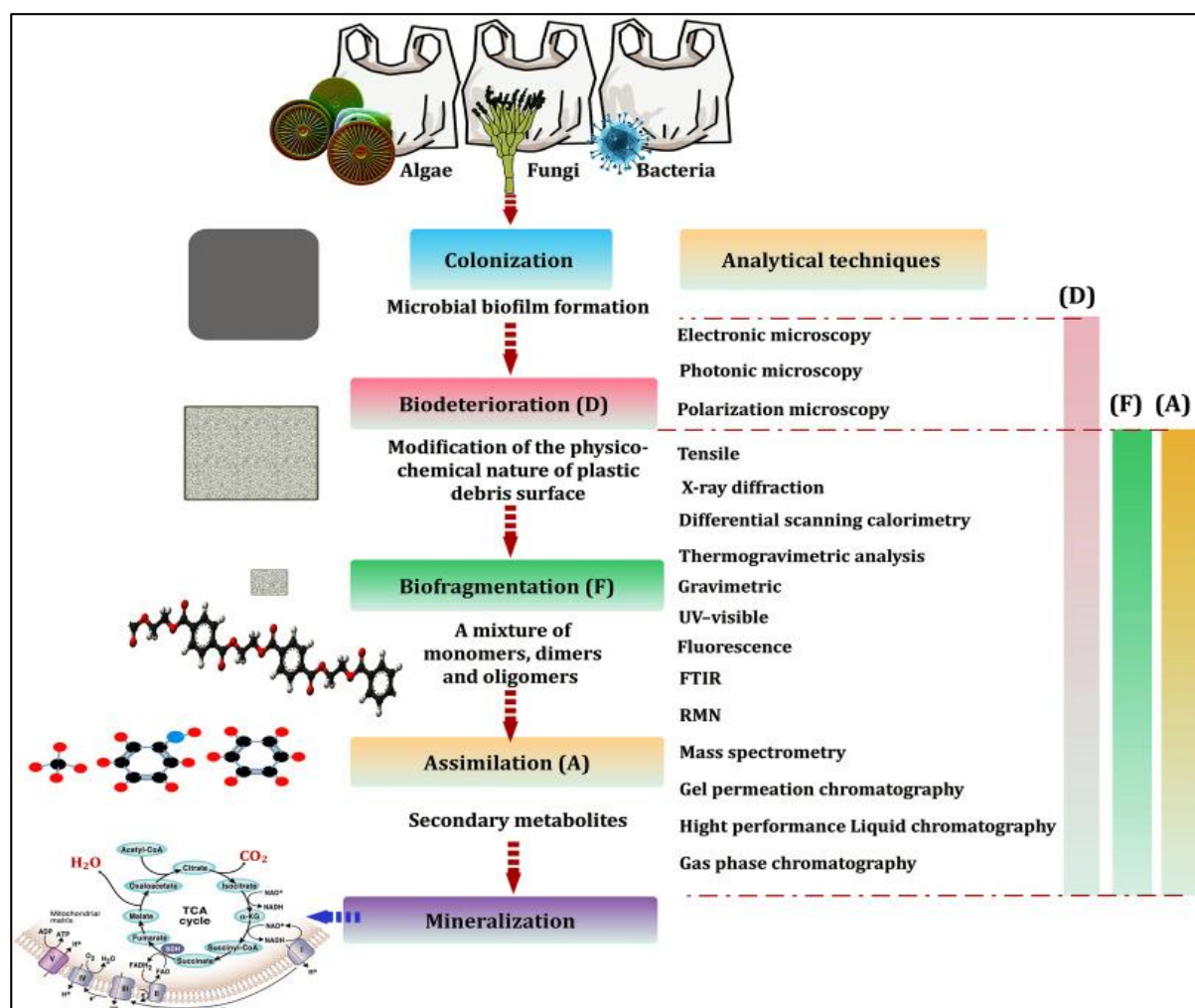


Fig 2: The biodegradation stages of a plastic material and the analytical techniques used to detect each stage's potential ^[41].

During the biofragmentation stage, plastic polymers are broken down into smaller fragments by enzymes such as hydrolases, oxidoreductases, depolymerases, peroxidases and oxidases. Since the chemical bonds in synthetic polymers are similar to those found in lignocellulosic materials, lignocellulose-degrading enzymes may also assist in plastic degradation ^[5, 9]. Hydrolysis and oxidative make the polymer more susceptible to microbial attack by

introducing functional groups and generating free radicals that facilitate chain cleavage. However, the degradation of linear polymers is often restricted because enzymes cannot easily reach the inner portions of polymer chains ^[31, 40]. Biofragmentation can be evaluated through techniques such as X-ray diffraction (XRD), differential scanning calorimetry (DSC), fluorescence spectroscopy and tensile strength analysis.

The assimilation stage involves the uptake and utilization of monomers and other small molecular compounds produced during the biofragmentation of plastics. These compounds serve as important sources of carbon and energy, supporting microbial growth and cellular metabolism. However, certain degradation products may not be readily transported across the microbial cell membrane. To overcome this limitation, microorganisms can modify these compounds through biotransformation, an enzymatic process that changes complex molecules into forms that are more easily utilized by the same organism or by other microorganisms within the community [8, 31]. The assimilation process can be assessed using analytical methods such as thermogravimetric analysis (TGA), UV-visible spectroscopy, fourier-transform infrared spectroscopy (FTIR) and high-performance liquid chromatography (HPLC).

After assimilation, the absorbed compounds undergo metabolic degradation through various catabolic pathways, including aerobic respiration, anaerobic respiration and fermentation [5, 8, 22]. The final phase of the biodegradation process is mineralization, where the organic intermediates are completely converted into simple inorganic end products such as carbon dioxide, water and mineral salts. The extent of mineralization can be measured using advanced analytical tools, including nuclear magnetic resonance spectroscopy (NMR), gel permeation chromatography (GPC), mass spectrometry (MS) and gas chromatography-mass spectrometry (GC-MS).

Current Advances

Recent developments in microbial biotechnology have greatly enhanced the prospects for plastic biodegradation by bacteria. A landmark discovery was the identification of the enzymes PETase and MHETase from *Ideonella sakaiensis*, which showed the ability to biologically convert polyethylene terephthalate (PET) into its monomeric components, terephthalic acid and ethylene glycol [62]. Subsequent studies employing structure-based protein engineering have improved the catalytic activity and thermal stability of PETase, leading to the development of enzyme variants with enhanced PET-degrading performance [25, 47]. In addition, genomic and metagenomic technologies have supported the discovery of new plastic-degrading microorganisms and enzymes from a variety of terrestrial and marine habitats, thereby broadening the range of biological tools available for plastic waste treatment. Another significant advancement was achieved by Alain Tournier and colleagues, who engineered a PET depolymerase capable of degrading more than 90% of PET waste within a relatively short period, demonstrating the feasibility of enzyme-based recycling approaches [55]. Furthermore, progress in synthetic biology, metabolic engineering and the design of microbial consortia is facilitating the creation of highly efficient biodegradation systems considerable strong industrial potential. Together, these innovations promote the integration of biological recycling technologies into sustainable waste management and circular economy initiatives.

Future prospects

Plastic pollution, due to plastic waste accumulation, is of major environmental concern worldwide. The problem of polymers biodegradation lies in their own nature that

hinders the polymer breakdown into monomers. In fact, microbial enzyme systems are useless against non-hydrolyzable synthetic polymers. The occurrence and activity of polymer-degrading depend on the prevailing environmental conditions. Therefore, the recommendations from this review are summarized as follows:

1. The biodegradation process and its influencing factors require further investigation to evaluate the ability of other microorganisms to degrade polymeric materials and to identify their enzymatic degradation mechanisms.
2. The use of molecular techniques is essential for identifying the most effective polymer-degrading microorganisms are to be identified. In this view, research should focus on the fields of proteomics and genomics.
3. The application of nanotechnology in plastics manufacturing may help address the limitation of plastic biodegradation and improve bioremediation.
4. It is critical to balance the aim of reducing plastic packaging waste with reducing food waste as well as to increase the use of agricultural and horticultural waste as a source of natural fibres and as a raw material for biopolymer production.
5. Biomass-based biopolymers such as poly (lactic acid), polyhydroxyalkanoates, and thermoplastic starch show considerable potential, particularly for packaging and other single-use applications. However, their promotion as a more environmentally friendly alternative is not fully justified without the availability of effective industrial composting or anaerobic digestion facilities.

Conclusion

The rapid accumulation of plastic waste has become a major environmental concern of the twenty-first century due to the resistance of synthetic polymers to natural degradation and their long-term persistence in terrestrial and aquatic environments. Among the various remediation approaches, bacterial biodegradation has gained significant attention as an eco-friendly and sustainable method for managing plastic pollution. This process relies on microbial enzymes to convert complex polymeric materials into simpler molecules that can be assimilated and metabolized. Several bacterial groups, including *Pseudomonas*, *Bacillus*, *Streptomyces*, *Thermobifida fusca*, *Arthrobacter*, and *Ideonella sakaiensis*, have shown the ability to degrade plastics such as polyethylene (PE), polyurethane (PU), and polyethylene terephthalate (PET). The identification of PETase and MHETase enzymes in *I. sakaiensis* has provided valuable insights into microbial plastic metabolism and has promoted the development of biological recycling technologies. However, several challenges remain, including high polymer crystallinity, hydrophobicity, restricted enzyme access, and environmental fluctuations, all of which reduce degradation efficiency under natural conditions. Advances in genomics, proteomics, metabolic engineering, synthetic biology, and microbial biotechnology are expected to enhance the performance of plastic-degrading microorganisms and microbial consortia. Future studies should focus on the discovery of potential microbes, novel enzymes, comprehensive characterization of degradation mechanisms, and the development of integrated biodegradation systems aligned with circular economy concepts. Such efforts could enable bacterial biodegradation

to become a practical and viable solution for sustainable plastic waste management and ultimately for the protection of environment.

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