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Bacterial Biodegradation of Plastics – Towards a Sustainable Solution to Plastic Pollution

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Abstract

The rapid expansion of plastic production and consumption, combined with limited recycling efficiency and the intrinsic resistance of most synthetic polymers to degradation, has resulted in the accumulation of plastic waste in terrestrial and marine ecosystems (Geyer et al., 2017; Lebreton & Andrady, 2019; PlasticsEurope, 2025). This persistent pollution poses serious environmental, ecological, and potential health risks. Conventional waste management strategies, including landfilling, incineration, and mechanical recycling, remain insufficient to address the scale of the problem and may generate secondary pollutants (Geyer *et al.*, 2017).

In this context, microbial biodegradation has emerged as a promising complementary strategy for mitigating plastic pollution. Certain bacterial taxa, notably species belonging to the genera *Pseudomonas*, *Bacillus*, and *Enterobacter* have demonstrated the ability to colonise plastic surfaces and promote polymer deterioration through enzymatic and oxidative processes (Shah *et al.*, 2008; Urbanek *et al.*, 2018). Although complete mineralisation of most petroleum-based plastics remains limited, significant progress has been made in understanding the mechanisms involved in surface modification, depolymerisation of ester-based plastics, and the role of biofilms in enhancing degradation efficiency (Danso *et al.*, 2019; Wei & Zimmermann, 2017).

This review provides a critical overview of bacterial plastic biodegradation, focusing on the types of plastics involved, the key bacterial species and enzymes reported in the literature, and the main limitations and future prospects of this emerging biotechnological approach.

Keywords: Plastic pollution; Biodegradation; Plastic-degrading bacteria; Biofilms; Enzymes; Bioremediation

1. Introduction

Plastic materials have become indispensable in modern society due to their durability, low cost, and versatility. However, these same properties have led to their accumulation in natural environments, where most synthetic polymers persist for decades or longer (Geyer et al., 2017; Lebreton & Andrady, 2019). Global plastic production has increased exponentially over the past decades, while recycling and recovery rates remain comparatively low, particularly in developing and emerging regions (PlasticsEurope, 2025). As a result, plastic waste has become a major environmental concern in terrestrial, freshwater, and marine ecosystems (Jacquin et al., 2019).

Biological degradation of plastics has attracted increasing scientific attention as a potential complementary strategy to conventional waste management approaches. Microorganisms, particularly bacteria, are capable of colonising plastic surfaces and inducing physicochemical changes through biofilm formation, oxidative reactions, and enzymatic activity (Shah *et al.*, 2008; Urbanek *et al.*, 2018). Although complete mineralisation of most petroleum-derived plastics is rare, microbial activity can contribute to polymer fragmentation and surface modification, thereby facilitating further degradation processes (Danso et al., 2019). Understanding these mechanisms is essential for assessing the realistic potential of bacterial biodegradation within environmental and biotechnological contexts.

Plastics have become indispensable materials in modern society due to their low cost, durability, versatility, and ease of manufacture. Since the mid-twentieth century, plastic production has increased exponentially, replacing traditional materials such as glass, metals, and natural fibres across industrial, medical, agricultural, and domestic sectors. However, these same properties have rendered plastics highly persistent in natural environments, where they may remain for decades or even centuries.

A substantial fraction of plastic waste accumulates in marine and coastal ecosystems, with approximately 80% originating from terrestrial sources. Although plastic pollution has gained considerable attention in marine research, its ecological consequences in terrestrial systems remain comparatively underexplored. The resistance of synthetic polymers to biological and chemical degradation has positioned plastic pollution among the most pervasive global environmental challenges.

Current mitigation strategies, including recycling and bans on certain single-use plastics, address only a limited proportion of total plastic waste. Consequently, alternative and complementary approaches are required. Microbial biodegradation, particularly by bacteria capable of colonising and modifying plastic surfaces, represents a promising avenue for reducing long-term plastic persistence. This review synthesises current knowledge on bacterial plastic biodegradation, emphasising mechanisms, representative bacterial taxa, enzymatic systems, and practical limitations.

2. Plastic Pollution and Types of Plastics

Plastics are man-made, high-molecular-weight organic polymers derived from non-renewable petrochemical resources such as crude oil, natural gas, and coal. They consist of repeating monomeric units linked by strong covalent bonds, most commonly carbon–carbon (C–C) backbones, which confer high chemical stability. Their widespread adoption since the mid-twentieth century has resulted in the replacement of traditional materials across industrial, medical, agricultural, and domestic sectors. The inherent resistance of most plastics to biological and chemical degradation has positioned plastic pollution among the most pervasive global environmental challenges (Geyer et al., 2017). Their properties, such as light weight, low production cost, ease of manufacturing, bio-inertia, and resistance to environmental influence and microbial action, contribute to plastics' extensive commercialization. Everyday plastic use has shown an exponentially increasing trend for production and consumption, reaching about 350 million tons in 2019. However, a sharp growth rate drop of 8.5% was registered in 2020 due to COVID-19. The production level before the COVID-19 pandemic in the EU_{27} will not be reached again until 2022. Employed in the European plastics industry are more than 1.56 million people in 55,000 companies with over 350 billion euros of turnover. As can be seen from Figure 1 (Atanasova et al., 2021), plastic producers are spread worldwide, the biggest contributors being Asia, Europe, and North America.

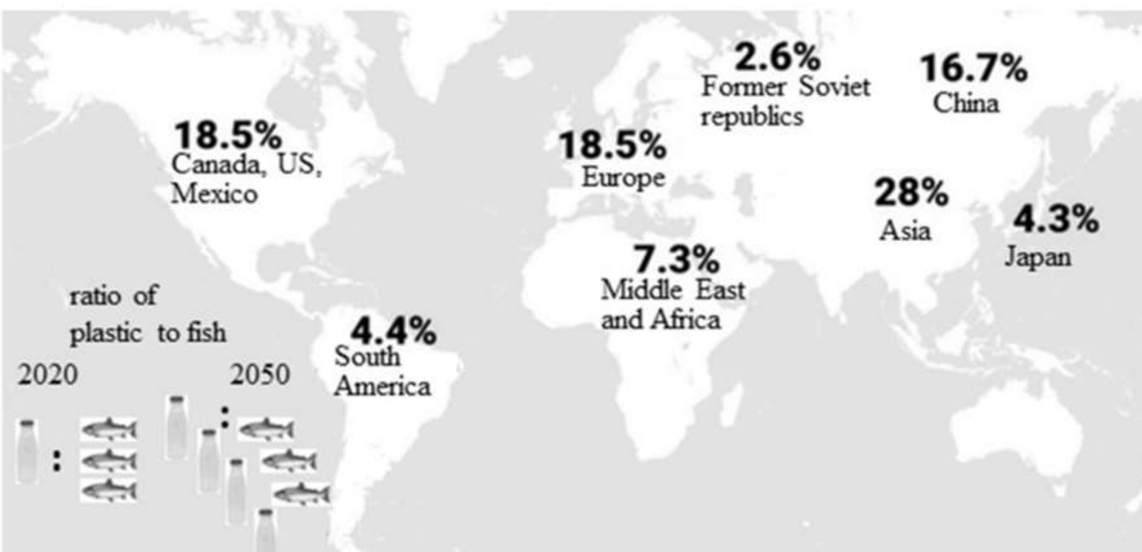

Figure1. Worldwide distribution of plastic producers (Atanasova et al., 2021).

The first synthetic polymer, Bakelite, was produced in the beginning of 20th century; the true mass production of plastics thrived from the 1950s onwards. Over that period, their properties have been continuously improved. The most widely used polymer materials are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), poly(ethylene terephthalate) (PET), poly(butylene terephthalate) (PBT) (Tokiwa et al., 2009). Currently, more than 5300 grades are produced for plastic commerce with a range of chemical additives including plasticizers, pigments, stabilizers, surfactants, and inorganic fillers. Plastics have a wide range of applications in the industries for food and packaging, pharmaceuticals, agriculture, cosmetics, detergents and chemicals, Figure 2. Synthetic plastics have taken an impressive position in the packaging sector as a replacer of cellulose-based wrapping materials and now account for around 40% of the plastics produced in Europe (PlasticsEurope, 2025).

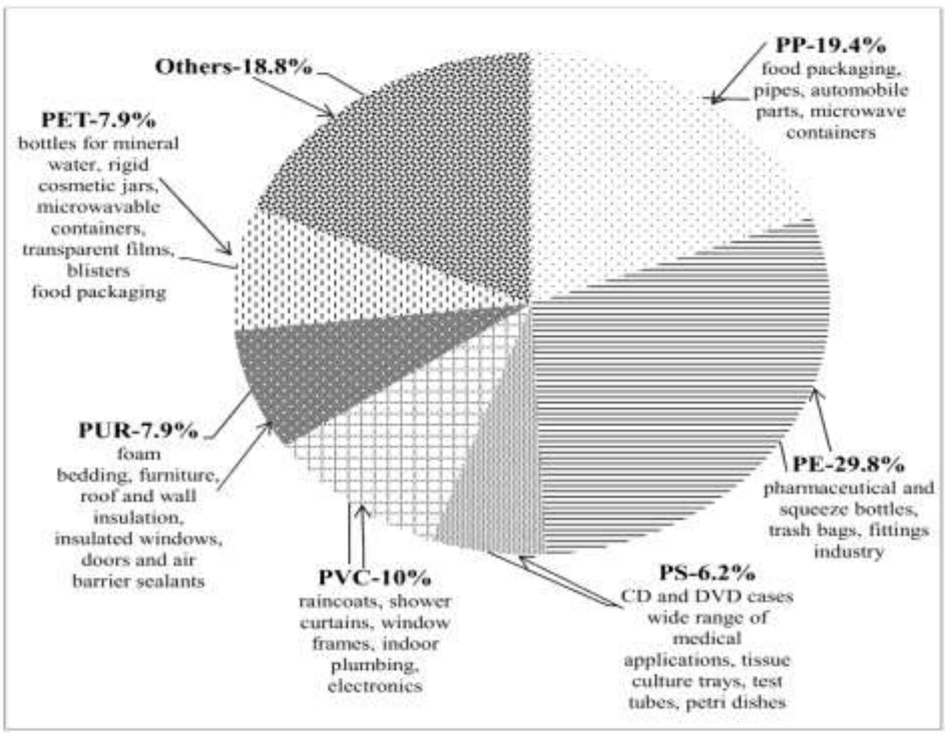

Figure2. Demand distribution and use of different plastics, (Atanasova et al., 2021).

3. Principles of Plastic Biodegradation

Bacterial biodegradation of plastics is a multi-step process that typically begins with the attachment of microbial cells to the polymer surface, followed by biofilm formation and extracellular enzymatic activity (Urbanek et al., 2018), Figure 3. The initial colonisation stage is critical, as biofilms enhance microbial persistence on hydrophobic plastic surfaces and create microenvironments conducive to enzymatic reactions

(Danso et al., 2019). Once established, bacteria secrete extracellular enzymes and oxidative agents that induce surface oxidation, chain scission, or hydrolysis of susceptible chemical bonds within the polymer.

The efficiency of biodegradation is strongly influenced by polymer properties, including molecular weight, crystallinity, hydrophobicity, and the presence of functional groups. Plastics containing hydrolysable ester bonds are generally more amenable to microbial attack than polymers composed exclusively of carbon–carbon backbones (Wei & Zimmermann, 2017). Environmental factors such as temperature, ultraviolet radiation, oxygen availability, and nutrient levels further modulate degradation rates and pathways.

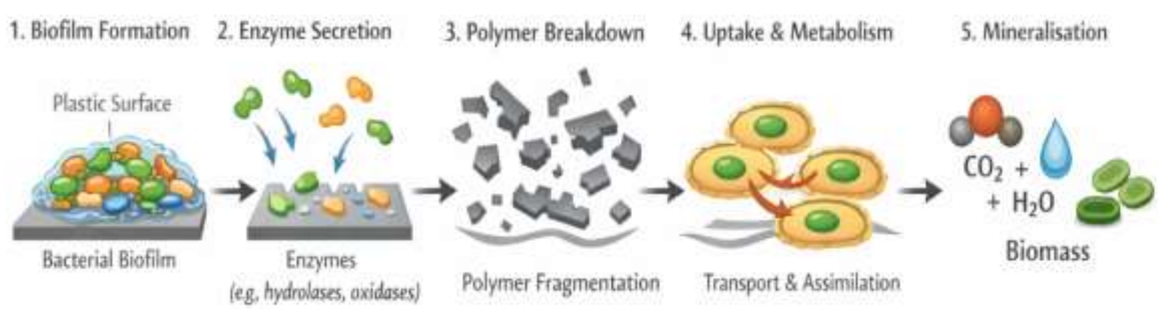

Figure 3. The outlined steps of bacterial degradation illustrate a generalised schematic of bacterial plastic biodegradation, highlighting the sequential steps from surface colonisation and biofilm development to enzymatic depolymerisation and microbial assimilation of degradation products. This image has been generated for this review using AI tools.

Biodegradation refers to the biological transformation of complex polymers into simpler chemical compounds through the activity of living organisms. In microbial plastic degradation, this process typically involves a consortium of microorganisms performing sequential roles. Primary degraders initiate surface modification and depolymerisation, while secondary degraders metabolise low-molecular-weight intermediates.

Plastic biodegradation is influenced by multiple factors, including polymer structure, molecular weight, crystallinity, surface area, and the presence of functional groups such as ester or amide bonds. Environmental conditions, including temperature, pH, oxygen availability, and ultraviolet radiation, also play a significant role. Importantly, most synthetic plastics cannot be directly internalised by microbial cells; instead, extracellular enzymes and oxidative processes are required to initiate degradation.

Biodegradation is generally described as a multi-step process involving surface colonisation, biofilm formation, enzymatic or oxidative polymer modification, fragmentation into oligomers or monomers, and eventual microbial assimilation and mineralisation.

4. Types of Plastics and Their Susceptibility to Biodegradation

The susceptibility of plastics to bacterial degradation varies widely depending on their chemical structure and physical properties, Figure 4. Ester-based polymers such as poly(ethylene terephthalate) (PET), polylactic acid (PLA), and certain polyurethanes exhibit relatively higher biodegradability due to the presence of hydrolysable bonds that can be targeted by microbial enzymes (Wei & Zimmermann, 2017; Yoshida et al., 2016). In contrast, polyolefins such as polyethylene (PE) and polypropylene (PP) are highly resistant to biodegradation owing to their chemically inert carbon–carbon backbone, high crystallinity, and hydrophobic nature (Shah et al., 2008; Danso et al., 2019).

Numerous studies have reported bacterial-induced changes in polyolefin materials, including surface oxidation, increased brittleness, and partial fragmentation. However, these effects should be interpreted as ageing or weathering processes rather than true biodegradation involving complete polymer breakdown and mineralisation.

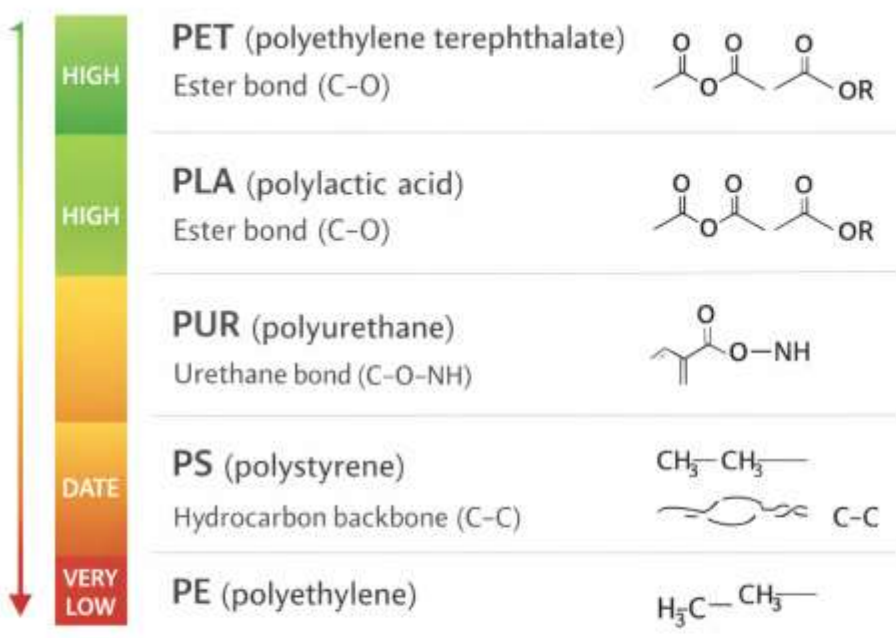

Figure 4 Comparative overview of the relative susceptibility of common plastics to bacterial degradation based on polymer chemistry and enzymatic accessibility. This image has been generated for this review using AI tools.

5. Plastics degrading bacteria

A wide range of bacterial taxa have been associated with plastic surface colonisation and degradation-related processes. These organisms are commonly isolated from plastic-contaminated soils, landfills, marine environments, and insect digestive systems (Ahmed et al., 2018).

Biodegradation is a cost-effective solution for plastic waste, using microorganisms to break down polymers into safer compounds through enzymatic action. The direct microbial degradation of carbon–carbon bonds is especially efficient, and many plastic-degrading bacterial strains have been identified, see Table 1.

Table 1. Ten (10) types of plastics degrading bacteria

(1) PET (Polyethylene Terephthalate): A strong, lightweight plastic commonly used for water and soda bottles. It's durable and has good resistance to moisture.
(2) PET/PS: A blend of PET and PS (Polystyrene), combining the clarity and strength of PET with the moldability of PS. It is often used in packaging.
(3) LDPE (Low-Density Polyethylene): A flexible, lightweight plastic used for plastic bags, food wraps, and some types of containers. It's known for being soft and bendable.
(4) PE (Polyethylene): A general term for polyethylene, one of the most widely used plastics. It's used in a variety of products, including bags, bottles, and pipes.
(5) Not all types of *E. coli* degrade plastic, only the genetically modified ones.
(6) PS/LDPE: A blend of PS (Polystyrene) and LDPE, which combines the rigidity of PS with the flexibility of LDPE. It is used in some packaging applications.
(7) PLA (Polylactic Acid): A biodegradable plastic made from renewable resources like corn. It is environmentally friendly and commonly used for eco-friendly packaging.

Bacteria	Sources	Plastic Types
Bacillus megaterium	LDPE Contaminated Soil	PET (1)
Bacillus subtilis	culture	PET/PS (2)
Bacillus cereus	Mangrove sediment	LDPE (3)
Enterobacter sp. D1	Isolated from Gut of *Galleria mellonella*	PE (4)
Escherichia coli (5)	Hydrocarbon Enriched Soil	LDPE (6)
Pseudomonas auroginosa	Landfill Soil	PS/LDPE
Pseudomonas putida	Garbage Soil	PE
Pseudomonas sp. MKY1	Digester Sludge	PLA (7)

5.1 *Bacillus Species*

Species of the genus *Bacillus* are Gram-positive, spore-forming bacteria widely distributed in soil and aquatic environments. Several strains, including *Bacillus megaterium*, *Bacillus subtilis*, and *Bacillus cereus*, have been reported to promote degradation of ester-containing plastics and to induce surface deterioration of polyethylene films. These effects are primarily attributed to the secretion of extracellular hydrolases such as lipases and esterases, as well as the formation of robust biofilms that enhance enzyme–substrate interactions (Gajendiran et al., 2016; Xue et al., 2025).

5.1.1 *Bacillus megaterium:*

Bacillus megaterium is a Gram-positive, spore-forming bacteria classified under the phylum Firmicutes and the family Bacillaceae. It thrives in diverse environments, growing optimally at temperatures between 25-40°C and a pH range of 6-8. This bacteria is facultatively anaerobic, allowing it to survive in both aerobic and anaerobic conditions [26]. Bacillus megaterium plays a crucial role in plastic biodegradation, particularly in breaking down polyethylene terephthalate (PET). It achieves this through the secretion of hydrolytic enzymes, such as polyester hydrolase, which cleaves ester bonds in plastic polymers. Additionally, it produces exopolymerases that degrade surface layers of plastics, facilitating further breakdown. The resulting degradation products are then utilized by the bacterium as carbon and energy sources. Due to these capabilities, *Bacillus megaterium*, is considered a promising candidate for bioremediation applications aimed at reducing plastic pollution.

5.1.2 *Bacillus subtilis*:

Bacillus subtilis, a fascinating Gram-positive bacterium, belongs to the phylum *Firmicutes*, nestled within the class Bacilli and the order *Bacillales*, under the family *Bacillaceae*. It's quite celebrated in the world of biological research and industrial applications, often referred to as a model organism due to its remarkable versatility and resilience. This little powerhouse flourishes best in environments where the temperature hovers between 30 and 37°C, and the pH balances comfortably between neutral and slightly alkaline, around 6.5 to 7.5. It prefers the company of oxygen since it's a facultative aerobe, but what's truly impressive is its ability to endure in harsh, nutrient-scarce environments by forming tough endospores[29].that can withstand challenging conditions. When it comes to tackling plastic waste, *B. subtilis* shows its impressive capabilities. Research has revealed that it produces a variety of enzymes, including esterases, lipases, and cutinases, all of which are crucial for breaking down ester bonds found in biodegradable plastics like polycaprolactone (PCL) and polylactic acid (PLA). Through this enzymatic action, it dismantles these plastics into smaller, more manageable compounds that it can feast on for carbon and energy. What's interesting is that the efficiency of this nifty biodegradation process is heightened when the conditions are just right in the conditions of proper aeration, optimal temperatures, and especially when these plastics are the sole source of carbon available. This scenario sparks the bacterium's enzyme production, hopefully turning the course of plastic pollution.

5.1.3 *Bacillus cereus:*

Bacillus cereus is a Gram-positive, rod-shaped bacterium belonging to the phylum *Firmicutes*, class *Bacilli*, order *Bacillales*, and family *Bacillaceae*. This bacterium is notable for its ability to form endospores, which enables it to survive under harsh environmental conditions. *Bacillus cereus* can thrive in a wide range of environments, with optimal growth temperatures between 30°C and 37°C, although it is capable of growing between 4°C and 50°C. It tolerates pH levels from 4.9 to 9.3, with a preference for neutral to slightly alkaline conditions, and it is a facultative aerobe, meaning it can grow in both the presence and absence of oxygen. Regarding plastic biodegradation, *Bacillus cereus* has demonstrated the ability to degrade certain synthetic polymers, such as low-density polyethylene (LDPE) and polyurethane (PU), by producing specific enzymes like esterases, lipases, and hydrolases that break down the chemical bonds within the polymer chains. The biodegradation process involves two main steps: first, the enzymatic depolymerization of the plastic into smaller oligomers and monomers, followed by the microbial assimilation of these breakdown products as carbon and energy sources. During this process, *Bacillus cereus* converts the plastic-derived compounds into simpler substances such as carbon dioxide, water, and organic acids [38]. Notably, the efficiency of plastic degradation by *Bacillus cereus* can be enhanced through pre-treatment methods like UV irradiation or by employing microbial consortia that work synergistically to accelerate biodegradation. These capabilities position *Bacillus cereus* as a promising candidate for biotechnological applications aimed at addressing plastic pollution.

5.2 *Pseudomonas* Species

Members of the genus *Pseudomonas* are metabolically versatile Gram-negative bacteria frequently associated with polluted environments. *Pseudomonas putida*, *Pseudomonas aeruginosa* and *Pseudomonas* sp. MKY1 have been extensively studied for their ability to degrade polyurethane and to oxidise polyethylene surfaces. Their metabolic flexibility allows them to utilise a wide range of xenobiotic compounds and to adapt to hydrophobic polymer substrates through biofilm formation and surface colonisation. Although complete mineralisation of polyolefins is rare, these bacteria contribute to polymer ageing and fragmentation through oxidative enzymes and biosurfactant production, facilitating subsequent abiotic and biotic degradation processes (Palleroni, 2010).

5.2.1 *Pseudomonas putida:*

Pseudomonas putida is a Gram-negative, rod-shaped bacterium belonging to the phylum *Proteobacteria* and class Gamma *proteobacteria*. It is known for its ability to survive in diverse environments rich in organic compounds, making it an ideal candidate for environmental applications. This bacterium grows at moderate temperatures between 25 and 30°C, preferring a neutral pH environment (pH 6–8), and is an aerobic organism that relies on oxygen for its vital processes. *P. putida* exhibits a unique ability to degrade certain types of plastics, such as polyurethane, by secreting enzymes such as polyurethane esterase, which breaks down the chemical bonds in the polymer into smaller units. After breaking down the polymers, the bacteria absorb the resulting molecules and use them in their metabolic pathways for energy, producing carbon dioxide and water as final outputs. The importance of *P. putida* lies in its natural ability to tolerate polluted environments, as well as its ease of genetic modification to increase its efficiency in degrading plastics.

5.2.2 *Pseudomonas aeruginosa:*

Pseudomonas aeruginosa is a species of bacteria classified under the kingdom *Bacteria*, phylum *Proteobacteria*, class *Gammaproteobacteria*, and family *Pseudomonadaceae*. This bacterium is highly adaptable to diverse environments, thriving at temperatures between 25°C and 37°C, and tolerating up to 42°C. It is a facultative aerobe, meaning it can grow in both the presence and absence of oxygen. Remarkably, *Pseudomonas aeruginosa* demonstrates the ability to degrade certain plastics, such as polyurethane, by secreting enzymes like *esterase* and *oxygenase*, which break down the chemical bonds in plastic polymers into smaller compounds that the bacterium can utilize as sources of carbon and energy. Furthermore, the bacterium promotes biodegradation through oxidative processes that enhance the breakdown of plastic materials in natural environments.

5.2.3 *Pseudomonas sp. MKY1:*

Pseudomonas sp MKY1 is classified within the phylum *Proteobacteria*, class *Gammaproteobacteria*, order *Pseudomonadales*, family *Pseudomonadaceae*, and the genus *Pseudomonas*, which is well known for its ability to degrade complex compounds such as plastics. This bacterium grows under aerobic conditions, with optimal temperatures ranging from 30 to 37°C, and in environments with a neutral pH between 6.5 and 7.5. It demonstrates a remarkable capacity to utilize plastic as an alternative carbon and energy source, particularly in nutrient-limited environments. The plastic degradation mechanism of *Pseudomonas sp. MKY1* involves multiple stages, beginning with the formation of a biofilm on the plastic surface, which facilitates enzyme interactions with the polymer. Subsequently, the bacterium secretes various extracellular enzymes, such as hydrolases and esterases, that break the chemical bonds in plastic polymers into smaller monomeric units.

These monomers are then absorbed and metabolized to generate energy or serve as building blocks for cellular components, ultimately converting plastic waste into environmentally friendly end products like carbon dioxide and water. Altogether, these properties make *Pseudomonas sp. MKY1* a promising candidate for biotechnological applications in plastic waste bioremediation.

5.3 *Enterobacter* and Related Genera

Enterobacter species isolated from insect guts and contaminated soils have demonstrated the ability to degrade polyethylene under laboratory conditions, particularly when plastic serves as the sole carbon source. The degradation process is often enhanced by synergistic microbial communities and involves oxidative and hydrolytic enzymes (Ren et al., 2019).

5.3.1 *Enterobacter sp.* D1:

Enterobacter sp. D1 is a bacterium belonging to the family *Enterobacteriaceae*, within the phylum *Proteobacteria* and class *Gammaproteobacteria*. This microorganism thrives under moderate conditions, with an optimal growth temperature range between 30°C and 37°C, and a preferred pH between 6 and 8, ideally around neutral pH (≈7). Its plastic-degrading activity is enhanced when cultured in carbon-limited media, where plastic polymers serve as the'sole' carbon source.

The biodegradation mechanism of *Enterobacter sp*. D1 involves the secretion of several enzymes such as hydrolases, which cleave chemical bonds in polymer structures; esterases, which break ester linkages; and oxygenases, which incorporate oxygen atoms into polymer chains, making them more susceptible to fragmentation. The process begins with bacterial adhesion to the plastic surface, followed by oxidative reactions that initiate polymer breakdown. This leads to the depolymerization of long polymer chains into smaller fragments, which the bacterium metabolizes as sources of carbon and energy, ultimately producing simple end products such as carbon dioxide, water, and new cellular biomass.

Enterobacter sp. D1 has demonstrated promising efficiency in bioremediation applications, especially in plastic-contaminated environments. It has been studied for its potential to degrade various synthetic polymers, including polyethylene (PE) and polycaprolactone (PCL).

5.3.2 *Escherichia coli:*

Escherichia coli is classified as a Gram-negative, rod-shaped bacterium belonging to the family *Enterobacteriaceae*, naturally residing in the intestinal microbiota of humans and animals. The optimal growth conditions for *E. coli* include moderate temperatures around 37°C, a neutral pH environment (6.5–7.5), and a nutrient-rich medium containing glucose and essential minerals to support efficient cellular metabolism.

While *E. coli* does not inherently degrade plastics, advancements in genetic engineering have enabled the bacterium to express enzymes like PETase and MHETase, allowing it to break down plastics such as polyethylene terephthalate (PET) into environmentally benign monomers. Moreover, engineered strains have demonstrated the capacity to degrade complex organic pollutants, structurally similar to polymers, presenting a promising avenue for bioremediation applications[59]. Finally, by incorporating synthetic metabolic pathways, researchers have transformed *E. coli* into a biological chassis for plastic degradation in controlled industrial environments.

5.5 Genetically Engineered Bacteria

Advances in synthetic biology have enabled the heterologous expression of plastic-degrading enzymes in model organisms such as *Escherichia coli*. Engineered strains expressing PETase and MHETase enzymes have shown significant potential for PET depolymerisation under controlled conditions, highlighting the importance of bioengineering in overcoming the limitations of natural biodegradation (Yoshida et al., 2016; Effendi et al., 2024).

6. Plastic-Degrading Bacteria and Enzymes

A diverse range of bacterial taxa has been associated with plastic degradation or surface modification. Frequently reported genera include *Pseudomonas*, *Bacillus*, *Enterobacter* and *Rhodococcus* many of which are known for their metabolic versatility and ability to thrive in diverse environments (Shah et al., 2008; Urbanek et al., 2018). These bacteria often operate within complex biofilm communities, where synergistic interactions may enhance degradation efficiency.

At the molecular level, several classes of enzymes have been implicated in plastic biodegradation, including esterases, lipases, cutinases, and PETase-like hydrolases. The discovery of *Ideonella sakaiensis* and its PET-degrading enzymes represented a major milestone in the field, providing direct evidence of enzymatic PET depolymerisation under mild conditions (Yoshida et al., 2016). Subsequent structural and biochemical studies have further elucidated enzyme–substrate interactions, informing efforts in protein engineering and biotechnological optimisation (Wei & Zimmermann, 2017). Enzymes Involved in Plastic Degradation

Plastic-degrading bacteria employ a range of extracellular enzymes to initiate polymer breakdown. These include lipases, esterases, cutinases, oxidases, and, more recently, PETase and MHETase. Ester-based plastics are particularly susceptible to hydrolysis by these enzymes, whereas polyolefins require initial oxidative modification before further degradation can occur.

The efficiency of enzymatic degradation is influenced by enzyme structure, substrate accessibility, and polymer crystallinity. Recent structural and bioinformatic studies have provided valuable insights into enzyme–substrate interactions, enabling the rational design and optimisation of plastic-degrading enzymes for biotechnological applications.

To better understand the biochemical mechanisms employed by various bacteria in plastic biodegradation, it is essential to examine the specific enzymes they produce. These enzymes, including lipases, esterases, oxidases, and the recently discovered PETase and MHETase, play pivotal roles in catalysing the breakdown of complex plastic polymers into simpler, environmentally benign compounds. The diversity and specificity of enzymatic activity among different bacterial genera reflect their potential for targeted biotechnological applications in plastic waste management. Table 2 summarises the main plastic-degrading enzymes identified in selected bacterial strains, highlighting their role in facilitating polymer hydrolysis and subsequent microbial assimilation.

Table 2. Plastic-degrading enzymes listed per bacteria

Bacteria	**Enzymes**
Bacillus megaterium	Lipase, Catalase
Bacillus subtilis	Lipase, Protease
Bacillus cereus	Lipase, Esterase
Pseudomonas putida	PETase-like enzyme, Oxidase
Pseudomonas auroginosa	Lipase, Oxidase
Pseudomonas sp. MKY1	PETase, MHETase
Escherichia coli	PETase (heterologous expression)
Enterobacter sp. D1	Protease, Lipase
Ochrobacterum anthropi	Esterase

7. Discussion

The growing body of literature on bacterial plastic biodegradation highlights both the promise and the current limitations of biological approaches to plastic waste management. While numerous bacterial species have been reported to interact with synthetic polymers, it is increasingly clear that the term "biodegradation" encompasses a wide spectrum of processes, ranging from superficial surface oxidation and biofilm-associated deterioration to true enzymatic depolymerisation and, in rare cases, near-complete mineralisation.

Ester-based plastics such as poly(ethylene terephthalate) (PET) and certain polyurethanes represent the most realistic targets for microbial degradation, as their chemical structure provides hydrolysable bonds accessible to enzymes such as cutinases, esterases, and PETase-related hydrolases (Yoshida et al., 2016; Wei & Zimmermann, 2017). In contrast, polyolefins such as polyethylene and polypropylene remain highly resistant due to their inert carbon–carbon backbone, high hydrophobicity, and crystallinity. Reported bacterial effects on these polymers are therefore best interpreted as ageing, fragmentation, or partial oxidation rather than complete biodegradation (Shah et al., 2008; Danso et al., 2019).

Another important consideration is the role of microbial consortia and environmental context. In natural ecosystems, plastic-associated biofilms (the so-called plastisphere) consist of complex microbial communities whose collective metabolic activities may enhance polymer modification compared with single laboratory strains. However, translating these observations into scalable and controlled biotechnological processes remains challenging. Environmental factors such as temperature, oxygen availability, ultraviolet radiation, and nutrient limitation strongly influence degradation rates and outcomes.

Recent advances in structural biology, bioinformatics, and synthetic biology provide new opportunities to overcome some of these limitations. Structural analyses of plastic-degrading enzymes have revealed key determinants of substrate binding and catalytic efficiency, enabling rational enzyme engineering and directed evolution approaches. Similarly, bioinformatics screening of metagenomic datasets has accelerated the discovery of novel plastic-active enzymes from diverse environments. These developments suggest that future progress in plastic biodegradation is likely to depend on integrated strategies combining microbial ecology, enzyme engineering, and process optimisation rather than reliance on naturally occurring strains alone.

8. Limitations and Future Perspectives

Despite encouraging laboratory results, bacterial plastic biodegradation remains a slow and incomplete process under natural environmental conditions. Most studies report surface erosion, weight loss, or fragmentation rather than full mineralisation. Consequently, biodegradation should be viewed as a complementary strategy rather than a standalone solution to plastic pollution (Sahith et al., 2025).

Future research should focus on microbial consortia, enzyme engineering, pretreatment strategies, and the integration of biodegradation with existing waste management systems. Advances in structural biology, bioinformatics, and synthetic biology are expected to play a central role in enhancing degradation efficiency and scalability.

9. Conclusion

Bacterial biodegradation of plastics represents a promising and environmentally friendly approach to mitigating plastic pollution, particularly as a complementary strategy to conventional waste management practices. While the biodegradation of ester-based plastics such as PET has been convincingly demonstrated, the degradation of polyolefins remains limited to surface modification and slow fragmentation. Continued research integrating microbiology, enzyme engineering, structural biology, and bioinformatics is essential to improve degradation efficiency and scalability.

Many actions are focused on addressing plastic accumulation by encouraging the active participation of consumers, producers, industry, and businesses. In 2016, for the first time, more plastic packaging waste was recycled than landfilled (EU/Norway/Switzerland). Unfortunately, landfill remains the first choice for plastic waste treatment in many countries. Therefore, new solutions are needed. In addition to reducing, reusing, and recycling plastic waste, two other considerations must be considered: energy recovery and molecular redesign. The latter is expected to contribute to the development and widespread application of new bioplastics in reducing the environmental impact of plastic. Interactions between plastics and microorganisms are in urgent need of further study. Biodegradation of plastic waste using plastic-degrading bacteria is a valuable treatment for plastic waste and must be implemented to protect environmental quality from the problems caused by plastic waste. This process has fewer, if any, side effects that pollute the environment. Plastic biodegradation involves certain hydrolases and oxidases produced by various microbes, including bacteria. This enzymatic process breaks down resistant plastic polymers into microbial biomass and other environmentally safe compounds through several steps, including surface colonization and biofilm formation, enzyme secretion, and absorption of degraded compounds. Optimizing suitable environmental conditions is the key to enhancing the ability of bacteria to degrade plastic waste.

For regional and educational contexts, such as those targeted by our journal, the *Journal of Concepts in Structural Biology & Bioinformatics - JSBB*, bacterial plastic biodegradation offers a valuable framework for understanding applied environmental biotechnology and the realistic potential of biological solutions to global environmental challenges.

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