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# Emerging Biodegradation Technologies for Sustainable Plastic Waste Management

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## Abstract

*The extensive use of synthetic polymers has caused some of the most critical as well as complicated environmental issues of the 21st century. One of the major issues among them is rapid accumulation of plastic waste. Traditional methods for waste disposal like landfilling, incineration and ocean dumping are held responsible for causing several severe ecological and public health risks. The traditional methods also failed as a long-term and sustainable solution for plastic waste. In recent years, certain modern approaches like microbial and enzymatic biodegradation have shown greater efficiency in curbing issues linked to plastic waste management. Microbial biodegradation emphasizes on breaking of complex polymer chains into simpler monomers through the action of enzymes. These plastic-based compounds are utilized as carbon and energy sources by microbes. Advances in biotechnology, environmental microbiology, synthetic biology, genetic engineering and enzyme technology have enhanced the efficiency of microbes and enzymes involved in plastic degradation. PETase and MHETase are the enzymes that have previously shown capability to degrade one of the most used plastics i.e., polyethylene terephthalate (PET). The technical advancements such as molecular engineering, microbial consortia designing and CRISPR-based genome editing strategies such as PlastiCRISPR are becoming vital for developing engineered and modified microbial strains and systems that show optimized and enhanced capabilities for plastic degradation and formation of useful biochemical residues. This review aims to emphasise on greater environmental and economic causes through the application of scientific temperament. It provides an overview on plastic pollution, limitations of traditional waste management approaches and advancing biodegradation technologies. Detailed emphasis is placed on microbial biodegradation mechanisms, enzymatic degradation pathways, and advanced biotechnological methods that can help tackle plastic waste problems and convert them into other useful by-products, cycling into the circular economy.*

Keywords: Plastics, enzymes, biodegradation, genetic engineering, sustainability

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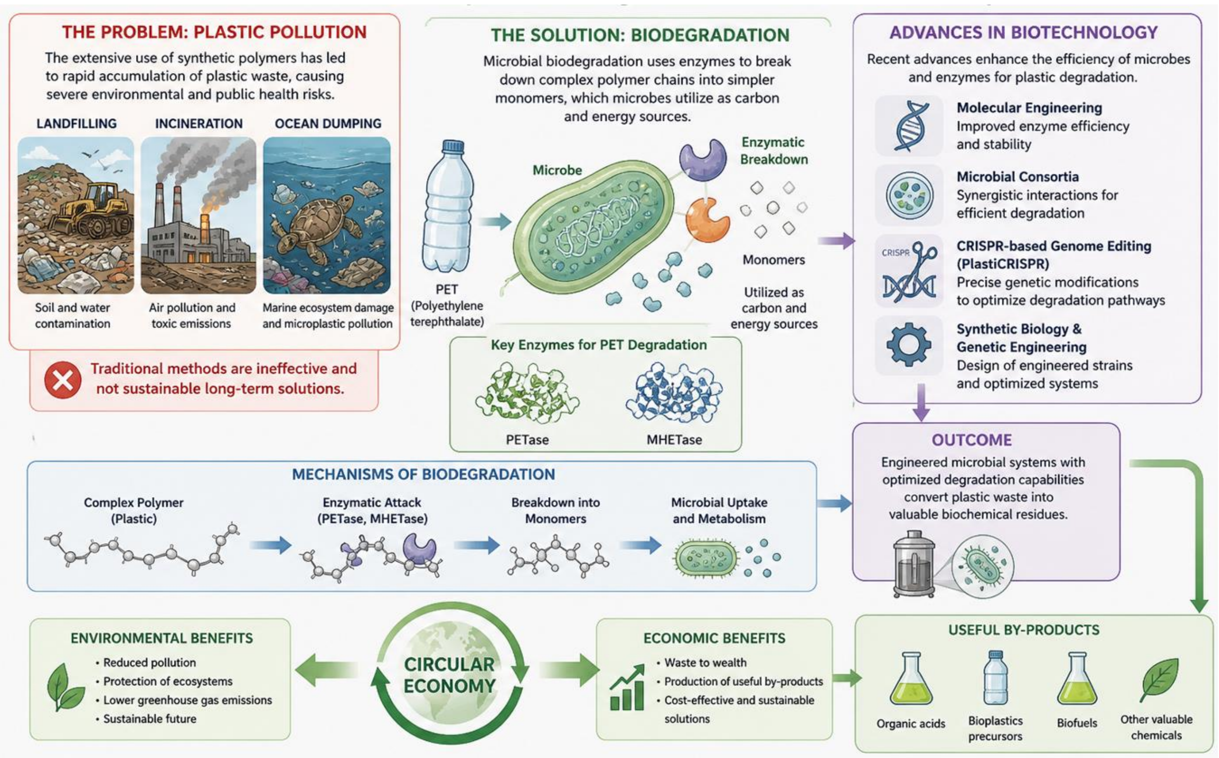
**Graphical Abstract**



## 1. Introduction

The dramatic increase in global plastic production is observed in the past few decades. This increase was seen due to the fact that plastic serves as a more compact, durable, flexible, cheap and versatile material used in industrial, commercial and domestic settings. The durability of the plastics makes it economically valuable and that is the reason for their persistence in the environment. Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET) are some synthetic polymers that can remain undegraded in the environment for even 100 years (Geyer et al., 2017).

Terrestrial and aquatic ecosystems have been largely affected by plastic waste accumulation. Degraded plastic fragments into micro-plastics which then pollutes soil, rivers and oceans. From these sources, micro-plastic fragments can reach food chains and then they may possess adverse effects on health. Micro-plastic particles have been traced in marine organisms, drinking water of some areas and even in some individual’s tissues, although in trace amounts, but even then, it is concerning (Shilpa et al., 2022).

Landfilling and incineration were widely practised as conventional waste management strategies to manage plastic waste, but they came with certain environmental concerns. Methane and toxic leachates from landfills contaminated groundwater and agricultural land. Also, incineration of plastic or undegradable waste leads to release of harmful gases that includes dioxins and particulate matter (Roy et al., 2024).

Rapid urbanization and industrialization have led to significant increase in plastic waste. In India cities like Chennai, Mumbai, Kochi, Visakhapatnam and Sunderbans mangrove and other regions located at coasts are some of the most affected regions due to plastic accumulation. As suggested by several studies, these are the regions that require potent bioremediation for plastic waste management (Santhosh et al., 2025; Sharma et al., 2024). Recent studies based on NITI Aayog and Central Pollution Control Tracking (CPCB) suggested that India generates approximately 62 million tonnes of municipal solid waste annually. It also stated that urban citizens are key contributors to plastic waste by producing roughly 0.5 kg per capita daily. This garbage is expected to reach an alarming volume of 165 million tonnes annually by 2030 (NITI Aayog, 2026).

To address these issues and provide sustainable alternatives for plastic waste management, researchers have been exploring biological degradation processes that basically involve microorganisms and enzymes that can degrade plastic polymers into simpler molecules. Recent advances in biotechnology, molecular biology, genetic and metabolic engineering, have helped in developing engineered microbial strains and systems that can convert complex toxic chemicals into simpler biological products.

## 2. Conventional Plastic Waste Management technologies and their Limitations

Traditional waste management practices were based primarily on ease and cost-effectiveness and weren't derived through environmental consciousness.

### *2.1 Landfilling*

Currently the most widely used waste disposal method seems to be landfilling which gradually buries plastic waste under the soil layers in sometimes designated and many times undesignated landfill sites. Landfilling generally seems relatively inexpensive until one tries to explore hidden complications it causes to land, groundwater, soil usage patterns due to its slowly degrading and hydrophobic nature and high molecular weight that makes it long-term contaminant for the environment (Roy et al., 2024). Landfilling is favoured historically for its cost-effectiveness and perceived simplicity. This method removes the waste from the site rather than eliminating it (Maalouf & Mavropoulos, 2022). Anaerobic and highly compact environment of a landfill severely suppresses the natural biodegradation process that makes accumulation of synthetic polymers possible, over the centuries (Chamas et al., 2020). As a result, such sites function as long-term repositories where these synthetic polymers frequently interact with ecological cycles. This causes gradual breakdown of plastics into microplastics and potentially harmful chemical leachates.

Toxic additives and greenhouse gases emerge because of physical deterioration of land-filled plastics. The Shivari landfill in Lucknow, India indicated severe risk of aquifer contamination as the Leachate Pollution Index (27.54) crossed critical thresholds, which directly originated from municipal solid wastes (Singh & Singh, 2024). Similarly in Poland, a detailed study in 2024 analysed that the groundwater contained significantly hazardous levels of total organic carbon and heavy metals like cadmium, that exceeded permissible limits up to 0.042 mg/L, due to a closed municipal waste landfill. This showcased the potential of inactive sites as persistent emission sources (Przydatek et al., 2025). Also, these environments when exposed to mechanical stress and weathering accelerate the degradation of plastics and are starkly documented near the Brahmapuram landfill in Kerala. Hereby a 2024 report stated significant post-fire surges in microplastics concentration in nearby water bodies (Amal and Devipriya, 2024).

### *2.2 Incineration*

The burning of plastic waste at higher temperatures to decrease the waste volume significantly and sometimes generation of energy is known as incineration (Kaza et al., 2018). This reduces the waste volume while causing air pollution by releasing gases such as carbon dioxide, nitrogen oxides, sulfur dioxide and toxic compounds including dioxins and furans (Verma et al., 2016) .

Moreover, this thermal destruction of synthetic polymers shifts the pollution burden from solid wastes to volatile atmospheric gases, persistent bottom ash and hazardous particulate matter. Since plastics are derived from petrochemicals, their combustion creates problems like release of potent greenhouse gases and other reactive pollutants, which further requires complex technologies for emission control (Davies, 2024).

Incineration of municipal non-biodegradable waste poses acute health risks along with severe ecological damage due to atmospheric pollutants rising from there. There was a toxicological study conducted in 2024 that aimed to analyse direct health impacts triggered by plastic incineration. In some research, primary human respiratory epithelial cells were exposed to smoke condensates and it revealed that acute exposure was directly responsible for severe oxidative stress, marked cellular inflammation and disrupted mitochondrial bio-energetics (Rogers et al., 2024). The combustion state drastically influences the type of pollutant released. The smouldering phase of commonly used plastics like PVC and polystyrene when compared to complete flaming combustion, emits highly concentrated submicron nanoplastic plastics particles and volatile organic compounds that possess far more severe risk of respiratory problems (Shen et al., 2025).

The Life Cycle Assessment (LCA) study of 2025 analysed the fate of plastic waste and reported that the environmental overstretching of incineration is also caused by factors such as utilisation of massive chemical demands required just for neutralizing of toxic flue gases like nitrogen dioxides, before releasing them into the atmosphere (Gautam, 2025). Energy generation through these sites is also a point of concern as research shows that unpredictable, rapid and haphazardous atmospheric transport of microplastics from sites allows horizontal as well as vertical movement of these pollutants over longer ranges. This accelerates their global cycle and toxic impacts on our ecosystem (Jiang et al., 2025).

### *2.3 Ocean Dumping*

The ocean being vast was mistaken as an infinite source to dilute solid waste and chemical pollutants without causing much harm to ecology (Borrelle et al., 2020). Disposal of wastes such as municipal garbage, industrial run-off and plastic trash into large water bodies and marine ecosystems such as oceans and seas, was also one such traditional malpractice related to waste disposal.

Ocean dumping disrupts aquatic ecosystems by exposing oceans to synthetic polymers, differing in chemical composition, buoyancy and density. Slow photodegradation and mechanical weathering causes fragmentation of microplastics that circulate in the water column and sediment into deep seabeds (Lau et al., 2020). Studies in Sundarbans mangrove ecosystem have reported that large traces of micro-plastics enter the region daily through river systems. This affects marine ecosystems and promotes microbial communities capable of degrading plastics (Saini et al., 2026).

Ocean dumping can also cause bioaccumulation of toxic compounds in humans as well as other marine organisms by disrupting marine food-chain and biodiversity. This has affected even highly endangered species like Logger-head sea turtles which had high concentrations of polyethylene and polystyrene, penetrated deep inside their eggshells along the coast of Florida. This field assessment proved severe environmental exchange and direct maternal transfer of toxins (Curl et al., 2024).

## 3. Microbial Biodegradation of Plastics

Plastic-degrading microbes are basically found in environments potentially contaminated by plastic waste such as landfills, marine sediments and industrial waste streams (Kaur et al., 2023). These microbes form bio-films to ease degradation of polymer chains by colonising plastic surfaces. High molecular weight, hydrophobicity and structural stability of plastics force formation of bio-films on polymer surface, which is followed by physical and chemical interaction with the substrate (Yadav et al., 2025). The colonization is then succeeded by extracellular enzyme secretion that performs chain scission and breaks long polymer chains into low-molecular-weight compounds (Yadav et al., 2025). Further metabolization of low-molecular-weight compounds formed after they are transported into microbial cell membranes, they enter central metabolic pathways like β-oxidation or the citric acid cycle and are mineralized into carbon dioxide and water for energy production and bio-mass formation (Yadav et al., 2025).

Over 100 micro-organisms identified till date have shown capability to degrade plastics, mainly belonging to genera *Pseudomonas*, *Bacillus*, *Streptomyces* and *Ideonella* (Kaur et al., 2023). Few are listed in table 1.

Researchers have isolated bacterial strains that have shown capability to degrade plastic. For example - marine bacteria such as *Bacillus tropicus* and *Bacillus cereus* that were isolated from Rameswaram coast were reported to disintegrate polypropylene microplastics (Jeyavani et al., 2024). Certain strains were isolated from soil samples collected from plastic waste dump sites in Punjab and Chandigarh and these isolated strains were capable of rupturing polyethylene and polystyrene polymers (Kumar et al., 2025).

**Table 1: Plastic-degrading microorganisms**

| S. No | **Plastic** | **Microorganisms** | **Origin of Discovery** | **Reference** |
|---|---|---|---|---|
| 1 | PET | *Ideonella sakaiensis* | Isolated from a microbial consortium from Sakai City, Osaka, Japan | Tanasupawat et al., 2016 |
| 2 | HDPE | *Micrococcus luteus strain CGK112* | Bovine microbiome / Cow dung (Uttarakhand) | Gupta et al., 2022 |
| 3 | Polyurethane | *Aeromicrobium strain LTX1* | Coastal Regions, China | Zhang et al., 2025 |
| 4 | Polystyrene | *Alcanivorax spp.* | Research conducted at Coimbatore, Tamil Nadu, India | Kaviarasi et al., 2026 |
| 5 | Polyethylene | *Streptomyces coeruleorubidus SALG1* | Swabs taken directly from an untreated, naturally degraded plastic bottle found washed up on a seashore of Bejaia, Algeria | Belabbas et al., 2025 |
| 6 | HDPE | *Klebsiella pneumoniae CH001* | Solid waste disposal sites (Uttar Pradesh) | Awasthi et al., 2017 |
| 7 | HDPE | *Arthrobacter spp. & Pseudomonas spp.* | Marine ecosystem of the Gulf of Mannar (Tamil Nadu) | Balasubramanian et al., 2010 |
| 8 | Polyethylene | *Pseudomonas spp.* | Research conducted at Ithaca, New York, USA | Wilkes and Aristilde, 2017 |
| 9 | LDPE | *Pseudomonas aeruginosa strain ISJ14* | Industrial waste soil | Das and Kumar, 2015 |
| 10 | LDPE & HDPE | *Bacillus vallismortis & Pseudomonas protegens* | Plastic-contaminated cow dung (Karnataka) | Skariyachan et al., 2017 |

## 4. Enzymatic Biodegradation Mechanisms

Enzymatic biodegradation provides a catalytic pathway for plastic de-polymerization, which is a highly specific process and independent functioning from complex physiological constraints cell microbial colonization (Dhali et al., 2024). In this process, modified or secreted enzymes like hydrolases, lipases, cutinases, oxireductases and esterases are used to directly target and cleave hydrolytically vulnerable bonds of synthetic polymers. It does not rely on physical biofilm formation. Due to this rapid catalytic scission, high-molecular weight and hydrophobic polymer chains are converted into low-molecular-weight oligomers and miscible monomers. These low-molecular-weight oligomers and miscible monomers can be recovered for closed-loop chemical recycling (Tournier et al., 2020).

The studies have reported that optimally targeted *in-silico* mutations in *Thermobifida fusca* cutinase improved its molecular binding affinity. This allowed high efficiency and simultaneous degradation of both polyethylene terephthalate and polyurethane (Sabari et al., 2025). Few researchers suggest that by complementing these molecular innovations, modifications in recalcitrant polymers like poly-lactic acid (PLA) with natural plant-fiber inclusions, significantly increase biological porosity and accelerate the insertion and hydrolytic efficiency of degrading enzymes (Momeni et al., 2023). Isolation of *Brucella intermedia* IITR130, showed the effective use of lipase and esterase enzymes to cleave PET ester bonds and produced terephthalic acid along with yielding approximately 26% physical degradation within 60 days (Srivastava et al., 2024).

### *4.1 PETase and MHETase*

A key breakthrough in plastic biodegradation research was the discovery of the bacterium *Ideonella sakaiensis*, which produces two enzymes, PETase and MHETase that work together to break down polyethylene terephthalate (PET) plastics (Yoshida et al., 2016). PETase breaks down the PET polymers into mono-2-hydroxyethyl terephthalate (MHET) which is subsequently broken down by MHETase into terephthalic acid and ethylene glycol. Microbial cells are able to utilize these products as a source of carbon.

The recent results have produced extensions of PETase, including Fast-PETase and DuraPETase that are more thermo-stable and active catalysts than natural enzymes (Liu et al., 2025). Enzymes to speed up the decomposition of plastics have also been developed in India at IIT-Roorkee by Indian scientists, and Indian biotechnology research continues to contribute in the area (Das et al., 2025).

## 5. Advanced Biotechnological Strategies

### *5.1 Enzyme Engineering*

Enzyme engineering alters the natural enzymes to improve their catalytic power, preservation and selectivity. Highly efficient PET-degrading enzymes have been prepared by techniques like directed evolution and rational protein design. The engineered PETase enzymes can be used to destroy PET plastics with greater efficiency and enhance enzyme-substrate interactions and thermal stability (Sherigar et al., 2025). The figure 1, illustrates the steps involved in enzyme engineering during the plastic biodegradation.

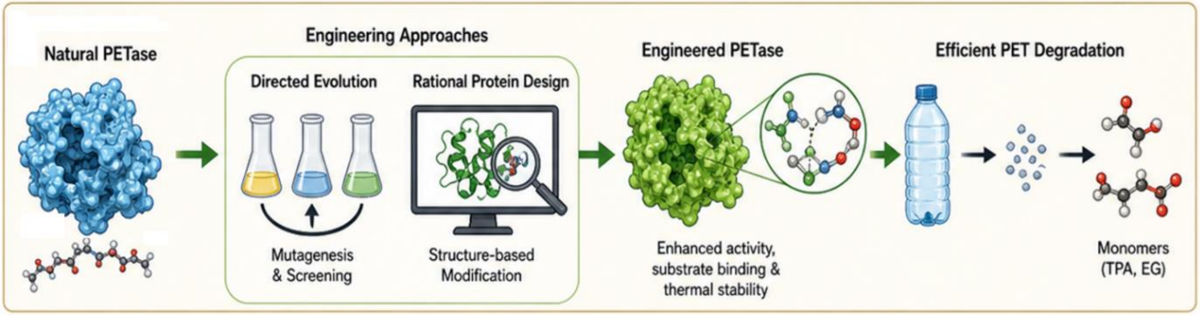


**Figure 1: Flow diagram involved in enzyme engineering for the plastic biodegradation**

### *5.2 Genetically Engineered Microorganisms*

Genetically engineered microorganisms (GEMs) are microorganisms whose genomes have been modified to internalize plastic degradation ability. Such organisms may be designed to synthesize more plastic-degrading enzymes or be able to more effectively process degradation products of plastics (Hernández-Sancho et al., 2024). The most common examples of microbial hosts used in genetic engineering are *Escherichia coli* and *Pseudomonas putida* that have a well-developed metabolic profile and can process aromatic complexes formed in the process of plastic degradation (de Lorenzo et al., 2024). Figure 2 illustrates the construction of genetically engineered microorganisms.

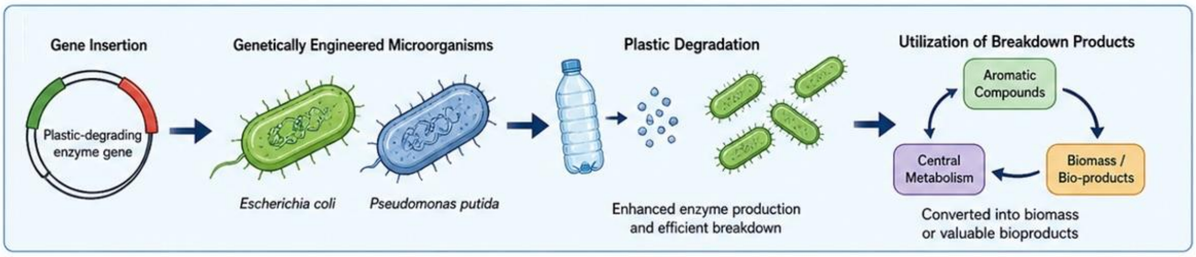


**Figure 2: Construction of Genetically engineered microorganisms (GEMs)**

### *5.3 CRISPR-Based Genome Editing and PlastiCRISPR*

CRISPR-Cas9 genome editing system has made a great impact concerning microbial biotechnology as it has facilitated the exact genetic alterations. CRISPR systems allow the insertion of genes which encode plastic-degrading enzymes into microbial hosts by the scientist. The new idea of the PlastiCRISPR was to design microorganisms which will effectively break down plastic polymers and at the same time the desired chemical produced because of plastic degradation can be reused (Palit et al., 2025). CRISPR based microbes have demonstrated the capability to break plastics including PET and polyethylene better than the natural strains of microbes (Riaz et al., 2025). Figure 3 illustrates the steps involved in designing the plastic degrading microbes using CRISPR-Cas9 genome editing system.

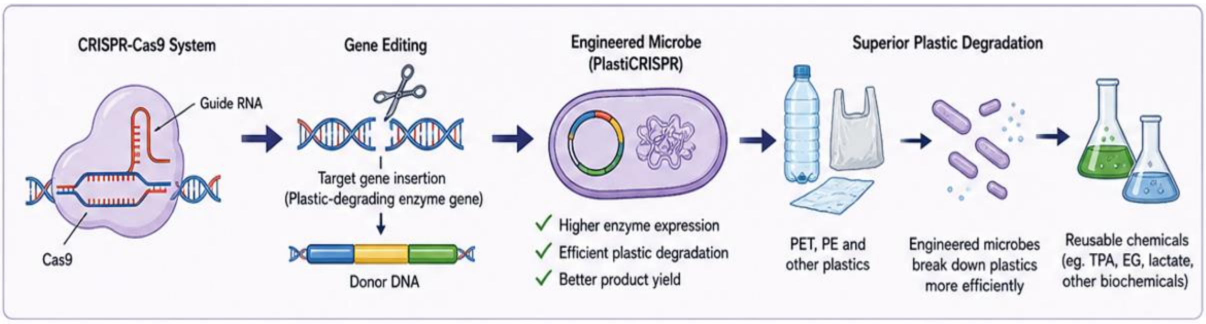


**Figure 3: CRISPR-Cas9 genome editing system to design plastic degrading microbes (PlastiCRISPR)**

### *5.4 Plastic Valorization and Circular Economy*

The microbial degradation of plastics has one promising side, that is the plastics waste can be turned into valuable products. Plastic-derived compounds, like terephthalic acid, can be converted into industrial chemicals, like muconic acid and biodegradable polymers, using engineered microorganisms designed with the help of metabolic engineering. These initiatives reinforce the creation of a circular economy whereby plastic waste can be used as a raw material to gain new chemicals and materials.

## 6. Challenges and Future Perspectives

Despite the potential of biodegradation technologies in the management of plastic wastes, there are several obstacles which have not yet been overcome before using the techniques on a large scale. Transition from laboratory settings to industrial settings remains one of the key hurdles. Other challenges include optimal integration of required enzymes, slow rate of microbial decay, resilience of genetically modified organisms (GMO) in the environment and regulatory frameworks regarding genetically modified organisms (GMO) (Mhaddolkar et al., 2024).

The further studies to be undertaken are expected to enhance the effectiveness of enzymes, creation of microbial consortia that have the capability to decompose mixed plastic waste and combining the biological degradation process with the high-tech methods of recycling trash and having industrial scalability potential.

## 7. Conclusion

Plastic pollution is one of the significant environmental issues that need new original and sustainable methods. Traditional methods of managing waste like landfilling and incineration cannot be used to tackle the increasing plastic waste.

Alternatives to plastic waste treatment by biodegradation should be considered as microbial and enzymatic biodegrading technologies which will ensure proper treatment of plastic waste in a more sustainable way. Advanced technology such as enzyme engineering, synthetic biology, and genome editing like CRISPR are making it possible to design microbial systems which can degrade plastic polymers more efficiently. As more research is required on interdisciplinary areas to explore technological innovation to get the solution of the plastic problem. The biodegradation technologies will be able to make plastic waste no longer a pollutant to the environment but a resource in a circular economy.

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**Conflict of Interest and Ethical Compliance: All authors confirm that:**

i. Any potential conflicts of interest, whether financial or non-financial, have been fully disclosed. – Yes / Not Applicable.

ii. All sources of funding and financial support received for the conduct of the study have been appropriately acknowledged, including any updates made during revision. – Yes / Not Applicable.

iii. Necessary ethical approvals have been obtained from the relevant institutional or regulatory bodies for studies involving human participants, animals, or sensitive data, wherever applicable, and are clearly stated in the manuscript. – Yes / Not Applicable.

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