



Isolation of plastic-degrading bacteria from soil: A systematic review

Aastha Nresht¹, Lavanya Bhatt¹, Shatakshi Rawat¹, Anita Chauhan^{2*}

¹ Department of Biotechnology, St. Bede's College, Navbahar, Shimla, Himachal Pradesh, India

² Assistant Professor, Department of Biotechnology, St. Bede's College, Navbahar, Shimla, Himachal Pradesh, India

Corresponding Author: Anita Chauhan

Abstract

Plastic pollution has become one of the most pressing global environmental concerns due to the persistence and recalcitrance of synthetic polymers in nature. Conventional disposal methods, such as landfilling and incineration, are unsustainable and pose ecological risks. Microbial degradation, particularly through bacteria, has emerged as a promising eco-friendly approach. Reported degradation rates vary from 5–30% weight reduction for polyethylene films after 30–90 days, depending on the bacterial strain. This review compiles data from studies isolating bacteria from landfill sites, industrial waste zones, marine sediments, agricultural fields, and compost pits. Common isolation methods include pre-enrichment with polyethylene films, mineral salt media supplemented with polymers, and screening via clear-zone formation or weight-loss measurements. This review summarizes recent progress in the isolation of plastic-degrading bacteria, including the sources from which they are obtained, the enrichment and screening techniques used, and the key bacterial genera reported to degrade different plastic types. Key bacterial genera—including *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Rhodococcus*—are highlighted for their reported ability to degrade polyethylene, PET, PVC, and other polymers. This review compiles current research on the isolation of plastic-degrading bacteria from soil, marine, landfill, and compost environments. It discusses enrichment culture techniques, polymer-supplemented media, zone-of-clearance assays, and biochemical or molecular tools used for identifying potent degraders. The role of enzymes such as PETase, MHETase, lipases, and laccases is also discussed. Finally, current challenges and future perspectives in enhancing bacterial plastic degradation are highlighted, emphasizing the potential of biotechnology and genetic engineering to address plastic waste accumulation.

Keywords: Plastic degradation, biodegradation, plastic-degrading bacteria, isolation techniques, PETases, microbial ecology

Introduction

The widespread use of plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene has resulted in large-scale environmental contamination. Plastics are resistant to natural degradation due to their stable carbon-carbon bonds and hydrophobicity. With global plastic production exceeding 400 million tons annually, alternative strategies to manage plastic waste are urgently needed. Microorganisms, particularly bacteria, have shown the ability to degrade plastics by secreting extracellular enzymes. Low density polyethylene (LDPE) is one of the major sources of environmental pollution. Polyethylene is a polymer made up of repeating units of ethylene monomers. The use of this synthetic polymer is growing at a rate of 12% per year and about 140 million tons of synthetic polymers are produced worldwide each year. It causes serious threats to the environment both during its production and after its disposal (Singh *et al.*, 2014) ^[1]. In 1950, the global production of plastics (excluding fiber) was 1.3 million tons, and by 2018, it reached an alarming level of 359 million tons (excluding fiber), resulting in widespread environmental contamination. It is estimated that only 10% of plastic waste is recycled, 14% is incinerated, and the rest is dumped into landfills, ultimately entering the natural environment. Plastics are transported through air and water currents; therefore, they not only affect the natural environment but also pose adverse ecological impacts in the deep-sea sediments and Polar Regions (Cai *et al.*, 2023) ^[12]. The isolation, identification, and characterization of microorganisms with plastic-degrading potential are frequently conducted from

aquatic environments, waste disposal landfills, or places that are in direct contact with the plastic, such as plastic refineries. However, growing microorganisms outside their natural environments using conventional approaches is extremely challenging and limits the number of isolated species that can be cultured and studied to as little as 1% or lower. Studying single microbial isolates also limits our understanding of the microbial ecology of plastic degradation, where microbial consortia have been found to act synergistically, producing more enzymes and degrading plastics more efficiently than individual species (Zrimec *et al.*, 2021) ^[26]. Traditional solid waste treatment methods, such as landfills and incineration, have limitations in terms of secondary pollution and limited land resources. The main thermomechanical and chemical recycling methods are energy-intensive, require high temperatures, and can result in alterations to the properties of the PET plastic. Thus, there is a growing interest in less energy-intensive or more “natural” methods for processing this material.

The discovery of the PET-degrading enzyme PETase from *Ideonella sakaiensis* (IsPETase) in 2016 provided hope for a biological solution in using enzymes and microbial factories for processing this inert plastic. Enzyme-catalysed PET recycling or bioprocessing can proceed under mild reaction conditions with minimal energy and chemical usage. This method of recycling is thus a more environmentally responsible alternative to petroleum-derived production processes (Tiong *et al.*, 2023) ^[38]. This breakthrough has opened new possibilities for sustainable recycling methods that minimize chemical usage and reduce dependence on petroleum-derived plastic pollution. This

review discusses the methodological framework and recent findings in the field, emphasizing soil-based isolation and laboratory protocols.

Diversity of Plastic-Degrading Bacteria

Plastic-degrading bacteria have been isolated from a wide variety of ecological niches, including landfill soil, marine water, sewage wastewater, composting sites and industrial dumping grounds. Studies report bacteria such as *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Streptomyces*, and *Ideonella sakaiensis* as dominant degraders due to their ability to attach to polymer surfaces and secrete depolymerizing enzymes (Singh *et al.*, 2014) [1]. Further work on landfill soil confirmed the presence of multiple indigenous bacteria capable of degrading polythene and LDPE waste (Pratiksha *et al.*, 2019) [2]. Additional screening studies from garbage-dumped soil also identified several bacterial strains with high degradation efficiency (Rosario, 2017).

In wastewater environments, diverse bacterial isolates including *Pseudomonas*, *Enterobacter* and *Acinetobacter* have been shown to degrade plastics under laboratory conditions (Ali *et al.*, 2023) [4]. Bacteria from highly polluted waste-disposal sites also show enhanced degradation efficiency due to continuous adaptation to plastic-degrading microorganisms (Javid *et al.*, 2024) [5]. Moreover, coastal and marine surveys – such as those in Jakarta Bay – have been identified new PET-degrading strains, demonstrating the wide global distribution of distribution of plastic-degrading microorganisms (Azizi *et al.*, 2024) [6].

Together, these findings show that plastic-degrading bacteria are abundant, ecologically diverse, and widespread across terrestrial, aquatic and industrial environments.

Enzymes Involved in Polymer Degradation

Bacterial degradation of synthetic plastics largely depends on extracellular and intracellular enzymes capable of breaking down stable polymer structures. One of the most significant breakthroughs in this field was the discovery of PETase and MHETase enzymes, which are responsible for the hydrolysis of polyethylene terephthalate (PET) into its monomeric components (Mohan and Sharma, 2020) [16]. PETase initiates the degradation process by converting PET into mono-(2-hydroxyethyl) terephthalate (MHET), while MHETase subsequently converts MHET into terephthalic acid and ethylene glycol, completing the depolymerization pathway (Maity *et al.*, 2021) [22].

The biodegradation of other plastics requires distinct enzymatic systems. For instance, polyethylene (PE) and polypropylene (PP), which are more resistant to biodegradation, are initially attacked by oxidative enzymes such as laccases, alkane hydroxylases, monooxygenases, cutinases, and cytochrome P450 enzymes (Yeom *et al.*, 2022; Ali *et al.*, 2021) [18, 39]. These enzymes introduce oxygen-containing functional groups into the polymer backbone, weakening carbon-carbon bonds and enhancing susceptibility to further enzymatic degradation (Gates and Crook, 2024) [31].

Microbial plastic degradation typically involves both intracellular and extracellular enzymes that catalyze the breakdown of polymers into simpler, environmentally benign organic compounds (Gu, 2003) [8]. Among these, hydrolases represent a key enzyme class, including

esterases, lipases, cutinases, and polyester hydrolases, which are particularly effective in cleaving ester bonds found in plastics such as PET, polycaprolactone (PCL), and polylactic acid (PLA) (Mohan and Sharma, 2020; Gates and Crook, 2024) [16, 31]. A well-studied example is *Ideonella sakaiensis*, where PETase hydrolyses PET into MHET, and MHETase further converts MHET into terephthalic acid and ethylene glycol (Maity *et al.*, 2021) [22].

Oxidative enzymes such as laccases, peroxidases, monooxygenases, and cytochrome P450s play a crucial role in initiating surface oxidation of non-biodegradable polymers like PE and PP, increasing their hydrophilicity and facilitating subsequent enzymatic action (Yeom *et al.*, 2022; Ali *et al.*, 2021) [18, 39]. Additionally, biofilm-associated enzyme systems significantly enhance plastic degradation, as biofilms enable the collective secretion of multiple enzymes that synergistically act on plastic surfaces (Howard and McCarthy, 2023; Howard *et al.*, 2023) [17, 25, 29].

Recent advancements in protein engineering have led to the development of improved PETase variants with enhanced thermostability and catalytic efficiency, allowing faster degradation under industrially relevant conditions (Tiong *et al.*, 2023) [38]. Comprehensive reviews of microbial metabolism further highlight the diversity of enzymes involved in the degradation of multiple plastic types and the regulatory mechanisms governing their expression within bacterial cells (Lv *et al.*, 2024) [20, 21]. Broader analyses of plastic biodegradation pathways emphasize the central roles of oxygenases, esterases, and depolymerases in the microbial breakdown of complex synthetic polymers (Cai *et al.*, 2023) [12]. Collectively, these enzyme systems constitute the biochemical foundation of microbial plastic degradation and are pivotal to the development of efficient biological recycling and bioremediation technologies.

Mechanisms of Bacterial Plastic Biodegradation

Microbial plastic biodegradation proceeds through four fundamental stages: biodeterioration, depolymerization, assimilation, and mineralization. During the initial biodeterioration phase, bacteria attach to the polymer surface and form biofilms, leading to surface erosion, microcracks, and increased polymer fragility (Cai *et al.*, 2023) [12]. Depolymerization follows, wherein extracellular enzymes cleave long polymer chains into smaller oligomers and monomers. Comprehensive reviews of microbial degradation mechanisms highlight that oxidative enzymes, including oxygenases and dehydrogenases, initiate bond cleavage in highly resistant polymers such as polyethylene (Lv *et al.*, 2024) [20, 21]. Assimilation occurs when these low-molecular-weight compounds are transported into microbial cells and incorporated into metabolic pathways such as β -oxidation and the tricarboxylic acid (TCA) cycle. The final stage, mineralization, results in the conversion of plastic-derived carbon into carbon dioxide, water, and microbial biomass. Detailed biochemical analyses emphasize that depolymerization represents the rate-limiting step in plastic biodegradation (Gates and Crook, 2024) [31]. Furthermore, microbial consortia exhibit enhanced degradation efficiency due to synergistic metabolic interactions among different microbial species (Edwards *et al.*, 2022) [23].

Plastic biodegradation is therefore a multistep process regulated by microorganisms through combined physical, chemical, and enzymatic actions. The process is commonly

described in four stages: surface colonization, depolymerization, assimilation, and mineralization (Gu, 2003; Mohanan and Sharma, 2020; Gates and Crook, 2024) [8, 16, 31].

1. Surface Colonization and Biofilm Formation

Surface colonization involves the attachment of microorganisms to plastic substrates, followed by the formation of biofilms. Bacterial genera such as *Pseudomonas*, *Bacillus*, *Rhodococcus*, and *Ideonella* adhere to plastic surfaces through the secretion of extracellular polymeric substances (EPS), enabling stable and long-term colonization (Howard and McCarthy, 2023; Howard *et al.*, 2023) [17, 25, 29]. Biofilm formation significantly enhances degradation efficiency by maintaining close contact between secreted enzymes and the polymer surface, facilitating sustained enzymatic activity (Howard and McCarthy, 2023) [17, 25, 29].

2. Depolymerization

Following surface modification, microorganisms secrete extracellular depolymerizing enzymes that cleave high-molecular-weight polymers into oligomers and monomers. Hydrolases such as cutinases, esterases, lipases, and polyester hydrolases play a dominant role in the degradation of ester-linked polymers including polyethylene terephthalate (PET), polylactic acid (PLA), and polycaprolactone (PCL) (Mohanan and Sharma, 2020; Maity *et al.*, 2021; Gates and Crook, 2024) [16, 22, 31]. In PET biodegradation, PETase catalyses the hydrolysis of PET into mono-(2-hydroxyethyl) terephthalate (MHET) and bis-(2-hydroxyethyl) terephthalate (BHET), which are subsequently converted into terephthalic acid and ethylene glycol by MHETase (Maity *et al.*, 2021) [22]. These low-molecular-weight products can then be transported into microbial cells for further metabolism.

3. Assimilation and Mineralization

The degradation products generated during depolymerization are assimilated by microbial cells and metabolized through central metabolic pathways such as β -oxidation, glycolysis, and the TCA cycle, leading to energy production and biomass formation (Lv *et al.*, 2024; Lv *et al.*, 2024) [20, 21]. Ultimately, complete mineralization converts plastic-derived carbon into carbon dioxide, water, and inorganic compounds, thereby completing the biodegradation process (Gates and Crook, 2024; Ali *et al.*, 2021) [31, 39].

Environmental Factors Affecting Degradation Efficiency

Environmental parameters play a crucial role in determining the efficiency of plastic biodegradation by bacteria. Factors such as temperature, pH, moisture, oxygen availability, and salinity significantly influence microbial growth, enzyme activity, and biofilm formation. Salinity, for example, has been shown to markedly reduce microbial degradation efficiency in river-to-ocean systems by inhibiting enzyme activity and suppressing bacterial growth (Dong *et al.*, 2023) [19]. Temperature and pH strongly regulate enzymatic pathways and biofilm stability, with most plastic-degrading enzymes exhibiting optimal activity under moderate environmental conditions (Mohanan and Sharma, 2020; Cai *et al.*, 2023) [12, 16]. Studies on plastic-associated biofilms demonstrate that stable microbial films substantially

enhance polymer degradation by increasing surface attachment and local enzyme concentrations (Howard and McCarthy, 2023) [17]. Environmental investigations in municipal landfills further indicate that seasonal temperature fluctuations and moisture availability strongly influence the diversity, distribution, and activity of plastic-degrading bacteria (Li *et al.*, 2022) [24]. Overall, environmental conditions affect plastic degradation through both physical and chemical processes and directly influence microbial metabolism and enzymatic efficiency (Gu, 2003; Lv *et al.*, 2024; Cai *et al.*, 2023; Gates and Crook, 2024) [8, 12, 20, 21, 31].

1. Temperature

Temperature significantly affects microbial metabolic activity and enzymatic reactions involved in plastic degradation. Elevated temperatures enhance polymer chain mobility, increasing susceptibility to enzymatic hydrolysis and oxidative cleavage (Gu, 2003; Mohanan and Sharma, 2020) [8, 16]. Thermophilic and mesophilic bacteria isolated from landfill soils, sewage systems, and marine environments have demonstrated increased degradation efficiency at temperatures ranging from 30 to 50 °C (Ali *et al.*, 2023; Javid *et al.*, 2024; Maity *et al.*, 2021) [4, 5, 22]. However, extreme temperatures may destabilize enzymes and inhibit microbial growth, ultimately reducing degradation rates (Lv *et al.*, 2024; Ali *et al.*, 2021) [20, 21, 39].

2. Moisture and Water Availability

Moisture is essential for microbial colonization and biofilm development on plastic surfaces. Adequate water availability facilitates enzymatic hydrolysis reactions and enables efficient diffusion of degradation intermediates and metabolic by-products (Cai *et al.*, 2023; Mohanan and Sharma, 2020) [12, 16].

3. pH

Environmental pH influences microbial survival, enzyme stability, and polymer hydrolysis. Most plastic-degrading bacteria exhibit optimal enzymatic activity under neutral to slightly alkaline conditions, typically within a pH range of 6.5–8.5 (Lv *et al.*, 2024; Gates and Crook, 2024) [20, 21, 31]. Deviations from this optimal range can lead to denaturation or reduced catalytic efficiency of plastic-degrading enzymes such as PETase and MHETase, thereby limiting degradation performance (Maity *et al.*, 2021) [22].

4. Oxygen Availability

Oxygen availability determines whether plastic degradation proceeds through aerobic or anaerobic pathways. Aerobic conditions generally promote faster degradation due to oxidative reactions and higher microbial energy yields (Gu, 2003; Ali *et al.*, 2021) [8, 39]. Many efficient plastic-degrading bacteria, including *Pseudomonas* and *Bacillus* species, are aerobic and demonstrate enhanced degradation activity in oxygen-rich environments (Singh *et al.*, 2014; Ali *et al.*, 2023; Howard *et al.*, 2023) [1, 4, 17, 25, 29].

5. Salinity

Salinity is a critical environmental factor affecting plastic degradation, particularly in marine and estuarine ecosystems. Elevated salinity levels have been shown to reduce the abundance and metabolic activity of plastic-

degrading bacteria, especially those originating from freshwater environments (Dong *et al.*, 2023) [19]. Research indicates a significant decline in enzymatic degradation efficiency as plastic debris transitions from riverine to oceanic systems, primarily due to osmotic stress imposed on microbial communities (Azizi *et al.*, 2024; Dong *et al.*, 2023) [6, 19].

In conclusion, environmental factors play an essential role in regulating microbial growth and enzymatic activity during plastic biodegradation. Understanding these parameters provides opportunities to develop genetically modified or environmentally adapted microorganisms with enhanced plastic-degrading capabilities, thereby improving the efficiency of bioremediation strategies (Ali *et al.*, 2021; Safdar *et al.*, 2024) [39, 40].

Genetic engineering and enzyme modification in plastic degradation

Genetic engineering and enzyme modification have emerged as powerful strategies to enhance microbial plastic degradation by improving enzyme activity, stability, and substrate specificity. Natural plastic-degrading enzymes often exhibit low efficiency under environmental conditions; therefore, molecular engineering approaches are employed to overcome these limitations (Martín-González *et al.*, 2024; Klauer *et al.*, 2024) [15, 30, 42].

1. Genetic engineering in plastic degrading microorganisms

Genetic modification involves introducing or improving the plastic degradation genes in microbial hosts to enhance the breakdown of polymer into simpler forms. Genes that code for enzymes like PETase, MHETase, cutinases, laccases, and monooxygenases are replicated into microorganisms such as *Pseudomonas putida*, *Escherichia coli*, and *Bacillus subtilis* that multiply at a fast rate, helping to increase enzyme yield and degradation efficiency (Martín-González *et al.*, 2024; Schneier *et al.*, 2024) [15, 34, 42]. Engineered strains have shown improved ability to utilize plastic-derived monomers as carbon sources, thereby accelerating biodegradation and biomass formation (Howard *et al.*, 2025; Su *et al.*, 2025) [17, 32].

2. Enzyme engineering and protein modification

Enzyme modification techniques like site-directed mutagenesis, rational protein design, and directed evolution are used to improve catalytic performance. Structural improvements in PETase have resulted in increased thermostability and higher hydrolytic activity toward crystalline PET, making enzymatic recycling more feasible under industrial conditions (Maity *et al.*, 2021; Klauer *et al.*, 2024) [22, 30]. Mutations in the enzyme active site improve substrate binding, while alterations in surface charge enhance enzyme-polymer interactions (Gates and Crook, 2024) [31].

3. Engineering synthetic and multienzyme systems

Studies have shown that synthetic enzyme pathways can be established to stimulate natural plastic degradation processes. When enzymes such as PETase and MHETase are present in a single organism, stepwise hydrolysis of polymers like PET into simple monomers is enhanced (Maity *et al.*, 2021) [22].

Biofilm engineering and regulation of enzyme expression

Biofilm-associated genetic modifications have been shown to enhance plastic degradation by increasing enzyme retention and local substrate concentration. Engineering biofilm-forming bacteria to overexpress plastic-degrading enzymes significantly improves degradation rates and polymer surface erosion (Howard and McCarthy, 2023; Howard *et al.*, 2023) [17, 25, 29]. Regulatory pathway manipulation further allows controlled enzyme expression in response to plastic presence, optimizing metabolic efficiency (Howard *et al.*, 2023) [17, 25, 29].

Although extensively used biofilm engineering face a lot of limitations and challenges:

1. Intrinsic Resistance of Plastic Polymers

The polymers themselves are considered to be the main obstacle in plastic degradation by microbes because polymers like polyethylene, polypropylene, polystyrene, and PVC are designed in such a way that they are long-lasting, highly durable and resist chemicals. Most of the plastics mentioned above make good packing materials with excellent qualities that come in everyday use making it available in abundance in the environment and causing environmental hazard.

These plastics have long carbon chains making them tightly packed and highly crystalline. Along with this the surfaces of these polymers are hydrophobic due to which water cannot easily interact over the surface and even cannot penetrate inside, and no gaps in between due to its tight packing also make it hard for the microbes to employ themselves in plastic degradation. Under natural conditions even if the bacteria are present, they are unable to attach, colonize and set in motion for plastic degradation. (Zhao *et al.*, 2024; de Albuquerque *et al.*, 2021; Buranyi, 2023) [11, 14, 37]

2. Constrained Effectiveness of Plastic- Degrading Enzymes

Enzymes possessed by plastic degrading bacteria do have their own shortcomings. Enzymes like PETase and Mhetase work at a slow pace under native environment conditions and are considered to be highly sensitive towards temperature and pH changes, though they can breakdown PET to a certain level. Certain enzymes are highly specific in degrading PET but are largely ineffective in breaking down more challenging and demanding polymers like PE or PP.

Residual products after the breakdown of plastic tend to accumulate around enzymes and inhibit their capability and deaccelerating the whole process. Therefore, the degradation under natural conditions is exceptionally slow and sometimes even no effect is seen as compared to the degradation done in lab under controlled condition showing comparatively faster degradation results as the enzymes clearly cannot retain the equivalent functional performance. (Roman *et al.*, 2024; Buranyi, 2023; Cai *et al.*, 2023; Choi *et al.*, 2023) [12, 14, 28, 36].

3. Environmental Limitations Lowering Natural Degradation

Numerous environmental factors influence the natural microbial degradation. For instance, in high- latitude regions or oceanic depths enzyme activities slows down drastically and in the same way in marine ecological zones having low

temperature and nutrient availability along with salinity generate extreme conditions. Even the excellent plastic degrading bacteria barely functions at such conditions. Presence of diminished number of microbes may also occurs because of salinity alone. This explains why the plastic no evidence breakdown manifestations could be seen in plastic and it can stay afloat over oceans and other water bodies for multiple decades. (Zrimec *et al.*, 2021; Johnson, 2024; Zhao *et al.*, 2024) ^[11, 26, 27].

4. Differences Separating Real-World Waste and Laboratory Studies

Significant challenge identified is between natural plastic degradation in the environment and laboratory testing and degradation under controlled condition. Approaches like cleaning, sterilizing, UV-treatment, pre-cutting into small pieces and powdering of the sample plastic are applied before starting the actual experiment resulting in tenderization, amplified surface area leading to uncomplicated microbial opportunity for providing good degradation results. On the other hand, plastic found in natural environment are coated in mud, dust, oily substances, pigments and supplementary substances all mixed together. This provides us with the view the plastic degradation might look easier and promising in laboratory condition as compared to the degradation occurring in natural environment over a certain period of time with slower and less efficient results. (de Albuquerque *et al.*, 2021; Buranyi, 2023; Gu, 2003) ^[8, 14, 37].

5. Complications of Plastic Waste Mixture

Plastics are never observed isolates especially in locations like garbage dumping sites, landfills, sewage, waterbodies and also keeping in mind that these comprise of sites which are highly preferred for sample collections of plastics for laboratory experimentations and these are the sites which are also kept in surveillance for constant checking of desired degradation occurring naturally. Even if the microbe having efficiency of degrading PE is present it will not show any effects because the plastics contain soil, dirt, pigments, oils forming the mixed layer over the surface of plastic making it hard for the microbe to interact or penetrate for breaking down reactions. This kind of mixture lead inhibition of other enzyme's activities due to the fact that no single enzyme can deal with all types of plastic, creating major obstacles in one another's pathway. (Javid *et al.*, 2024; Zhao *et al.*, 2024., Howard and McCarthy, 2023) ^[5, 11., 17, 25, 29].

6. Biofilm Constrains

Biofilm is the slimy layer formed by microorganisms on their surface. Biofilms peculiarly play a role with benefits and drawbacks. The sticky slimy layers help the microorganism to stick and adhere to the plastic surface along with enzyme secretion and on the other hand if the thickness of biofilms increases continuously it blocks the oxygen flow, capture degradation enzymes, not making them reach the actual plastic surface where they can act resulting in protecting the plastic instead of actually degrading it. Biofilms have been modified keeping in mind the limitations but this biofilm may expose specific microbes to the natural environment which are not necessarily required which can raise concerning situations. (Cai *et al.*, 2023; Gates and Crook, 2024; Howard and McCarthy, 2023) ^[12, 17, 25, 29, 31].

7. Partial Mineralization and Lagging Degradation

Even when the degradation occurs instead of comprehensive breakdown it concludes in fragments. Plastics first breakdown into microplastics and further to nano plastics. Nano plastics are considered even more harmful due to their ability to enter into the food chain. True mineralization that is conversion of plastic into carbon dioxide, water and biomass is hardly ever achieved and is exceptionally slow in void of specific microbes that too under controlled laboratory conditions. (Buranyi *et al.*, 2023; Zhao *et al.*, 2024; de Albuquerque *et al.*, 2021) ^[11, 14, 37].

8. Biological Safety Issues with Degraders

Some studies expose the fact that certain microbes contain some plastic degrading characteristics that are not safe for environmental applications. For example, *Pseudomonas aeruginosa*, possesses genes enabling plastic-associated survival and degradation. Using such organisms outside controlled environments invites risks of infection, unintended ecological shifts, and horizontal gene transfer. (Martín-González *et al.*, 2024; Howard and McCarthy, 2023; Maity *et al.*, 2021) ^[15, 17, 22, 25, 29, 42].

9. Economic and Stability Complications

Despite the fact that some enzymes and microbes work really good in degradation, scaling them up for the industrial productions is very expensive. Bioreactors require controlled conditions like proper aeration, nutrients, enzymes, temperature, pH, mixing, heating and many more conditions according to the culture condition which requires significant energy. Due to financial constrain culturing of these organisms become difficult and make the whole process even slower though the microbes might have excellent ecological potential. (Cf *et al.*, 2021; Sharma, Kaur and Shree, 2023; Yeom, Le and Yun, 2022) ^[13, 18, 33].

Emerging trends in the field of plastic degradation

1. Protein Maximization and Enzyme Modification

The success rate of the experiment relies with the enzyme itself. Tracing down the evolution help the researchers to engineer the enzymes according to the desired traits like enhancement of stability and flexibility with respect to different plastics and also modify their activities in increased temperatures and other harsh conditions. With the help of such approach's researchers can achieve enzymes which can tackle exceptionally resistant plastics like polyethylene. (Roman *et al.*, 2024; Choi *et al.*, 2023; Buranyi, 2023; Cai *et al.*, 2023) ^[12, 14, 28, 36].

2. Synthetic Biology Strategies

Single organism that can combine multiple degradation pathway can be produced using synthetic biology and such type of organisms are called "super microbes". These microbes can be engineered for the specific conditions like saline oceans, polluted streams, garbage dumping sites, landfills, etc. where it becomes hard for microorganisms to survive. Technique such as biosensing is also being added by the researchers which allow microbes to provide feedback on presence of plastic. This helps making the synthetic biology and unique and wide field of research in reference to plastic degradation. (Howard *et al.*, 2023; Ali *et al.*, 2021; Maity *et al.*, 2021; Howard and McCarthy, 2023) ^[17, 22, 25, 29, 39].

3. Microbial Associations and Cooperative Degradation

Scientists are now shifting towards finding microbial communities rather than a single isolate organism. In nature, species work in a coordinated manner like – one species breaks the plastic into fragments and other species feed on those fragments. This alliance coordination reveals the ability of microbes to bounce back and their adaptability to specific strains. This helps in getting good results in plastic degradation even from the mixed samples. (Howard and McCarthy, 2023; Schneier *et al.*, 2024; Gates and Crook, 2024; Lv *et al.*, 2024) [17, 20, 21, 25, 29, 31, 34].

4. Biological Material Valorization

Increasing scientific innovations also comprises of transforming plastics into something valuable rather than just focusing on its elimination. Plastic monomers can be converted into biodegradable plastics like PHA by microbes, also different industrial chemicals that can be used in detergents, paints, adhesives and even medical purposes can also be produced. Such transformations can make plastic degradation financially profitable. (Sharma *et al.*, 2023; Yeom *et al.*, 2022; Dong *et al.*, 2023) [13, 18, 19].

5. Environment Friendly and Bio-origin Plastics

Plastics like PLA and PHA are designed with the efficacy of natural degradation. Such types of plastics are produced from microbe and can be degraded by microbes as well, moreover with rapid growth and refinement this can even help us to replace the traditional petroleum derived products. (Liu *et al.*, 2025; Dong *et al.*, 2023; de Albuquerque *et al.*, 2021) [19, 35, 37].

6. Genomics and omics technologies

Thousands of promising plastic degrading genes integrated microbial populations around the globe can be discovered using high-throughput sequencing technologies. This will lead to rapid development in enzyme technology enhancing and providing different degradation pathways. All this is helping researchers not only to find new enzymes but discovering emerging microbial species that are adapted to plastic rich environment and also working upon plastic degradation simultaneously. (Howard *et al.*, 2025; Howard and McCarthy, 2023; Schneier *et al.*, 2024) [17, 25, 29, 32, 34].

7. Industrial convergence and strategic policy guidance

Increasing environmental concerns, government policies and economical growths have started to merge and align together. With demonstrating interest and profits biotech companies have initiated financing for processing of Enzymes- based recycling plants, leading to an eventual shift heading to industrial implementation and acceptance. Upon proper surveillance and regulation desirably, engineered microbe safely integrated in environment for degradation of plastics without any risks. (Cf *et al.*, 2021; Tiong *et al.*, 2023; Ali *et al.*, 2021) [33, 38, 39].

Onset of Plastic Degrading Microbes across the Globe

Researchers are frequently discovering microbes competent of different types of plastic degradation worldwide especially across continents- Asia, Europe, The Americas, and Island nations. Microbial communities indicating initial stages of plastic breakdown are hosted in different environment like landfills, marine coast, industrial dumps,

sewage and also including deep-sea sediments. This portrays that microbes around the globe are adapting and altering themselves to the large-scale presence of plastic everywhere (Singh *et al.*, 2014; Ali *et al.*, 2023; Javid *et al.*, 2024; Azizi *et al.*, 2024; Zrimec *et al.*, 2021) [1, 4, 5, 6, 26].

Lack of Balance in Research Emphasis: PET vs PE/PP

PETase are considered to be the revolutionized field, therefore maximum of the researchers have substantial focus over PET globally, showing a clear trend in research community. Whereas on the other hand polyethylene and polypropylene still lack effective microbial pathway. This clarifies why the heavy focus is on PET, and why its recycling has developed at a quicker pace than polyolefin degradation (Roman *et al.*, 2024; Choi *et al.*, 2023; Buranyi, 2023; Johnson, 2024) [14, 27, 28, 36].

Pollution – Driven Microbial Evolution

Worldwide studies strongly indicate that areas confirmed with high pollution (specifically plastic) have more number and emergence of microbial communities having genes that work upon microbial degradation. This allude to the fact that microbes are developing and evolving in response to pollution as feedback and are emerging with much stronger degradation competencies gradually with time (Zrimec *et al.*, 2021; Klauer *et al.*, 2024; Schneier *et al.*, 2024) [26, 30, 34].

Growth of Biofilm Strategies That Are Engineered

Engineered biofilms have gained attention because this helps microbes to deliberately adhere over the plastic surface and secrete concentrated enzymes. This helps in making degradation more productive and effective particularly in controlled environments like reactors because modified biofilms amplify the interactions between microbes and plastics (Cai *et al.*, 2023; Howard & McCarthy, 2023; Sharma *et al.*, 2023) [12, 13, 17, 25, 29].

Transition and Advancement Towards a Circular Polymer Economy

The traditional method of ‘use-and-dispose’ is now being replaced by a mindset for plastic reuse, remade and repurpose. Governments and industries have joined hands together for this circular model purpose. Biological upcycling and microbial degradation are beginning to appear as key ideal components of this emergence (Sharma *et al.*, 2023; Yeom *et al.*, 2022; Dong *et al.*, 2023; Klauer *et al.*, 2024) [13, 18, 19, 30].

Conclusion

Hence this review highlights the potential of bacteria to be used in the process of degradation for the plastics like PCL, Monofilament fibers of PCL, PHB/V, PBS. The bacterial species like Pseudomonas, Bacillus and Ideonella are some of the species found by the researcher to degrade the plastics through specialized enzymes like PETase, MHETase, and various oxygenases and hydrolases. These enzymes when released by the bacteria break the chemical bond present in the polymer hence resulting into the reduction in the size of the plastic, structural and chemical changes that occur with time or converting it into some organic products that are not harmful to the nature.

But plastic degradation through bacteria is a very time consuming process as this process can take few months to a complete year hence it cannot be considered a very effective

method to reduce plastic in very short period of time also the above mentioned species does reduce all type of plastic hence it is a selective method to reduce specific category of plastic that may be expensive an some bacteria may require genetic engineering, or controlled operating conditions. So, if we expand our research directions to either isolating these specialized enzymes on industrial scale and then using it for plastic degradation, using genetic engineering to modify the bacterial species or either generating methods for the treatment of plastic that helps to reduce the degradation time will help us to use bacteria to reduce the environmental pollution all around the world.

Conflict of Interest

Authors have no conflicts of interest.

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