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# Innovative biotechnological approaches for plastic degradation: A pathway to sustainable waste management

Akash Phillip * and Tushar Chauhan

*Department of Biotechnology, IIMT University, Meerut, Uttar Pradesh, India.*

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## Abstract

Plastic pollution has escalated into a global environmental crisis, with millions of tons of synthetic polymers accumulating within ecosystems and posing significant threats to both biodiversity and human health. Conventional methods of plastic waste management, such as mechanical and chemical recycling, exhibit limitations in terms of sustainability, particularly for polymers such as polyethylene (PE) and polystyrene (PS), which demonstrate a pronounced resistance to degradation. Biotechnological approaches that exploit microbial enzymes and synthetic biology offer a promising alternative to tackle this pressing issue. Enzymes such as PETase and MHETase, which facilitate the degradation of polyethylene terephthalate (PET), in conjunction with laccases and lipases that target more recalcitrant plastics, have manifested considerable potential in deconstructing plastics at the molecular level. Notwithstanding these advancements, challenges persist regarding degradation efficiency, especially for non-PET plastics, as well as the economic viability of scaling these biotechnological processes. Furthermore, environmental parameters including temperature, pH, and oxygen levels significantly influence enzyme functionality, while regulatory and societal obstacles impede the utilization of genetically modified organisms (GMOs). Nevertheless, emerging technologies such as protein engineering, CRISPR-based gene editing, and industrial applications like bioreactors present avenues for surmounting these challenges. This article investigates the current landscape, challenges, and prospects associated with biotechnological plastic degradation, emphasizing its potential contribution to achieving global circular economy objectives and enhancing sustainable waste management strategies.

**Keywords:** Synthetic plastics; Biodegradation; Microbial plastic degradation; Microplastics; Plastic pollution; Sustainable waste management

## 1 Introduction

Plastic pollution has become a critical environmental challenge with profound consequences for ecosystems, wildlife, and human health [1]. Over the past 70 years, the rapid rise in global plastic production has transformed daily life but also left a massive environmental burden [2].

Plastics, primarily derived from petrochemical sources, have seen global production rise considerably from around 1.5 million tons in 1950 to over 459.75 million tons in 2019 [2], as illustrated in Figure. 1. Their low cost, durability, and versatility have made plastics ubiquitous, infiltrating industries from packaging and textiles to electronics and construction. However, this convenience comes with a substantial environmental cost. Only about 9% of all plastics ever produced have been recycled, with the rest either incinerated or accumulating in landfills and natural environments [3]. As plastics degrade, they release harmful chemicals, including additives like phthalates, bisphenol A (BPA), and flame retardants [3]. These chemicals can leach into the environment, contaminating water and soil, and subsequently entering the food chain [4]. Wildlife, particularly at higher trophic levels, accumulates these toxins, leading to reproductive issues, developmental defects, and immune suppression [5]. Additionally, a significant portion,

* Corresponding author: Akash Phillip

approximately 8 million tons annually, ends up in the oceans, where it harms marine life and disrupts ecosystems [4]. In oceans, rivers, and lakes, plastics entangle wildlife and are mistaken for food by marine animals like fish, seabirds, and turtles [6]. The ingestion of plastic often leads to injury, starvation, and death, as it obstructs digestive tracts. According to Roman et al., (2019), a recent study estimated that 90% of seabirds have ingested plastic, and by 2050, plastic in oceans is projected to outweigh fish by mass [7].

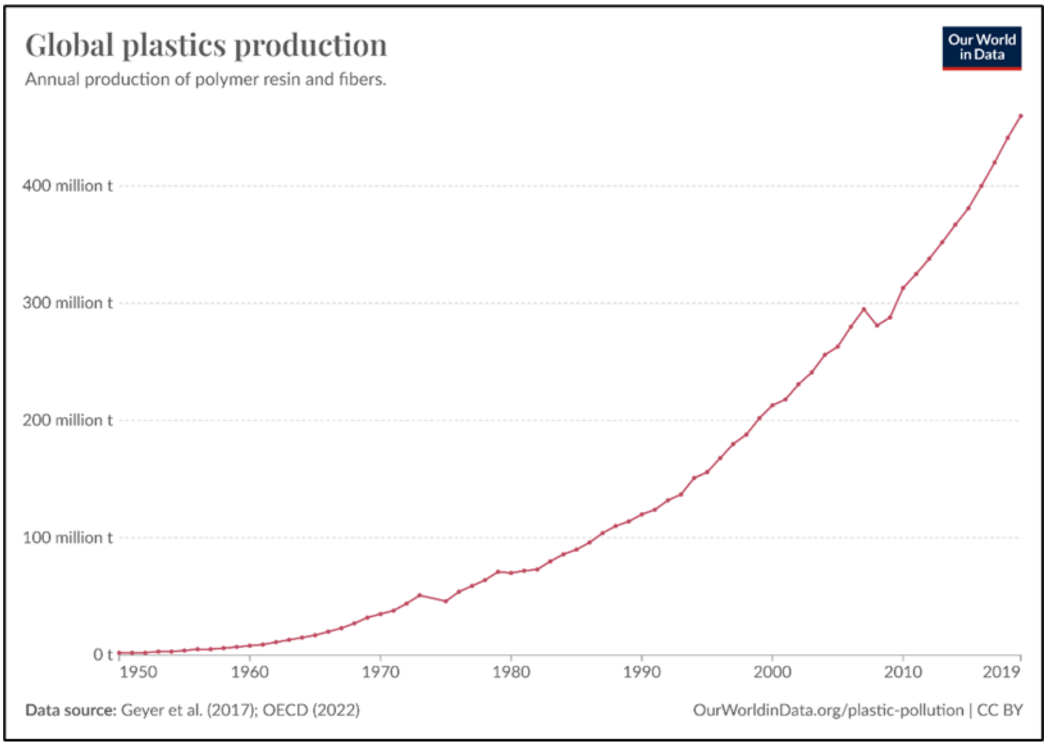


**Figure 1** Annual production of plastics worldwide from 1950 to 2019 (in million tons)

Due to their chemical structure, plastics are resistant to natural degradation processes, taking hundreds, if not thousands, of years to degrade completely [8]. At this time, larger plastic items break into smaller fragments, leading to the growing problem of microplastic pollution, microplastics (particles smaller than 5 mm) are a growing concern [9]. Found in nearly every corner of the Earth, from the depths of the Mariana Trench to Arctic ice, they permeate terrestrial and aquatic ecosystems. These tiny particles are ingested by wildlife and humans alike, entering our bodies through food, water, and even air [10]. Studies have detected microplastics in seafood, drinking water, table salt, and even human blood and placental tissue, causing inflammation, immune system disruption, oxidative stress, DNA damage, chronic health conditions such as cancer and cardiovascular diseases, as well as contributing to the environmental footprint [11].

Given the persistence of plastics and their far-reaching environmental impacts, biotechnological solutions present a promising avenue for addressing plastic pollution [12]. Traditional mechanical and chemical recycling approaches are limited in scope and efficiency, often leading to downcycled products of lower quality. Biotechnology, however, offers innovative approaches to degrade plastics or reduce their environmental footprint [13].

According to Zhi Xiang et al., (2023), the use of microorganisms (bacteria and fungi) and enzymes capable of breaking down plastics [14]. For instance, the bacterium *Ideonella sakaiensis* has been found to degrade polyethylene terephthalate (PET), a common plastic used in bottles, by secreting enzymes such as PETase [15]. Other studies focus on fungal species like *Aspergillus* and *Penicillium* which can degrade synthetic polymers [16]. Additionally, advancements in genetic engineering hold potential for enhancing plastic degradation. According to Arora et al., (2023), optimizing microbial strains through gene editing techniques like CRISPR, aims to increase their efficiency in breaking down complex plastics [17]. By engineering microbes to express higher levels of plastic-degrading enzymes, the biodegradation process can be accelerated. The development of bioplastics made from renewable biological sources (e.g., corn starch, and algae) offers a more sustainable alternative to conventional plastics [18]. These biodegradable plastics are designed to break down more readily under natural conditions, reducing their persistence in the environment. However, scalability and cost remain significant challenges for widespread adoption. Furthermore, microbial fuel cells (MFCs) and other bioengineering technologies are also being developed to convert plastic waste into energy, offering a dual benefit of waste reduction and energy recovery [19]. These innovative strategies help to minimize plastic waste while contributing to renewable energy generation.

## 2 Traditional recycling vs. Biodegradation

There are two primary forms of plastic recycling, mechanical and chemical [20]. Mechanical recycling involves shredding plastic waste and reprocessing it into new products, while chemical recycling breaks down plastics into their base monomers through high-energy processes like pyrolysis or gasification [21]. While these methods have seen some success, they come with limitations.

Mechanical recycling often leads to lower-quality materials, known as "downcycling." Repeated reprocessing can degrade the polymer chains, limiting the usefulness of the recycled product [22]. Chemical recycling is energy-intensive and expensive, making it less economically viable. It also has the challenge of creating toxic byproducts and requiring strict waste separation [23].

Biotechnological approaches involve using living organisms (such as microbes) and their enzymes to break down plastics into environmentally harmless byproducts like water, carbon dioxide, and biomass [24]. Biodegradation processes can occur under natural conditions, providing a more sustainable and energy-efficient solution [25]. Unlike traditional methods, biotechnology aims to fully degrade plastics rather than just repurposing or reprocessing them. This has the potential to be more cost-effective in the long term and can address the environmental issues associated with plastic waste that have persisted for centuries [26]. A thorough examination and comparison of the various processes involved in the degradation of synthetic plastic, specifically focusing on mechanical degradation, chemical degradation, and biodegradation, is meticulously presented and analyzed in the detailed Table 1.

**Table 1** A comparison between mechanical, chemical, and biodegradation of synthetic plastic

| Method | Cost Efficiency | Environmental Impact | Energy Consumption | Scalability | References |
|---|---|---|---|---|---|
| Mechanical Recycling | Moderate | Limited by downcycling | Moderate | High (but low-quality output) | [27] |
| Chemical Recycling | High | High potential, but energy-intensive | Very high | Moderate (energy and cost barriers) | [28] |
| Biodegradation | Lower long-term costs | High (complete degradation) | Low to moderate | Promising, but still in the research phase | [29] |

## 3 Categories of synthetic plastics and their biodegradability

Different types of synthetic plastics vary in their resistance to degradation, largely due to their molecular structure.

- *Polyethylene terephthalate (PET):* PET is widely used in plastic bottles and packaging. It is highly resistant to biodegradation because of its tightly packed molecular structure. PET typically persists in the environment for several hundred years [30].
- *Polyethylene (PE):* Found in plastic bags, films, and containers, polyethylene is one of the most commonly produced plastics. Its hydrophobic properties and long polymer chains make it resistant to microbial attack, contributing to its slow biodegradation rate in nature [31].
- *Polystyrene (PS):* Often used in packaging materials and disposable items, polystyrene is another persistent plastic that resists biodegradation. Its environmental persistence, coupled with its tendency to fragment into small pieces, makes it a significant environmental threat [32].
- *Polyvinyl chloride (PVC):* Known for its use in pipes and medical devices, PVC is highly resistant to biodegradation due to the presence of chlorine atoms in its structure. This makes it one of the most durable and environmentally problematic plastics [33].

Because these plastics do not easily break down in nature, the accumulation of synthetic polymers in landfills and oceans has become a major issue. Traditional disposal methods like landfilling or incineration further compound environmental concerns, prompting researchers to explore biotechnological degradation methods as a more sustainable alternative. A thorough and meticulous examination of the various classifications and categories of synthetic plastics, alongside an analysis of their respective biodegradability, and challenges, is comprehensively elaborated upon and presented in the detailed format of Table 2.

**Table 2** A comparison between different categories of synthetic plastic and their biodegradability

| Plastic Type | Description | Resistance to Biodegradation | Challenges | References |
|---|---|---|---|---|
| PET (Polyethylene terephthalate) | Common in bottles, textiles | High | Strong carbon-carbon backbone, resistant to microbial attack. | [30] |
| PE (Polyethylene) | Used in plastic bags, packaging films | High | Inert, hydrophobic, and lacks functional groups for enzyme attachment. | [31] |
| PS (Polystyrene) | Found in disposable cups, insulation | High | Long degradation time due to its aromatic structure, prone to fragmenting into microplastics. | [32] |
| PVC (Polyvinyl chloride) | Used in pipes, cables | Very High | Contains harmful additives like plasticizers and chlorine, which complicate degradation. | [33] |
| PP (Polypropylene) | Used in automotive parts, food containers | High | Low surface energy and hydrophobicity, make it hard for enzymes to bind. | [34] |
| PU (Polyurethane) | Found in foams, coatings | Medium to high | Contains urethane bonds, some of which are susceptible to microbial attack, but resistance varies. | [35] |

## 4 Novel biotechnological solutions for plastic degradation

Plastic pollution is a growing environmental problem that requires innovative solutions. While traditional recycling methods have been used for decades to manage plastic waste, biotechnological approaches, including microbial degradation and genetically engineered organisms, offer sustainable and efficient alternatives [25].

### 4.1 Microbial enzymes for plastic degradation

The ability of microbial enzymes to degrade synthetic plastics, which are resistant to natural degradation, is a promising biotechnological solution to the global plastic pollution problem [36]. Microorganisms produce enzymes capable of breaking down plastics into smaller components, offering an environmentally friendly alternative to mechanical and chemical recycling methods [37].

### 4.2 Mechanism of plastic-degrading enzymes

The enzymatic degradation of plastics typically involves hydrolysis, where enzymes break the bonds in polymer chains, converting complex plastics into simpler molecules like monomers [38].

#### *4.1.1 Hydrolysis of polymer bonds*

Enzymes attach to the polymer surface and break down specific chemical bonds within the plastic. For example, in plastics like polyethylene terephthalate (PET), enzymes hydrolyze the ester bonds, leading to the breakdown of long polymer chains into smaller monomeric units like terephthalic acid (TPA) and ethylene glycol (EG) [39].

#### *4.1.2 Specificity of enzymes*

Plastic-degrading enzymes are highly specific to the chemical structures of the polymers they target. This specificity means that different types of plastics require different enzymes for efficient degradation [38].

### 4.2 Key enzymes in plastic degradation

Several enzymes have been discovered and engineered to degrade common plastics [40]. A comprehensive analysis is presented in Table 3, wherein a meticulous comparison is made between a variety of enzymes that have been both discovered in nature and expertly engineered through biotechnological advancements, all of which exhibit the remarkable capability to degrade widely used plastic materials that pose significant environmental challenges.

**Table 3** A comparison between different enzymes that have been discovered and engineered to degrade common plastics

| Enzyme | Plastic Targeted | Mechanism of Action | Source | Degradation Products | Applications | Efficiency | References |
|---|---|---|---|---|---|---|---|
| PETase | PET (Polyethylene terephthalate) | Hydrolyzes ester bonds in PET, converting it to monomers | *Ideonella sakaiensis* | Mono(2-hydroxyethyl) terephthalate (MHET), Terephthalic acid (TPA) | PET recycling and biodegradation | High efficiency, especially after protein engineering modifications | [41] |
| MHETase | PET (works with PETase) | Breaks down MHET into terephthalic acid (TPA) and ethylene glycol (EG) | *Ideonella sakaiensis* | Ethylene glycol (EG), Terephthalic acid (TPA) | Completes PET degradation in combination with PETase | Works synergistically with PETase for complete PET degradation | [42] |
| Laccases | PE (Polyethylene), PS (Polystyrene) | Oxidizes plastic, producing free radicals that destabilize polymer chains | Fungi, Bacteria | Fragmented polymer chains | Mixed plastic waste management, particularly PS and PE | Moderate efficiency, less effective with highly crystalline plastics | [43] |
| Lipases | Polyurethane (PU), Polyester (PE) | Hydrolyzes ester bonds in polyesters, converting them to smaller molecules | Fungi, Bacteria | Alcohols, Carboxylic acids | Degradation of polyesters and polyurethanes | Moderate efficiency; useful for polyester-based plastics | [44] |

### 4.3 Recent developments in enzyme optimization for effective degradation of various types of plastics

Advances in protein engineering and synthetic biology have led to significant improvements in the efficiency of plastic-degrading enzymes. By enhancing these enzymes through genetic modification, researchers aim to optimize their performance in industrial settings.

#### *4.3.1 Protein engineering of enzymes*

Protein engineering techniques, such as directed evolution, have been applied to improve the efficiency of PETase and MHETase. Directed evolution involves making random mutations in the enzyme's genes, selecting the best-performing variants, and further optimizing them [45]. This approach has led to variants of PETase that can degrade PET up to six times faster than the wild-type enzyme [46].

#### *4.3.2 Enzyme optimization*

Enzymes are being optimized to function under a wider range of environmental conditions (e.g., higher temperatures, varying pH levels), which increases their practical utility for industrial-scale degradation [47]. Thermophilic enzymes that function at higher temperatures are particularly valuable, as heat speeds up the degradation process [48]. The recent advancements and enhancements in the optimization of enzymes, which are crucial for facilitating the effective degradation of various types of plastics, are comprehensively discussed and elaborated upon in the detailed presentation found in Table 4.

**Table 4** The recent advancements and enhancements in the optimization of enzymes for facilitating the effective degradation of various types of plastics

| Enzyme | Optimized Trait | Improved Efficiency | Application | References |
|---|---|---|---|---|
| PETase | Increased thermal stability | Degrades PET up to 6x faster | Industrial PET waste management | [49] |
| MHETase | Improved substrate affinity | Faster breakdown of MHET | Synergistic PET degradation | [45] |
| Laccase | Enhanced oxidative activity | Increased degradation of PS and PE | Degradation of mixed plastics | [50] |
| Lipase | Increased substrate specificity | Faster breakdown of PU and PE | Biodegradation of polyurethane | [51] |

#### *4.3.3 Combined enzymatic approaches*

Recent research focuses on combining different enzymes to target more resistant plastics. By using enzyme "cocktails" (e.g., PETase + MHETase or laccase + lipase), researchers can degrade plastics more effectively than with a single enzyme [52].

#### *4.3.4 Artificial intelligence (AI) in enzyme design*

AI is being leveraged to predict the optimal mutations for enhancing enzyme function. By analyzing large datasets of enzyme structures and their performance, AI models can suggest modifications that improve degradation rates [53].

#### *4.3.5 Synthetic consortia of enzymes*

Scientists are also engineering microbial consortia (groups of microorganisms) that work together to break down different components of plastic, leading to more comprehensive waste management solutions [54].

## 5 Advances in synthetic biology for plastic degradation

Synthetic biology has opened new avenues for addressing the global plastic pollution crisis by enabling the creation of genetically modified organisms (GMOs) designed to metabolize plastics [55]. Through tools such as gene editing and metabolic engineering, researchers can enhance microbial capabilities to degrade plastics more efficiently than naturally occurring organisms [56]. By manipulating metabolic pathways, introducing novel enzymes, and optimizing environmental adaptability, synthetic biology offers a sustainable and scalable solution to plastic waste [25].

### 5.1 Mechanism of synthetic biology enabled plastic degradation

#### *5.1.1 Gene insertion for enzyme expression*

Synthetic biology allows scientists to insert genes encoding plastic-degrading enzymes (like PETase) into bacteria, fungi, or algae, enabling these organisms to break down specific polymers like PET, polyethylene (PE), or polystyrene (PS) [57].

#### *5.1.2 Metabolic pathway engineering of microbes*

Engineered microbes can be designed not only to break down plastics but also to metabolize or recycle the breakdown products into valuable compounds (e.g., biofuels, and bioplastics). This adds an extra layer of sustainability by creating a closed-loop system for plastic waste management [58].

### 5.2 Examples of engineered organisms

#### *5.2.1 Escherichia coli expressing PETase*

To enhance PET degradation by equipping a well-characterized bacterium, Escherichia coli, with the ability to break down PET plastic. According to Benavides Fernández et al., (2022), inserting the PETase gene from *Ideonella sakaiensis* into E. coli, allowing the engineered strain to produce the PETase enzyme [59]. The modified E. coli successfully degraded PET into its monomers (terephthalic acid (TPA) and mono(2-hydroxyethyl) terephthalate (MHET)) at a significantly higher rate than *Ideonella sakaiensis* alone [60]. The process has been enhanced by optimizing expression systems and improving enzyme secretion pathways in E. coli [61]. This method demonstrates how metabolic engineering can be used to enhance the degradation process, making E. coli an efficient platform for large-scale PET recycling.

#### *5.2.2 Pseudomonas putida engineered for polyurethane (PU) degradation.*

To degrade polyurethane (PU), a widely used but highly durable plastic, and convert the breakdown products into useful byproducts. According to Ackermann et al., ( 2021), using synthetic biology, *Pseudomonas putida* is made to express enzymes that break down polyurethane into its constituent chemicals, such as 1,4-butanediol and ethylene glycol [62]. The engineered bacteria were further modified to metabolize these breakdown products, converting them into bioplastics or bio-based chemicals. The engineered strain of *P. putida* could degrade polyurethane and metabolize the intermediates, providing a pathway to convert plastic waste into valuable materials rather than simply reducing it to landfill waste [63]. This finding illustrates how metabolic engineering can create a circular economy where plastic waste is converted into economically valuable products.

### 5.3 CRISPR for pathway optimization of microbes

The precision of CRISPR-Cas9 gene editing technology has been a game-changer in optimizing plastic degradation pathways.

#### *5.3.1 Editing metabolic pathways of microbes*

CRISPR is employed to edit bacterial and fungal genomes, enhancing the expression of plastic-degrading enzymes. According to Zimmermann et al., (2024), by knocking out competing pathways or introducing regulatory elements, CRISPR helps ensure that microbial metabolism is focused on breaking down plastics efficiently [64].

#### *5.3.2 Multiplex gene editing in microbes*

CRISPR enables scientists to edit multiple genes at once, allowing for the simultaneous optimization of enzyme expression, secretion, and metabolism within a single organism. This is particularly useful for complex processes like PET degradation, where enzymes like PETase and MHETase need to work in concert [65].

Using CRISPR, researchers have improved the thermostability of PETase by introducing point mutations into its gene, allowing it to function effectively at higher temperatures, which accelerates the PET degradation process.

### 5.4 Synthetic consortia of microorganisms

Another approach in synthetic biology is creating synthetic microbial consortia, where multiple genetically engineered organisms work together to degrade different types of plastics.

A consortium of E. coli expressing PETase, combined with Pseudomonas putida engineered for PU degradation, can break down both PET and PU simultaneously [66]. This approach maximizes efficiency by dividing labor between different microbial species [67]. An analysis and evaluation of the relative effectiveness and applicability of CRISPR-Cas9 gene-editing technology in comparison with the innovative approach of Synthetic Consortia to facilitate the degradation and breakdown of plastic materials is discussed in Table 5.

**Table 5** A comparison of CRISPR cas-9 and Synthetic Consortia for breaking down plastic

| Technology | Application | Example | Impact | References |
|---|---|---|---|---|
| CRISPR-Cas9 | Editing genes for enzyme optimization | Improved thermostability of PETase in *E. coli* | Accelerates plastic degradation under varied conditions | [17] |
| Synthetic Consortia | Engineered microbial communities | *E. coli* + *P. putida* for PET and PU degradation | Broader plastic degradation capability | [66] |

## 6 Successful applications of novel biotechnological advancements in plastic degradation

As the global plastic pollution crisis intensifies, significant advancements in biotechnology, particularly the use of engineered enzymes and microbes, have opened new possibilities for tackling plastic waste. From industrial applications to field deployments, several success stories demonstrate the potential of plastic-degrading technologies to mitigate environmental harm and contribute to circular economy goals.

### 6.1 Carbios: commercial pet recycling using engineered enzymes

Carbios, a French biotechnology company, is a leader in the industrial application of engineered enzymes for PET (polyethylene terephthalate) recycling. They developed a proprietary process that uses engineered PETase enzymes to break down PET waste into its constituent monomers, which can then be reused to create new PET products, creating a closed-loop recycling system [68].

Carbios engineered a variant of the PETase enzyme to improve its efficiency at industrial scales. Their process involves the enzymatic hydrolysis of PET waste into terephthalic acid (TPA) and ethylene glycol (EG), which are purified and reused in new plastic production [69]. In 2021, Carbios successfully built a demonstration plant in France, with the ability to recycle thousands of tons of PET waste annually. This pilot project demonstrated the scalability of enzymatic PET recycling for future global applications [70]. Carbios has since announced plans to build the world's first commercial-scale PET recycling facility by 2025, highlighting the viability of enzyme-based plastic recycling on an industrial scale [71]. Carbios' technology offers a sustainable alternative to traditional plastic recycling methods, which often result in downcycled, lower-quality materials [72]. By closing the loop, Carbios contributes to the circular economy, where plastics can be continuously recycled into high-quality materials, reducing the need for virgin plastic production [72].

### 6.2 Academic Research Breakthroughs on Engineered PETases

Academic institutions have been critical in advancing plastic degradation technologies, particularly through research on enzyme engineering to improve the efficiency of PETases.

According to Bell et al., (2022), researchers at the University of Portsmouth developed a super-enzyme by combining PETase with MHETase, significantly accelerating PET degradation [73]. This breakthrough holds potential for large-scale applications in recycling plants and bioreactors, allowing for faster and more efficient plastic breakdown [74]. By optimizing enzyme stability and activity under industrial conditions (such as higher temperatures and pH ranges), these engineered enzymes are paving the way for future bioreactor-based recycling systems, where plastics can be efficiently broken down and recycled [75].

### 6.3 Plastic-Degrading Bacteria in Oceans and Landfills

Pilot projects have been initiated to deploy plastic-degrading bacteria in both marine environments and landfills to tackle plastic waste in situ.

According to Tadimeti and Sutton, (2020), scientists are experimenting with the deployment of engineered marine bacteria that can break down plastics like polyethylene (PE) and polystyrene (PS) in the ocean. These bacteria are equipped with laccases and lipases, enzymes capable of initiating the breakdown of plastic debris floating in the water [76]. Though still in the early stages, pilot projects show promise in mitigating microplastic pollution in coastal areas. In controlled environments, bacteria capable of degrading polyurethane (PU) and PET have been deployed in landfill sites [77]. These engineered microbes, including strains of *Pseudomonas putida*, can metabolize plastics into bio-based chemicals, which can be harvested and reused, thereby reducing plastic buildup in landfills [78].

### 6.4 Technological and Environmental Impact

#### *6.4.1 Reduction in Plastic Waste*

The deployment of biotechnological solutions for plastic degradation has shown measurable success in reducing plastic waste, both in pilot and industrial-scale applications. In the case of Carbios, their enzymatic recycling process not only reduces the amount of PET waste sent to landfills and incinerators but also prevents the need for fossil fuel extraction used in the production of virgin PETs [79].

By focusing on closed-loop recycling, these technologies align with the principles of a circular economy, an economic model designed to minimize waste and maximize resource efficiency [80]. Enzyme-based plastic degradation offers a pathway to recycle plastics repeatedly without quality loss, reducing the need for new plastic production [81].

#### *6.4.2 Environmental and Ecological Benefits*

Pilot projects using plastic-degrading bacteria in oceans and landfills have the potential to significantly reduce plastic pollution in these environments [82]. By breaking down plastics into less harmful byproducts or reusable chemicals, these projects contribute to a healthier ecosystem.

Reducing microplastic pollution in oceans prevents the ingestion of plastic particles by marine organisms, protecting biodiversity and ensuring the health of marine ecosystems. According to Willis and Fytianos, (2022), engineered marine bacteria could play a crucial role in addressing the microplastic crisis [83]. In landfills, plastic-degrading bacteria reduce the longevity of plastic waste, preventing leachates and toxic byproducts from contaminating the soil and water. These projects not only address waste but also generate usable byproducts, contributing to sustainable waste management [84].

## 7 Challenges and limitations of biotechnological approaches in plastic degradation

While biotechnological solutions for plastic degradation show significant promise, several challenges and limitations impede their widespread adoption. These obstacles must be addressed to fully harness the potential of microbial enzymes, synthetic biology, and other biotechnological interventions.

### 7.1 Efficiency of Biodegradation

The speed and efficiency of enzymatic degradation, especially for non-PET plastics {like polyethylene (PE), polypropylene (PP), and polystyrene (PS)}, remain a significant limitation. While engineered enzymes such as PETase have shown great success in breaking down PET, other common plastics like PE and PS are much more resistant to enzymatic attack due to their more hydrophobic and crystalline structures [85]. These plastics lack readily available sites for enzymatic hydrolysis, making them much harder to degrade efficiently [86].

Current microbial enzymes are often too slow for practical application at scale. Even PETase, one of the most advanced enzymes, requires days or even weeks to fully break down PET under optimal conditions, which is still much slower than conventional mechanical recycling processes [87]. According to Ali et al., (2021), ongoing research is attempting to overcome this limitation through protein engineering to improve enzyme stability and activity under a wider range of environmental conditions, but these advances are still in the developmental stages [88].

### 7.2 Economic Feasibility of biotechnological approaches

The cost of scaling up biotechnological solutions for plastic degradation is a major hurdle, especially when competing against traditional recycling and disposal methods. Enzyme production, particularly for engineered enzymes, is currently expensive [89]. The cost of cultivating microbes or producing enzymes at an industrial scale often outweighs the lower costs of traditional plastic recycling methods or even landfilling [90].

Though companies like Carbios are making strides toward commercial-scale applications, the economic feasibility of widespread enzyme-based recycling is not yet clear [91]. Competing with the well-established infrastructure of mechanical recycling and low-cost landfilling remains a significant challenge [91].

### 7.3 Environmental conditions required for plastic degradation

Optimal degradation of plastics by microbial enzymes often requires strictly controlled environmental conditions. This is a major limitation for the application of these technologies in real world scenarios, such as landfills or marine environments. Many enzymes, including PETase and laccases, operate efficiently only at specific temperatures, typically 30–50°C, far from ambient temperatures in most natural environments [92]. Maintaining these conditions in industrial settings requires significant energy input, reducing the sustainability of the process. Microbial plastic degradation also depends on the pH and oxygen levels of the environment. For instance, many enzymes require a neutral or slightly acidic pH to function optimally, and oxygen levels must be carefully controlled, especially for aerobic microbes [93]. Enzyme activity in uncontrolled environments, such as landfills or oceans, is far less predictable [94]. Fluctuating temperatures, pH, and the presence of contaminants or other competing microbes can inhibit enzyme activity, severely limiting the effectiveness of biotechnological solutions.

### 7.4 Regulatory and societal barriers regarding biotechnological approaches

The adoption of biotechnological solutions for plastic degradation also faces regulatory, societal, and policy-related challenges that hinder progress. The use of genetically modified organisms (GMOs) or engineered microbes in the environment is subject to strict regulatory oversight [95]. Many countries have stringent guidelines on the release of GMOs into the environment due to concerns over unintended ecological impacts [96]. There are concerns about the safety and ecological impact of releasing engineered microbes into natural ecosystems, which may delay or prevent large-scale field deployments [97]. Public mistrust of biotechnology, particularly in regions with strict anti-GMO regulations, could further slow progress [96]. The widespread adoption of biotechnological solutions for plastic degradation requires supportive government policies and financial incentives. In many cases, the cost-effectiveness of conventional plastic management (such as mechanical recycling and landfilling) means there is little financial incentive for companies to adopt newer, biotechnological approaches without substantial subsidies or regulatory mandates [98].

## 8 Future prospects for biotechnological plastic degradation

The future of biotechnological plastic degradation holds immense promise, with ongoing research aimed at overcoming current limitations and making these solutions viable on a larger scale. One of the primary areas of focus is improving the efficiency and versatility of microbial enzymes. According to Sharma et al., (2021), researchers are working on engineering enzymes that can degrade a wider variety of plastics, not just polyethylene terephthalate (PET), but also more resistant polymers like polyethylene (PE), polypropylene (PP), and polystyrene (PS) [99]. Techniques such as directed evolution and rational design are being used to create enzymes that can function more effectively under a range of environmental conditions, increasing their potential for use in both industrial applications and uncontrolled environments like oceans and landfills [100].

In addition to enzyme engineering, significant attention is being paid to the development of synthetic biology tools. By using gene editing technologies like CRISPR, scientists are working on creating genetically modified microorganisms that can degrade plastics more efficiently and at faster rates [101]. These engineered microbes can be tailored to specific waste streams or environments, providing a more targeted approach to plastic degradation [102]. The integration of metabolic engineering also shows promise, as it allows microbes to not only break down plastics but also convert them into valuable byproducts, such as biofuels or raw materials for new plastics [103]. This could help close the loop in the circular economy, where plastic waste is continuously recycled into useful products.

Scaling up these biotechnological solutions will also involve innovations in bioreactor design and industrial processes. Current research is focused on developing continuous flow systems where plastic waste can be enzymatically degraded in real time, potentially reducing the need for large, expensive facilities [104]. There are also ongoing efforts to reduce the energy and resource inputs required for microbial plastic degradation, making it a more economically viable alternative to traditional recycling methods [105]. This will be critical for ensuring that biotechnological solutions can compete with the well-established and cost-effective infrastructure of mechanical and chemical recycling.

From a policy and societal standpoint, there is growing interest in how governments and industries can support the adoption of biotechnological solutions. Future research will likely explore strategies for scaling these technologies within existing waste management frameworks, as well as developing regulations that allow for the safe deployment of genetically modified organisms (GMOs) in the environment [106]. Public education and outreach will also be essential in building trust around the use of biotechnological innovations, particularly when it comes to the release of engineered microbes [107].

## 9 Conclusion

Biotechnological approaches to plastic degradation offer a revolutionary solution to the growing global plastic waste crisis. While traditional recycling methods like mechanical and chemical processes have long been used, they face limitations in sustainability and efficiency, particularly for plastics that are resistant to degradation. Biotechnological methods, particularly through microbial enzymes and synthetic biology, present a promising alternative by breaking down plastics at the molecular level. Key enzymes like PETase, MHETase, laccases, and lipases have shown the ability to degrade various plastics, with recent advancements in protein engineering enhancing their efficiency.

However, these solutions are not without challenges. Issues like the slow degradation rates for non-PET plastics, the high costs of scaling biotechnological processes, and the need for controlled environmental conditions are significant hurdles. Additionally, regulatory and societal barriers, especially regarding the use of genetically modified organisms, present obstacles to widespread adoption. Despite these challenges, ongoing research and innovation in synthetic biology, enzyme engineering, and industrial applications are rapidly advancing the field.

The future of plastic waste management lies in the integration of biotechnological solutions with existing systems, alongside supportive policies and public acceptance. With continued advancements, these technologies have the potential to significantly reduce plastic waste, contributing to global circular economy goals and a more sustainable future.

## Compliance with ethical standards

### *Acknowledgment*

This research was conducted as a collaborative effort between both authors, with each contributing significantly to various aspects of the study, including the conceptualization, methodology, analysis, and interpretation of the results. Both authors were actively involved in reviewing and refining the manuscript to ensure the accuracy and quality of the work presented.

### *Disclosure of conflict of interest*

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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