The Plastisphere's Challenge: Microbial Biodegradation of Recalcitrant Polyethylene

Abstract

Polyethylene (PE), the world's most ubiquitous plastic, presents a profound environmental paradox: its exceptional durability, a key attribute for its widespread application, is also the source of its extreme persistence as a pollutant. With conventional recycling failing to manage the colossal volumes of PE waste, microbial biodegradation has emerged as a critical scientific frontier. This review critically examines the current state of PE biodegradation by microbial communities. We first contextualize the problem within the global plastic pollution crisis, highlighting the systemic failures that necessitate biological solutions. We then deconstruct the physicochemical barriers—including the inert carbon-carbon backbone, high molecular weight, crystallinity, and hydrophobicity—that render PE a formidable molecular fortress against microbial attack. A survey of the diverse bacteria and fungi implicated in PE degradation reveals that biofilms and synergistic consortia are central to the process, likely leveraging promiscuous enzymatic machinery co-opted from natural polymer degradation pathways. The biochemical assault is a multistage process initiated by extracellular oxidoreductases (e.g., laccases, peroxidases, and cytochrome P450s) that perform oxidative cleavage, followed by intracellular assimilation of the resulting oligomers via the beta-oxidation pathway. A critical assessment of the analytical methods used to validate biodegradation underscores the prevalent controversies, particularly the distinction between true mineralization and mere fragmentation, and calls for more rigorous, standardized protocols. We identify key knowledge gaps, including the slow kinetics of natural degradation and the incomplete characterization of enzymatic mechanisms. Finally, we provide a forward-looking perspective on the next decade of research, emphasizing how the convergence of metagenomics, enzyme engineering, and synthetic biology is poised to accelerate the discovery of novel biocatalysts and enable the design of efficient microbial systems for not only bioremediation but also the upcycling of PE waste into valuable bioproducts, paving the way for a circular bio-economy.

1. Introduction: The Polyethylene Paradox

The modern era is inextricably linked with the proliferation of plastics, materials prized for their versatility, low cost, and durability. Among these, polyethylene (PE) stands as the most produced and consumed polymer globally. However, this success has created an environmental paradox: the very durability that makes PE an ideal material for applications ranging from food packaging to industrial components also renders it extraordinarily persistent in the environment.[1]

The scale of the resulting pollution is staggering. Global plastic production has surged, more than doubling over the last two decades to exceed 450 million tonnes annually.[1] PE, in its various forms such as low-density (LDPE) and high-density (HDPE) polyethylene, is a primary contributor to this volume, driven largely by its use in single-use packaging, which constitutes 40% of all plastic applications.[4] The end-of-life management for this vast quantity of material is profoundly inadequate. An estimated 91% of all plastic waste is not recycled. Global analysis indicates that of the plastic waste collected, only about 15% is designated for recycling, with less than 9% actually being recycled after accounting for processing losses.[1] The remainder is incinerated (17%), landfilled (46%), or mismanaged (22%), with the latter portion contributing to the 19-23 million tonnes of plastic that leak into aquatic ecosystems each year.[4] Without urgent intervention, this environmental leakage is projected to triple by 2060.[3]

This data reveals a fundamental failure in our current waste management paradigm. The low effective recycling rate is not merely a consequence of consumer non-compliance but reflects deep-seated systemic issues, including the technical difficulty and economic non-viability of mechanically recycling contaminated, low-value PE films. This systemic bottleneck is a primary driver for exploring alternative, more sustainable solutions. Microbial biodegradation represents one such frontier, offering a potential pathway that operates under mild, environmentally benign conditions, in stark contrast to energy-intensive thermochemical recycling processes.[9] The ultimate vision extends beyond simple degradation to "bio-upcycling"—the engineered biotransformation of PE waste into value-added chemicals and materials, such as biodegradable polymers or biosurfactants.[12] Such a strategy could provide the economic incentives currently lacking in mechanical recycling, thereby addressing a root cause of plastic accumulation and fostering a truly circular economy. This review explores the biological and biochemical foundations of this ambitious goal, critically assessing the progress, challenges, and future directions in the microbial degradation of polyethylene.

2. The Molecular Fortress: Physicochemical Barriers to PE Biodegradation

The extreme recalcitrance of polyethylene is not an incidental property but a direct consequence of the molecular architecture that defines its performance. Microorganisms face a formidable "molecular fortress" protected by multiple layers of chemical and physical defenses, which must be overcome for biodegradation to occur.

Inherent Chemical Recalcitrance

At its core, PE is a simple long-chain alkane, with a chemical formula of $(C_2H_4)_n$.[14] This simple structure belies its chemical resilience.

- **The Carbon-Carbon Backbone:** The polymer is constructed from a saturated backbone of non-polar carbon-carbon (C-C) and carbon-hydrogen (C-H) single bonds. These bonds are thermodynamically stable and, crucially, non-hydrolyzable. Unlike biopolymers such as polyesters or polyamides, which contain heteroatoms (e.g., oxygen, nitrogen) that create susceptible ester or amide linkages, the PE backbone lacks functional groups that are readily targeted by the hydrolytic enzymes common in microbial metabolism.[2] This chemical inertness is the primary barrier to enzymatic attack.
- **Hydrophobicity:** The non-polar nature of the C-H bonds renders the PE surface extremely hydrophobic.[2] This property is advantageous for applications like packaging but presents a significant obstacle for biodegradation. Microbial enzymes operate in aqueous environments, and the hydrophobicity of PE repels water, hindering enzyme access to the polymer surface and inhibiting the initial attachment of microbial cells, a prerequisite for biofilm formation and degradation.[20]
- **High Molecular Weight:** Commercial PE possesses a very high molecular weight (MW), often exceeding 100,000 g/mol for HDPE and reaching into the millions for ultra-high-molecular-weight PE (UHMWPE).[14] Molecules of this size are far too large to be transported across the microbial cell membrane for intracellular metabolism.[19] Therefore, any biodegradation must be initiated by extracellular enzymes that can cleave the polymer into smaller oligomers. Seminal studies in the field noted that microorganisms could only readily metabolize very low MW alkanes and PE oligomers (e.g., MW < 4800 Da), highlighting the profound challenge posed by the sheer size of commercial PE polymers.[24]

Influence of Physical Properties

Beyond its chemical makeup, the physical organization of PE chains further reinforces its resistance to degradation.

- **Crystallinity:** PE is a semi-crystalline polymer, meaning its structure consists of highly ordered, densely packed crystalline regions (lamellae) interspersed with disordered, amorphous regions. This morphology directly impacts biodegradability. Microbial enzymes can more easily penetrate and attack the less-ordered polymer chains in the amorphous domains. However, the crystalline regions act as impenetrable barriers, severely limiting the extent of degradation.[19] The degree of crystallinity varies significantly among PE types—from around 50-60% in branched LDPE to over 90% in linear HDPE—and is inversely correlated with their susceptibility to microbial attack.[21]
- **Additives:** To achieve desired performance characteristics, commercial plastics are rarely pure polymers. They are complex formulations containing a variety of additives, including antioxidants to prevent thermal degradation, UV stabilizers, plasticizers, and colorants. These chemical additives can leach from the plastic matrix and may be toxic to microorganisms, inhibiting their growth and metabolic activity. Furthermore, they can physically mask the polymer surface, preventing enzymes from accessing the PE backbone.[28]

The combination of these properties creates a fundamental conflict between material science and environmental science. The very characteristics engineered into PE for superior performance—its chemical inertness, hydrophobicity, and high crystallinity—are the direct antagonists of biodegradation. This implies that a purely biological solution for degrading pristine, commercial-grade PE is unlikely to be efficient. A more promising strategy involves a synergistic approach, combining abiotic pre-treatments that first weaken this molecular fortress with subsequent, targeted biological degradation. This challenge also points toward a paradigm shift in polymer design, one that embraces an "end-of-life" perspective by intentionally engineering controlled instability—such as incorporating specific, enzymatically cleavable weak links—without compromising performance during the material's functional lifetime.

3. Nature's Decomposers: Microbial Communities Targeting PE

Despite the formidable barriers presented by polyethylene, nature is not without its own chemical arsenal. A growing body of research has identified a diverse array of microorganisms from various ecosystems that exhibit a capacity, albeit often limited, to colonize and degrade PE surfaces. These organisms form the foundation of our understanding of PE biodegradation and represent a rich genetic resource for future biotechnological applications.

A Survey of PE-Degrading Microorganisms

Microbes capable of degrading PE have been isolated from a wide range of environments, including plastic-polluted landfill soils, marine sediments, agricultural fields, and even the guts of plastic-ingesting insect larvae.[9] This diversity suggests that the metabolic potential to attack PE, or at least its constituent long-chain alkanes, is more widespread than previously thought. Both bacteria and fungi have been implicated as key players (Table 1).

Among bacteria, genera such as *Rhodococcus*, *Pseudomonas*, *Bacillus*, and *Streptomyces* are frequently reported.[32] Species like *Rhodococcus ruber* have been shown to form robust biofilms on PE surfaces and achieve measurable weight loss. Similarly, various *Pseudomonas* and *Bacillus* species isolated from dump sites have demonstrated the ability to alter the physical and chemical properties of LDPE films. Fungal genera, particularly *Aspergillus*, *Penicillium*, and *Fusarium*, are also prominent PE degraders.[32] Fungi are particularly well-suited for degrading solid substrates due to their hyphal growth mode, which allows them to physically penetrate the polymer surface, and their secretion of powerful extracellular oxidative enzymes.[39]

Table 1: Representative Microorganisms Implicated in Polyethylene Biodegradation

Organism (Genus, species)	Phylum/Class	Origin/Environment	PE Type	Key Findings/Enzymes Implicated	Reference(s)
Bacteria					
Rhodococcus ruber	Actinobacteria	Soil with agricultural plastic	LDPE	Formed biofilm, caused 8%	[20]

		waste		weight loss in 30 days. Laccase activity implicated.	
Pseudomonas aeruginosa	Proteobacteria	Dump sites, marine environments	LDPE	Efficient colonization of plastic surfaces; oxidative degradation capabilities.	[33]
Bacillus cereus	Firmicutes	Dandora dumpsite soil	LDPE	Caused 35.7% weight loss; FTIR showed formation of new functional groups.	[35]
Stutzerimonas stutzeri	Proteobacteria	Experimentally evolved consortia	PE	Dominant species expressing enzymes for PE degradation in a synergistic biofilm.	
Streptomyces spp.	Actinobacteria	Agricultural soil	LDPE	Associated with degradation, forming clear zones on	

				PE-containing agar.	
Fungi					
Aspergillus niger	Ascomycota	Dandora dumpsite soil, Pedosphere	HDPE, LDPE	Highest weight reduction (4.3-55%) among tested fungi in several studies.	[32]
Penicillium frequentans	Ascomycota	Soil	DPE (Degradable PE)	Formed a synergistic biofilm with *Bacillus mycoides*, causing ~7% weight loss.	
Cladosporium sp.	Ascomycota	Environmental isolate	LDPE	Degraded both untreated and heat-treated LDPE; secreted laccase.	
Fusarium sp.	Ascomycota	Polyethylene polluted sites	LDPE	Degraded 32% of LDPE sheets by weight in 4 weeks.	

The discovery of PE-degrading capabilities in microbes from pristine environments, such as alpine and forest soils, offers a profound clue about the evolutionary origins of this function.[34]

It suggests that the enzymatic machinery involved is not a recent adaptation to anthropogenic plastic pollution. Instead, it is more likely a case of enzymatic promiscuity, where enzymes that evolved to degrade naturally occurring recalcitrant polymers—such as lignin, cutin, or suberin—are co-opted to fortuitously attack the structurally analogous long-chain hydrocarbon backbone of PE.[25] This hypothesis explains both the widespread nature of the potential and the observed inefficiency of the process; these enzymes are not optimized for this novel, synthetic substrate. This realization redirects biodiscovery efforts, suggesting that environments rich in complex natural polymers, not just plastic-polluted sites, are promising sources for novel biocatalysts.

The Biofilm as a Degradation Hotspot

For a solid and hydrophobic substrate like PE, biodegradation is not the work of free-floating planktonic cells but is almost exclusively mediated by surface-attached microbial communities known as biofilms.[20] The formation of a biofilm is a critical, non-negotiable first step.

Microbes initiate the process by adhering to the PE surface. Once attached, they begin to secrete a matrix of extracellular polymeric substances (EPS)—a complex mixture of polysaccharides, proteins, lipids, and extracellular DNA. This EPS matrix creates a hydrated, nutrient-rich microenvironment that envelops the community, effectively overcoming the hydrophobicity of the plastic surface. It acts as a scaffold that concentrates cells and, crucially, retains the extracellular enzymes close to their substrate, preventing their diffusion away into the bulk environment and thereby increasing their catalytic efficiency.[10]

Furthermore, biofilms are often complex, multi-species consortia that exhibit a metabolic division of labor, leading to synergistic degradation that surpasses the capabilities of any single species.[42] For example, studies on experimentally evolved consortia have shown that some members, like *Stutzerimonas stutzeri*, may specialize in expressing the primary PE-degrading enzymes, while other community members contribute by secreting the polysaccharides necessary for robust biofilm formation. This cooperative strategy allows the community to function as a cohesive, highly efficient degradative unit.

4. The Biochemical Assault: Mechanisms of Enzymatic Depolymerization and Assimilation

The microbial breakdown of polyethylene is a complex, multi-stage process that spans from

the polymer surface to the core of cellular metabolism. It begins with an extracellular assault to break the polymer's formidable C-C backbone and concludes with the intracellular assimilation and mineralization of the resulting fragments. This entire pathway represents a remarkable feat of microbial biochemistry (Figure 1).

Stage 1: Surface Activation and Depolymerization (The Extracellular Attack)

Because of PE's inert nature, the biochemical attack cannot begin without an initial activation step that renders the polymer susceptible to enzymes.

- **Abiotic Pre-treatment as an Initiator:** In many laboratory studies and likely in the natural environment, the process is initiated by abiotic factors. Exposure to ultraviolet (UV) radiation from sunlight and thermal stress causes photo- and thermo-oxidation of the polymer.[48] This abiotic weathering is not trivial; it introduces oxygen-containing functional groups, primarily carbonyl (C=O) and hydroxyl (-OH) groups, onto the polymer's surface.[20] These groups disrupt the polymer's non-polar nature, increasing its hydrophilicity, which facilitates microbial attachment and provides initial "handles" for enzymatic attack.
- **The Oxidoreductase Toolkit:** The central and most challenging biochemical step is the enzymatic cleavage of the C-C backbone. This is an oxidative process, fundamentally different from the hydrolysis of biopolyesters. Microorganisms deploy a toolkit of powerful extracellular oxidoreductases to achieve this.
    - **Laccases and Peroxidases:** Lignin-degrading fungi and some bacteria secrete broad-specificity enzymes like laccases, manganese peroxidases (MnP), and lignin peroxidases (LiP).[22] These enzymes do not typically bind to a specific site on the polymer. Instead, they generate highly reactive, diffusible mediators or radicals that carry out a non-specific oxidative attack on the PE chain, leading to bond scission.[41]
    - **Alkane Hydroxylases (AHs) and Cytochrome P450s:** A more targeted mechanism involves enzymes known to metabolize long-chain alkanes, which are structural analogues of PE. Enzymes such as alkane hydroxylases and cytochrome P450 monooxygenases catalyze the terminal or subterminal oxidation of the PE chain.[18] This reaction inserts an oxygen atom into a C-H bond, forming an alcohol. This primary alcohol can then be sequentially oxidized by other enzymes (e.g., alcohol and aldehyde dehydrogenases) to an aldehyde and finally to a carboxylic acid.[18] This creates a fatty acid-like molecule from the end of the PE chain, which is now amenable to further metabolism. Strong evidence for this pathway comes from transcriptomic studies of PE-degrading consortia, which have identified the significant upregulation of a gene encoding a cytochrome P450 (CYP102 A5) during

growth on PE.[18]

Stage 2: Assimilation of Degradation Products (The Intracellular Metabolism)

The initial extracellular attack generates a heterogeneous mixture of smaller, more soluble molecules, including long-chain alkanes, alcohols, ketones, and dicarboxylic acids.[18] These degradation products are then transported into the microbial cell for catabolism.

- **Uptake and the Beta-Oxidation Pathway:** Once inside the cell, these fatty acid-like fragments are proposed to be funneled into the beta-oxidation pathway.[56] This is a core, highly conserved metabolic pathway used by a vast range of microorganisms to break down fatty acids. In a cyclic series of four enzymatic reactions, the long-chain molecule is progressively shortened, releasing a two-carbon unit in the form of acetyl-CoA with each cycle.
- **Mineralization via the TCA Cycle:** The acetyl-CoA generated from beta-oxidation then enters the central metabolic hub of the cell: the tricarboxylic acid (TCA) cycle. Here, it is completely oxidized to carbon dioxide (CO_2), generating cellular energy in the form of ATP and reducing equivalents (NADH and $FADH_2$) that fuel biosynthesis and cell growth. This final conversion of the polymer's organic carbon into inorganic CO_2 is termed **mineralization**. It represents the definitive endpoint of biodegradation, signifying the complete removal of the pollutant from the environment and its integration into the natural carbon cycle.[17]

This two-part mechanism reveals a critical insight: the true bottleneck in PE biodegradation is not the cell's ability to metabolize the breakdown products, but its ability to generate them in the first place. The beta-oxidation and TCA cycles are fundamental, widespread metabolic pathways. In contrast, the extracellular enzymes capable of initiating the oxidative cleavage of the inert PE backbone are highly specialized and, in their native form, inefficient against this synthetic substrate. This suggests that future efforts in synthetic biology should focus on a modular approach: discovering and engineering hyper-efficient extracellular "depolymerase" modules and deploying them in robust microbial chassis that are already optimized for the subsequent, more generic, intracellular metabolism.

Figure 1: Proposed Multistage Pathway of PE Biodegradation by a Microbial Community

(A) Abiotic Pre-treatment & Surface Activation: A schematic of a long polyethylene $(C_2H_4)_n$ polymer chain is shown. Arrows indicating UV radiation and heat point to the chain, causing the formation of carbonyl (C=O) and hydroxyl (O-H) groups at various points

along the backbone. This represents the initial photo- and thermo-oxidative weathering that increases surface hydrophilicity.

(B) Biofilm Colonization: A cross-section of the activated PE surface is depicted with various bacterial and fungal cells adhering to it. The cells are embedded within a matrix representing the extracellular polymeric substances (EPS) of the biofilm. This panel illustrates the formation of a hydrated microenvironment essential for degradation.

(C) Extracellular Enzymatic Depolymerization: From the biofilm, arrows labeled "Extracellular Oxidoreductases" point towards the PE chain. Magnified views show specific enzymes, labeled "Laccase/Peroxidase" and "Cytochrome P450/Alkane Hydroxylase," acting on the polymer. The Laccase/Peroxidase is shown generating radicals that cause random chain scission. The P450/AH is shown performing a targeted terminal oxidation, converting a $-CH_3$ end group into a carboxylic acid group $(-COOH)$. This process results in the release of smaller, soluble fragments, depicted as dicarboxylic acids and other short-chain oligomers.

(D) Intracellular Assimilation via Beta-Oxidation: A bacterial cell is shown with transporters on its membrane actively importing the dicarboxylic acid fragments from the extracellular space. Inside the cell, these fragments enter a cyclic pathway labeled "Beta-Oxidation." With each turn of the cycle, a two-carbon unit, labeled "Acetyl-CoA," is cleaved off.

(E) Mineralization in the TCA Cycle: The Acetyl-CoA molecule is shown entering another cyclic pathway labeled "Tricarboxylic Acid (TCA) Cycle." Arrows exiting this cycle show the final products of complete mineralization: CO_2 (carbon dioxide), H_2O (water), and "Biomass/ATP," signifying the integration of the polymer's carbon and energy into cellular growth and metabolism.

---

5. Validating the Unseen: A Critical Assessment of Analytical Methods

Demonstrating the biodegradation of a highly recalcitrant polymer like polyethylene is a significant analytical challenge. The process is slow, the changes are subtle, and artifacts can easily lead to misinterpretation. A major source of controversy and irreproducibility in the field stems from the use of inadequate or incomplete analytical evidence.[61] Conclusive proof requires a multi-faceted approach, employing a hierarchy of techniques that together build a compelling case for true biodegradation, from initial surface deterioration to complete mineralization (Table 2).

A Tiered Approach to Evidence

The analytical methods used to study PE biodegradation can be organized into tiers based on the level of evidence they provide.

- **Tier 1: Visual and Physical Evidence (Indicative but Ambiguous):** These methods detect macroscopic or microscopic changes to the polymer but cannot, on their own, distinguish biodegradation from simple physical or chemical deterioration.
    - **Weight Loss:** Measuring the reduction in mass of a PE sample over time is the simplest and most common assay.[16] However, it is notoriously unreliable as a sole indicator of biodegradation. Weight loss can be caused by the leaching of soluble additives from the plastic matrix or by the physical abrasion and fragmentation of the material into smaller pieces that are lost during sample recovery, rather than microbial consumption.[21]
    - **Surface Morphology Analysis (SEM, AFM):** Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) are powerful techniques for visualizing the polymer surface at high resolution. They can provide clear evidence of microbial colonization, biofilm formation, and surface erosion, such as the formation of pits, cracks, and cavities.[34] These observations are strong proof of **biodeterioration**—the initial stage of degradation—but they do not confirm that the polymer has been metabolized.
- **Tier 2: Chemical and Structural Changes (Evidence of Depolymerization):** These techniques probe the molecular structure of the polymer, providing direct evidence of chemical modification and chain cleavage.
    - **Fourier Transform Infrared Spectroscopy (FTIR):** FTIR is essential for detecting changes in the chemical bonding within the polymer. Its primary use in PE biodegradation studies is to identify the appearance of new functional groups, particularly the characteristic absorption bands of carbonyl (C=O) and hydroxyl (-OH) groups.[18] The formation of these groups is a hallmark of the oxidation of the PE backbone and serves as strong evidence that a chemical transformation has occurred.
    - **Gel Permeation Chromatography (GPC):** GPC (also known as Size Exclusion Chromatography, SEC) separates polymer molecules based on their size, allowing for the determination of the material's molecular weight and molecular weight distribution. A measurable decrease in the average molecular weight of the PE sample is a key indicator of **depolymerization**, confirming that the long polymer chains have been cleaved into shorter fragments.[16]
- **Tier 3: The Gold Standard (Proof of Mineralization and Assimilation):** These methods provide definitive, quantitative proof that the carbon from the PE polymer has been processed through microbial metabolism.

- **CO_2 Evolution Measurement (Respirometry):** This technique involves incubating the PE sample with microorganisms in a closed system and measuring the amount of CO_2 produced over time. Since CO_2 is the end product of aerobic respiration, its evolution above background levels is direct evidence of **mineralization**.[16]
- **^{14}C-Isotope Labeling:** This is the most unambiguous and rigorous method for proving biodegradation.[62] In this approach, custom-synthesized PE containing the radioactive isotope carbon-14 (^{14}C) is used as the substrate. After incubation with the microbial community, the fate of the ^{14}C label is tracked. The detection of ^{14}C in the evolved CO_2 ($^{14}CO_2$) and incorporated into microbial biomass provides irrefutable proof that the carbon atoms from the polymer backbone have been assimilated and metabolized by the microorganisms.

Controversies, Limitations, and the Need for Standardization

The primary controversy in the field revolves around the distinction between **biodegradation** and **fragmentation**.[61] Many studies, particularly earlier ones, have claimed biodegradation based solely on Tier 1 evidence like weight loss or surface pitting. However, abiotic processes can cause PE to fragment into microplastics, which increases the surface area but results in persistent, potentially more harmful, secondary pollution.[21] This is not biodegradation. True biodegradation requires evidence of chemical change and, ideally, mineralization.

This issue is compounded by a severe lack of standardization across studies. Researchers use different types of PE (LDPE, HDPE, films, powders), various and often unspecified additives, inconsistent pre-treatment methods, and diverse incubation conditions.[8] This heterogeneity makes it nearly impossible to compare results between laboratories, hindering progress and fueling debates about reproducibility.[61]

The practical challenges associated with the gold-standard methods have inadvertently created a "hierarchy of evidence" in the published literature. The high cost and technical complexity of synthesizing and working with ^{14}C-labeled polymers make this definitive technique inaccessible for many routine screening studies. This forces many researchers to rely on less conclusive but more accessible methods from Tiers 1 and 2. Consequently, the literature is populated with studies of varying rigor, leading to a landscape where claims of biodegradation must be critically evaluated based on the analytical methods employed. To move forward, the field urgently needs to establish standardized testing protocols and develop more accessible, intermediate-level assays—perhaps based on specific biomarkers or advanced mass spectrometry—that can bridge the gap between simple screening and definitive isotopic proof.

Table 2: Critical Comparison of Analytical Techniques for Assessing PE Biodegradation

Technique	Principle	What It Measures	Strengths	Limitations & Controversies
Weight Loss	Gravimetric analysis of sample mass before and after incubation.	Overall mass reduction of the polymer sample.	Simple, inexpensive, and widely accessible for initial screening.	Highly ambiguous; cannot distinguish between biodegradation, leaching of additives, and physical fragmentation. Not sufficient proof of biodegradation alone.[16]
SEM / AFM	Electron/probe microscopy to visualize surface topography.	Changes in surface morphology (e.g., pits, cracks, roughness) and biofilm formation.	Provides direct visual evidence of microbial interaction and surface deterioration. High resolution.	Qualitative; provides proof of biodeterioration but not of depolymerization or mineralization. Cannot quantify the extent of degradation.[64]
FTIR Spectroscopy	Infrared radiation absorption by molecular bonds.	Formation or disappearance of specific chemical functional groups (e.g., C=O, O-H).	Provides direct evidence of chemical modification (oxidation) of the polymer backbone. Relatively	Does not directly measure chain scission or mineralization. Changes can be subtle and limited to the

			accessible.[38]	surface.
GPC / SEC	Chromatographic separation of molecules by hydrodynamic volume.	Changes in average molecular weight and molecular weight distribution.	Provides direct, quantitative evidence of polymer chain scission (depolymerization), a key step in biodegradation.[16]	Requires polymer to be soluble in a solvent, which can be challenging for PE. Does not confirm assimilation or mineralization.
CO_2 Evolution	Measurement of CO_2 production in a closed system (respirometry).	Rate and extent of conversion of polymer carbon to inorganic carbon (CO_2).	Provides definitive, quantitative proof of mineralization, the final step of biodegradation. Standardized methods exist (e.g., ISO 14855).[19]	Can be slow and long-term. Requires careful controls to subtract background respiration from other carbon sources in the system.
^{14}C-Isotope Labeling	Tracking a radioactive (^{14}C) label from the polymer into products.	Unambiguous transfer of carbon from the PE backbone to CO_2 and microbial biomass.	The "gold standard"; provides irrefutable, quantitative proof of both assimilation and mineralization. The most definitive method available.[62]	Technically complex, expensive (requires custom synthesis of labeled polymer), and requires specialized facilities for handling radioactivity.

6. Current Challenges and Knowledge Gaps

Despite significant progress in identifying potential PE-degrading microorganisms and elucidating a plausible biochemical pathway, the field of polyethylene biodegradation is still in its infancy. Several critical challenges and knowledge gaps must be addressed before this research can be translated into practical, large-scale environmental technologies.

- **The Kinetics Problem:** Perhaps the most significant barrier is the extremely slow rate of microbial degradation observed under laboratory conditions, let alone in natural environments. Reported weight losses are often in the low single digits over incubation periods of months or even years.[18] These rates are orders of magnitude too slow to be ecologically relevant for managing the current flux of plastic waste or for industrial application.[61] Overcoming this kinetic barrier is the central challenge for the field.
- **The "Black Box" of Enzymology:** While several classes of oxidoreductase enzymes have been implicated in the initial attack on PE, the precise enzymes responsible for C-C bond cleavage in most identified organisms remain unconfirmed. The exact catalytic mechanisms are poorly understood, and it is still a matter of debate whether degradation is primarily driven by specific enzymes directly interacting with the polymer or by non-specific, highly reactive chemical species (e.g., reactive oxygen species, ROS) generated by these enzymes as a secondary effect.[62] Without a clear understanding of the key biocatalysts and their mechanisms, rational engineering efforts are severely hampered.
- **The Lab-to-Environment Gap:** There is a profound disconnect between highly controlled laboratory experiments and the complex, dynamic conditions of a real-world environment.[16] Most studies demonstrating measurable degradation rely on significant abiotic pre-treatment (e.g., intense UV or heat) and often use pure microbial cultures or simple consortia with optimized nutrient media.[49] How these organisms and processes function *in situ*—in competitive, nutrient-limited environments like soil or marine ecosystems, where PE is not pre-treated—is largely unknown. The ecological principles governing the succession and function of plastisphere communities remain a major knowledge gap.
- **Metabolic Byproducts and Ecotoxicity:** Complete mineralization of PE to CO_2 and water is the ideal outcome. However, incomplete degradation, which is far more likely given the slow kinetics, can lead to the formation and accumulation of a variety of intermediate metabolic byproducts, such as dicarboxylic acids and other oxygenated oligomers. The full range of these intermediates has not been characterized, and their potential ecotoxicity and long-term fate in the environment are critical, yet largely unaddressed, questions.
- **The Challenge of Additives:** Real-world plastic waste is not pure polymer. It is a

complex mixture of PE and numerous chemical additives. The impact of this complex chemical milieu on microbial activity is a significant unknown. Additives may be toxic, inhibitory, or they may be preferentially consumed by microbes, leading to an apparent but misleading degradation of the plastic item while the PE backbone remains untouched.

Addressing these challenges will require a shift from descriptive studies that simply document degradation to mechanistic studies that unravel the underlying biochemical, genetic, and ecological processes.

7. Perspective: Engineering a Future for PE Bioremediation and Upcycling

The future of polyethylene biodegradation will be defined by a transition from observing natural, inefficient processes to engineering rapid, controlled, and economically viable solutions. The challenges of slow kinetics and incomplete degradation are not insurmountable but require a deliberate move toward the rational design of biological systems. The convergence of systems biology, enzyme engineering, and synthetic biology offers a powerful toolkit to achieve this, with the ultimate goal shifting from mere remediation to value-added upcycling within a circular bio-economy.

Discovery Engines for Novel Biocatalysts

The search for effective PE-degrading enzymes can no longer rely solely on slow, culture-based screening methods. The vast majority of microbial life is unculturable, representing an enormous untapped reservoir of genetic and catalytic diversity.

- **'Omics' Approaches:** High-throughput sequencing technologies are revolutionizing biodiscovery. **Metagenomics** allows for the direct sequencing of DNA from entire environmental communities (e.g., from landfill soils, insect guts, or marine plastispheres), bypassing the need for cultivation.[43] This provides access to the complete genetic blueprint of a community, enabling the discovery of novel genes encoding putative plastic-degrading enzymes. **Metatranscriptomics** and **metaproteomics** go a step further, identifying which of these genes are actively expressed and which proteins are produced in the presence of PE, thus directly linking genetic potential to functional activity.[44] The application of machine learning and artificial intelligence to these massive

datasets can then predict enzyme function from sequence information, dramatically accelerating the identification of promising candidates.[71]

Synthetic Biology and Enzyme Engineering

The enzymes discovered in nature are unlikely to be optimal for industrial processes. They have evolved for different substrates and conditions.

- **Rational Design and Directed Evolution:** Once a candidate enzyme is identified, protein engineering techniques can be employed to enhance its properties. **Rational design** uses knowledge of the enzyme's structure and mechanism to make targeted mutations to improve activity or stability. **Directed evolution**, a process that mimics natural selection in the laboratory, can be used to screen vast libraries of enzyme variants for desired traits, such as increased catalytic efficiency, higher thermostability (to better match the physical properties of PE), or altered substrate specificity.[78]
- **Constructing Synthetic Consortia:** Rather than relying on a single "super-bug," the future lies in the design of defined, synthetic microbial consortia.[67] In such systems, the complex task of PE degradation can be divided among specialist strains. For example, one engineered strain could be optimized for surface adhesion and biofilm formation, another for secreting a highly active, engineered oxidoreductase for C-C bond cleavage, and a third for efficiently taking up and metabolizing the resulting oligomers. This modular, assembly-line approach could dramatically outperform any naturally occurring organism.

The Circular Bio-Economy: From Waste to Value

The most transformative vision for the future is not just to make PE disappear but to use it as a resource. Bio-upcycling aims to convert plastic waste into a valuable chemical feedstock.

- **Metabolic Engineering:** The degradation products of PE, such as dicarboxylic acids and acetyl-CoA, are valuable metabolic intermediates. Using the tools of metabolic engineering, robust industrial microorganisms (chassis organisms like *E. coli* or *Pseudomonas putida*) can be engineered to channel these intermediates into specific biosynthetic pathways. This would allow for the production of a wide range of high-value products, including biodegradable polymers like polyhydroxyalkanoates (PHAs), biosurfactants, specialty lipids, or other platform chemicals.[13] This strategy transforms a costly waste management problem into a profitable manufacturing opportunity, creating

the powerful economic incentive needed to drive large-scale plastic collection and recycling.

5–10 Year Outlook

The next decade is poised for transformative breakthroughs. The field will likely move beyond proof-of-concept demonstrations to tackling the core challenges of rate and efficiency. We anticipate the discovery and engineering of the first enzymes and microbial systems capable of degrading untreated, high-MW PE at rates that approach commercial relevance. Pilot-scale demonstrations of a complete "waste-to-product" pipeline, integrating abiotic pre-treatment, enzymatic depolymerization, and microbial upcycling, will likely be achieved. The success of this endeavor will hinge on fostering deep, interdisciplinary collaborations between microbiologists, polymer chemists, data scientists, and biochemical engineers, all working in concert to dismantle the polyethylene fortress and rebuild it into the foundations of a sustainable future.

References

United Nations. (2023). *Explainer: What is plastic pollution?* UN Sustainable Development. Available at: https://www.un.org/sustainabledevelopment/blog/2023/08/explainer-what-is-plastic-pollution/

Monterey Bay Aquarium. (2024). *Statistics on plastic pollution*. Available at: https://www.montereybayaquarium.org/newsroom/media-kits/sej-2024/stopping-plastic-pollution/statistics-on-plastic-pollution

Ritchie, H., & Roser, M. (2018). *Plastic Pollution*. Our World in Data. Available at: https://ourworldindata.org/plastic-pollution

UNEP. (n.d.). *Plastic pollution*. UN Environment Programme. Available at: https://www.unep.org/plastic-pollution

UNEP. (n.d.). *Plastic pollution*. UN Environment Programme - Topics. Available at: https://www.unep.org/topics/chemicals-and-pollution-action/plastic-pollution

Wastedirect. (n.d.). *Plastic Waste Statistics*. Available at:

https://wastedirect.co.uk/blog/plastic-waste-statistics/

Wikipedia. (n.d.). *Polyethylene*. Available at: https://en.wikipedia.org/wiki/Polyethylene

PolymerProcessing.com. (n.d.). *poly(methylene) (PE) Properties*. Available at: https://www.polymerprocessing.com/polymers/PE.html

SpecialChem. (n.d.). *Polyethylene (PE) Plastic: Properties, Types & Applications*. Available at: https://www.specialchem.com/plastics/guide/polyethylene-plastic

ResearchGate. (n.d.). *Polyethylene-structure, crystallinity and properties*. Available at: https://www.researchgate.net/publication/230084537_Polyethylene-structure_crystallinity_and_properties

Xometry. (n.d.). *What Is Polyethylene?*. Available at: https://www.xometry.com/resources/materials/polyethylene/

ACS Sustainable Chemistry & Engineering. (2019). *Title of reference*. Available at: https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635

Fiveable. (n.d.). *Biodegradation*. Available at: https://fiveable.me/polymer-chemistry/unit-8/biodegradation/study-guide/NPh8HFf9HkRidSUy

Wikipedia. (n.d.). *Biodegradation*. Available at: https://en.wikipedia.org/wiki/Biodegradation

Biosphereplastic. (n.d.). *Microbial Biodegradation of Polymeric Materials*. Available at: https://biosphereplastic.com/information/microbial-biodegradation-of-polymeric-materials

ResearchGate. (n.d.). *Microbial Biological Degradation of Polymers: Recent Trends*. Available at: https://www.researchgate.net/publication/379735041_Microbial_Biological_Degradation_of_Polymers_Recent_Trends

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2673-6209/3/2/23

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC6630276/

ResearchGate. (n.d.). *A Review on Biodegradation of Polythene: The Microbial Approach*. Available at: https://www.researchgate.net/publication/235682993_A_Review_on_Biodegradation_of_polytheneThe_Microbial_Approach

ResearchGate. (n.d.). *Microbial degradation and deterioration of polyethylene - A review*. Available at: https://www.researchgate.net/publication/259995084_Microbial_degradation_and_deteriorati

on_of_polyethylene_-_A_review

Semantic Scholar. (n.d.). *Title of reference*. Available at: https://pdfs.semanticscholar.org/2646/f03a2c7596f3852934422366dadb67b721d2.pdf

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2073-4360/17/2/169

OMICS Online. (n.d.). *A Review on Biodegradation of Polythene: The Microbial Approach*. Available at: https://www.omicsonline.org/a-review-on-biodegradation-of-polythene-the-microbial-approach-2155-6199.1000164.php?aid=8679

The Pharma Journal. (n.d.). *Title of reference*. Available at: https://www.thepharmajournal.com/archives/2023/vol12issue9/PartAB/12-9-168-119.pdf

ResearchGate. (n.d.). *Polyethylene biodegradation by a developed Penicillium-Bacillus biofilm*. Available at: https://www.researchgate.net/publication/283803718_Polyethylene_biodegradation_by_a_developed_Penicillium-Bacillus_biofilm

ResearchGate. (n.d.). *Polyethylene Degradation by Microbes (Bacteria & Fungus): A Review*. Available at: https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2309-608X/9/6/605

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1077588/full

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC6034791/

IROST. (n.d.). *Title of reference*. Available at: https://aet.irost.ir/article_1133_ebda643b859ba72344fab37d7b82abfd.pdf

ResearchGate. (n.d.). *Colonization, biofilm formation and biodegradation of Polyethylene by a strain of Rhodococcus ruber*. Available at: https://www.researchgate.net/publication/8487558_Colonization_biofilm_formation_and_biodegradation_of_Polyethylene_by_a_strain_of_Rhodococcus_ruber

The ISME Journal. (n.d.). *Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms*. Available at:

https://academic.oup.com/ismej/advance-article/doi/10.1093/ismejo/wraf223/8277623?searchresult=1

Biorxiv. (n.d.). *Title of reference*. Available at: https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full-text

ACS Applied Energy Materials. (n.d.). *Title of reference*. Available at: https://pubs.acs.org/doi/10.1021/acsaenm.5c00179

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12305493/

Diva Portal. (n.d.). *Title of reference*. Available at: https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2076-2607/10/6/1180

MRForum. (n.d.). *Title of reference*. Available at: https://mrforum.com/wp-content/uploads/woocommerce_uploads/PDFxyz1/9781644901335/4.pdf

UPTlax. (n.d.). *Fungal enzymes for the degradation of polyethylene: Molecular docking*. Available at: http://uptlax.edu.mx/wp-content/uploads/2023/11/Fungal-enzymes-for-the-degradation-of-polyethylene-Molecular-docking-min.pdf

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC11445424/

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2076-2607/10/8/1537

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/1422-0067/26/18/8775

PubMed. (n.d.). *Title of reference*. Available at: https://pubmed.ncbi.nlm.nih.gov/28419654/

ResearchGate. (n.d.). *Biodegradation of Polyethylene Followed by Assimilation of Degradation Products*. Available at: https://www.researchgate.net/publication/229739671_Biodegradation_of_Polyethylene_Followed_by_Assimilation_of_Degradation_Products

ResearchGate. (n.d.). *A schematic illustration of potential polyethylene degradation pathway....* Available at: https://www.researchgate.net/figure/A-schematic-illustration-of-potential-polyethylene-degr

adation-pathway-summarizing-the_fig6_374737149

Taylor & Francis Online. (n.d.). *Title of reference*. Available at: https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861

Northwestern Scholars. (n.d.). *Degradation and metabolism of synthetic plastics and associated…*. Available at: https://www.scholars.northwestern.edu/en/publications/degradation-and-metabolism-of-synthetic-plastics-and-associated-p

MDPI. (n.d.). *A Review of Degradation and Life Prediction of Polyethylene*. Available at: https://www.mdpi.com/2076-3417/13/5/3045

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2076-3417/13/5/3045

Plastics Technology. (n.d.). *Understanding Polymer Degradation: Challenges and Solutions…*. Available at: https://www.plastics-technology.com/articles/polymer-degradation-plastics-industry

ResearchGate. (n.d.). *Factors affecting polymer biodegradation…*. Available at: https://www.researchgate.net/figure/Factors-affecting-polymer-biodegradation-adapted-from-Kijchavengkul-and-Auras-2008_fig3_346395486

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/

ResearchGate. (n.d.). *Biodegradation of polyethylene: a brief review*. Available at: https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review

Taylor & Francis Online. (n.d.). *Enhancing plastic biodegradation process: strategies and…*. Available at: https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10857199/

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2020.00689/full

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC12073353/

ResearchGate. (n.d.). *Proposed mechanism of PE degradation process…*. Available at: https://www.researchgate.net/figure/Proposed-mechanism-of-PE-degradation-process-by-abiotic-and-biotic-systems-Four-stages_fig4_374917416

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2073-4360/17/13/1798

ResearchGate. (n.d.). *Biodegradation of polyethylene and polypropylene*. Available at: https://www.researchgate.net/publication/228090462_Biodegradation_of_polyethylene_and_polypropylene

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC9694517/

Frontiers in Environmental Science. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1677793/full

ResearchGate. (n.d.). *The problem of polyethylene waste - Recent attempts for its mitigation*. Available at: https://www.researchgate.net/publication/371326633_The_problem_of_polyethylene_waste_-_Recent_attempts_for_its_mitigation

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2073-4360/12/1/123

ResearchGate. (n.d.). *A mini-review: current advances in polyethylene biodegradation*. Available at: https://www.researchgate.net/publication/339000929_A_mini-review_current_advances_in_polyethylene_biodegradation

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC8160376/

PNAS Nexus. (n.d.). *Title of reference*. Available at: https://academic.oup.com/pnasnexus/article/4/3/pgaf066/8063326

ResearchGate. (n.d.). *Metagenomic exploration and computational prediction of novel enzymes...*. Available at: https://www.researchgate.net/publication/387921065_Metagenomic_exploration_and_computational_prediction_of_novel_enzymes_for_polyethylene_terephthalate_degradation

ACS. (n.d.). *Discovery of polyethylene-degrading enzymes...*. Available at: https://acs.digitellinc.com/p/s/discovery-of-polyethylene-degrading-enzymes-pe-ases-from-yellow-mealworm-gut-microbiota-586773

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10997104/

University of Portsmouth. (n.d.). *Utilisation of nanopore sequencing for the discovery of novel...*. Available at: https://researchportal.port.ac.uk/en/projects/utilisation-of-nanopore-sequencing-for-the-dis

covery-of-novel-pla

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/1422-0067/17/8/1275

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2012.00184/full

PLOS ONE. (n.d.). *Title of reference*. Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0043432

ResearchGate. (n.d.). *Metatranscriptomics of microbial biofilm succession on HDPE foil....* Available at: https://www.researchgate.net/publication/386035501_Metatranscriptomics_of_microbial_biofilm_succession_on_HDPE_foil_uncovering_plastic-degrading_potential_in_soil_communities

MDPI. (n.d.). *Title of reference*. Available at: https://www.mdpi.com/2079-7737/13/11/848

SciePublish. (n.d.). *Title of reference*. Available at: https://www.sciepublish.com/article/pii/440

Protein Engineering, Design and Selection. (n.d.). *Title of reference*. Available at: https://academic.oup.com/peds/article/doi/10.1093/protein/gzae009/7666632

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10607142/

ResearchGate. (n.d.). *Enzymatic Degradation of Polyethylene and Polyethylene Terephthalate: A Mini Review*. Available at: https://www.researchgate.net/publication/373983620_Enzymatic_Degradation_of_Polyethylene_and_Polyethylene_Terephthalate_A_Mini_Review

Frontiers in Bioengineering and Biotechnology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2024.1349010/full

Royal Society of Chemistry. (n.d.). *Title of reference*. Available at: https://pubs.rsc.org/en/content/articlehtml/2025/gc/d4gc06566b

ResearchGate. (n.d.). *Cutting-edge developments in Plastic Biodegradation and Upcycling....* Available at: https://www.researchgate.net/publication/386221971_Cutting-edge_developments_in_Plastic_Biodegradation_and_Upcycling_via_engineering_approaches

University of Groningen. (n.d.). *Title of reference*. Available at: https://fse.studenttheses.ub.rug.nl/29661/1/mMBB_2023_AnnemaS.pdf

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at:

https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2024.1510817/full

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/

PubMed. (n.d.). *Challenges of polyethylene (PE) biodegradation - A perspective*. Available at: https://pubmed.ncbi.nlm.nih.gov/40975460/

PMC. (n.d.). *Title of reference*. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/

Frontiers in Microbiology. (n.d.). *Title of reference*. Available at: https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full

ACS Publications. (n.d.). *Title of reference*. Available at: https://pubs.acs.org/doi/10.1021/acs.est.7b04051

ResearchGate. (n.d.). *Biodegradation of polyethylene: a brief review*. Available at: https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review

ResearchGate. (n.d.). *Degradation pathways of PE-derived long-chain linear alkanes...*. Available at: https://www.researchgate.net/figure/Degradation-pathways-of-PE-derived-long-chain-linear-alkanes-by-oxidation-with-alkane_fig3_370519387

ResearchGate. (n.d.). *Degradation pathways of polyethylene containing pro-oxidant additives*. Available at: https://www.researchgate.net/figure/Degradation-pathways-of-polyethylene-containing-pro-oxidant-additives_fig1_338406283

ACS Publications. (n.d.). *Title of reference*. Available at: https://pubs.acs.org/doi/10.1021/acs.est.3c03778

Taylor & Francis Online. (n.d.). *Cascading Beta-oxidation Intermediates for the...*. Available at: https://www.tandfonline.com/doi/full/10.1080/15685551.2023.2179763

Diva Portal. (n.d.). *Title of reference*. Available at: https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf

PubMed. (n.d.). *A Cytochrome P450 Facilitates Polyethylene Metabolism...*. Available at: https://pubmed.ncbi.nlm.nih.gov/41009345/

To download this report, please use your browser's print function to save as a PDF or copy

the text into a word processor.

Works cited

1. Plastic Pollution - Our World in Data, accessed on October 23, 2025, https://ourworldindata.org/plastic-pollution
2. Degradation Rates of Plastics in the Environment - ACS Publications, accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635
3. Plastic pollution | UNEP - UN Environment Programme, accessed on October 23, 2025, https://www.unep.org/topics/chemicals-and-pollution-action/plastic-pollution
4. Fast Facts - What is Plastic Pollution? - United Nations Sustainable ..., accessed on October 23, 2025, https://www.un.org/sustainabledevelopment/blog/2023/08/explainer-what-is-plastic-pollution/
5. Statistics on plastic pollution | Stopping plastic pollution ..., accessed on October 23, 2025, https://www.montereybayaquarium.org/newsroom/media-kits/sej-2024/stopping-plastic-pollution/statistics-on-plastic-pollution
6. Plastic Waste Statistics & Trends (UPDATED 2025), accessed on October 23, 2025, https://wastedirect.co.uk/blog/plastic-waste-statistics/
7. Plastic Pollution - UNEP, accessed on October 23, 2025, https://www.unep.org/plastic-pollution
8. Plastic degradation in aquatic environments: a review of ... - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1677793/full
9. Polyethylene Degradation by Microbes (Bacteria & Fungus): A Review - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review
10. Harnessing Biofilm-Mediated Plastic Biodegradation: Innovating ..., accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acsaenm.5c00179
11. Harnessing Biofilm-Mediated Plastic Biodegradation: Innovating Smart Material Design - PMC - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC12305493/
12. (PDF) Cutting-edge developments in Plastic Biodegradation and ..., accessed on October 23, 2025, https://www.researchgate.net/publication/386221971_Cutting-edge_developments_in_Plastic_Biodegradation_and_Upcycling_via_engineering_approaches
13. Plastic bioremediation: An exploration of current developments - Student Theses Faculty of Science and Engineering - Rijksuniversiteit Groningen, accessed on October 23, 2025, https://fse.studenttheses.ub.rug.nl/29661/1/mMBB_2023_AnnemaS.pdf
14. Polyethylene - Wikipedia, accessed on October 23, 2025,

https://en.wikipedia.org/wiki/Polyethylene
15. Polyethylene (PE): Structure, Properties, and Applications - Xometry, accessed on October 23, 2025, https://www.xometry.com/resources/materials/polyethylene/
16. Biodegradation | Polymer Chemistry Class Notes - Fiveable, accessed on October 23, 2025, https://fiveable.me/polymer-chemistry/unit-8/biodegradation/study-guide/NPh8HFf9HkRidSUy
17. Microbial and Enzymatic Degradation of Synthetic Plastics - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/
18. A Cytochrome P450 Facilitates Polyethylene Metabolism in a ... - MDPI, accessed on October 23, 2025, https://www.mdpi.com/1422-0067/26/18/8775
19. Microbial Degradation of Synthetic Biopolymers Waste - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC6630276/
20. (PDF) Colonization, biofilm formation and biodegradation of ..., accessed on October 23, 2025, https://www.researchgate.net/publication/8487558_Colonization_biofilm_formation_and_biodegradation_of_Polyethylene_by_a_strain_of_Rhodococcus_ruber
21. (PDF) Biodegradation of polyethylene: a brief review - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
22. Fungal enzymes for the degradation of polyethylene: Molecular docking simulation and biodegradation pathway proposal - Universidad Politécnica de Tlaxcala, accessed on October 23, 2025, http://uptlax.edu.mx/wp-content/uploads/2023/11/Fungal-enzymes-for-the-degradation-of-polyethylene-Molecular-docking-min.pdf
23. Microbial biodegradation of polymeric materials - BioSphere Plastic, accessed on October 23, 2025, https://biosphereplastic.com/information/microbial-biodegradation-of-polymeric-materials
24. A Review on Biodegradation of Polythene: The Microbial Approach - Semantic Scholar, accessed on October 23, 2025, https://pdfs.semanticscholar.org/2646/f03a2c7596f3852934422366dadb67b721d2.pdf
25. A Review on Biodegradation of Polythene: The Microbial Approach | OMICS International, accessed on October 23, 2025, https://www.omicsonline.org/a-review-on-biodegradation-of-polythene-the-microbial-approach-2155-6199.1000164.php?aid=8679
26. Polyethylene (PE Plastic) – Structure, Properties & Toxicity - SpecialChem, accessed on October 23, 2025, https://www.specialchem.com/plastics/guide/polyethylene-plastic
27. Microbial Biological Degradation of Polymers: Recent Trends - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/379735041_Microbial_Biological_Degra

dation_of_Polymers_Recent_Trends
28. www.mdpi.com, accessed on October 23, 2025, https://www.mdpi.com/2076-3417/13/5/3045#:~:text=The%20chemical%20composition%2C%20molecular%20weight,bacteria%2C%20fungi%2C%20and%20microorganisms.
29. Understanding Polymer Degradation: Challenges and Solutions in the Plastics Industry, accessed on October 23, 2025, https://www.plastics-technology.com/articles/polymer-degradation-plastics-industry
30. Recent developments in bio-based polyethylene: Degradation studies, waste management and recycling - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/
31. (PDF) A Review on Biodegradation of polythene:The Microbial ..., accessed on October 23, 2025, https://www.researchgate.net/publication/235682993_A_Review_on_Biodegradation_of_polytheneThe_Microbial_Approach
32. Microbial degradation and deterioration of polyethylene – A review ..., accessed on October 23, 2025, https://www.researchgate.net/publication/259995084_Microbial_degradation_and_deterioration_of_polyethylene_-_A_review
33. Microbial Biodegradation of Synthetic Polyethylene and ... - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/17/2/169
34. Degradation of polyethylene plastic bags and bottles ... - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1077588/full
35. Isolation and identification of plastic degrading bacteria from dumpsites Lagos - Advances in Environmental Technology, accessed on October 23, 2025, https://aet.irost.ir/article_1133_ebda643b859ba72344fab37d7b82abfd.pdf
36. Polyethylene biodegradation by a developed Penicillium-Bacillus biofilm - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/283803718_Polyethylene_biodegradation_by_a_developed_Penicillium-Bacillus_biofilm
37. Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC6034791/
38. Biodegradation of Low Density Polyethylene by the Fungus Cladosporium sp. Recovered from a Landfill Site - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2309-608X/9/6/605
39. Microbes mediated polyethylene biodegradation for environmental sustainability - The Pharma Innovation Journal, accessed on October 23, 2025, https://www.thepharmajournal.com/archives/2023/vol12issue9/PartAB/12-9-168-119.pdf
40. Current Advances in Biodegradation of Polyolefins - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-2607/10/8/1537

41. Synergistic biodegradation of polyethylene by experimentally ..., accessed on October 23, 2025, https://academic.oup.com/ismej/advance-article/doi/10.1093/ismejo/wraf223/8277623?searchresult=1
42. Searching for new plastic-degrading enzymes from the plastisphere of alpine soils using a metagenomic mining approach - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10997104/
43. (PDF) Metatranscriptomics of microbial biofilm succession on HDPE ..., accessed on October 23, 2025, https://www.researchgate.net/publication/386035501_Metatranscriptomics_of_microbial_biofilm_succession_on_HDPE_foil_uncovering_plastic-degrading_potential_in_soil_communities
44. Fungal Enzymes Involved in Plastics Biodegradation - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-2607/10/6/1180
45. Revisiting the activity of two poly(vinyl chloride)- and polyethylene-degrading enzymes - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11445424/
46. Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms, accessed on October 23, 2025, https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full-text
47. www.tandfonline.com, accessed on October 23, 2025, https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861#:~:text=The%20widely%20adopted%20strategies%20of,action%20of%20microorganisms%20%5B8%5D.
48. Effect of Abiotic Treatments on Agricultural Plastic Waste: Efficiency of the Degradation Processes - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10857199/
49. UV Pretreatment Impairs the Enzymatic Degradation of Polyethylene Terephthalate - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2020.00689/full
50. The Role of Artificial Weathering Protocols on Abiotic and Bacterial Degradation of Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/17/13/1798
51. Full article: Enhancing plastic biodegradation process: strategies ..., accessed on October 23, 2025, https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861
52. A Review of Degradation and Life Prediction of Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-3417/13/5/3045
53. A Cytochrome P450 Facilitates Polyethylene Metabolism in a ..., accessed on October 23, 2025, https://pubmed.ncbi.nlm.nih.gov/41009345/
54. Biodegradation of Polyethylene Followed by Assimilation of Degradation Products | Request PDF - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/229739671_Biodegradation_of_Polyethylene_Followed_by_Assimilation_of_Degradation_Products

55. Degradation pathways of PE-derived long-chain linear alkanes by ..., accessed on October 23, 2025, https://www.researchgate.net/figure/Degradation-pathways-of-PE-derived-long-chain-linear-alkanes-by-oxidation-with-alkane_fig3_370519387
56. Degradation pathways of polyethylene containing pro-oxidant additives. - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/figure/Degradation-pathways-of-polyethylene-containing-pro-oxidant-additives_fig1_338406283
57. Full article: Cascading Beta-oxidation Intermediates for the Polyhydroxyalkanoate Copolymer Biosynthesis by Metabolic Flux using Co-substrates and Inhibitors, accessed on October 23, 2025, https://www.tandfonline.com/doi/full/10.1080/15685551.2023.2179763
58. Polyethylene Degradation by a Rhodococcous Strain Isolated from Naturally Weathered Plastic Waste Enrichment | Environmental Science & Technology - ACS Publications, accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acs.est.3c03778
59. Biodegradation of Polymers: Stages, Measurement, Standards and Prospects - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2673-6209/3/2/23
60. Challenges with Verifying Microbial Degradation of Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/12/1/123
61. Challenges of polyethylene (PE) biodegradation - A perspective, accessed on October 23, 2025, https://pubmed.ncbi.nlm.nih.gov/40975460/
62. Challenges with Verifying Microbial Degradation of Polyethylene - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
63. (PDF) Biodegradation of polyethylene and polypropylene, accessed on October 23, 2025, https://www.researchgate.net/publication/228090462_Biodegradation_of_polyethylene_and_polypropylene
64. Methods of Analyses for Biodegradable Polymers: A Review - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9694517/
65. Biodegradability of Plastics: Challenges and Misconceptions | Environmental Science & Technology - ACS Publications, accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acs.est.7b04051
66. Assembly strategies for polyethylene-degrading microbial consortia based on the combination of omics tools and the “Plastisphere” - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full
67. Polyethylene biodegradation, accessed on October 23, 2025, https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf
68. Bridging Three Gaps in Biodegradable Plastics: Misconceptions and Truths About Biodegradation - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8160376/

69. Natural-selected plastics biodegradation species and enzymes in ..., accessed on October 23, 2025, https://academic.oup.com/pnasnexus/article/4/3/pgaf066/8063326
70. Discovery of polyethylene-degrading enzymes ('PE-ases') from yellow mealworm gut microbiota - American Chemical Society, accessed on October 23, 2025, https://acs.digitellinc.com/p/s/discovery-of-polyethylene-degrading-enzymes-pe-ases-from-yellow-mealworm-gut-microbiota-586773
71. Utilisation of nanopore sequencing for the discovery of novel plastic degrading enzymes in the environment - University of Portsmouth, accessed on October 23, 2025, https://researchportal.port.ac.uk/en/projects/utilisation-of-nanopore-sequencing-for-the-discovery-of-novel-pla
72. Environmental Microbial Community Proteomics: Status, Challenges and Perspectives, accessed on October 23, 2025, https://www.mdpi.com/1422-0067/17/8/1275
73. Application of meta-transcriptomics and –proteomics to analysis of in situ physiological state, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2012.00184/full
74. Integrating Molecular Perspectives: Strategies for Comprehensive Multi-Omics Integrative Data Analysis and Machine Learning Applications in Transcriptomics, Proteomics, and Metabolomics - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2079-7737/13/11/848
75. Metagenomic exploration and computational prediction of novel enzymes for polyethylene terephthalate degradation - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/387921065_Metagenomic_exploration_and_computational_prediction_of_novel_enzymes_for_polyethylene_terephthalate_degradation
76. Synthetic Biology Boosts the Biological Depolymerization and ..., accessed on October 23, 2025, https://www.sciepublish.com/article/pii/440
77. Improving plastic degrading enzymes via directed evolution | Protein Engineering, Design and Selection | Oxford Academic, accessed on October 23, 2025, https://academic.oup.com/peds/article/doi/10.1093/protein/gzae009/7666632
78. Biotechnological Plastic Degradation and Valorization Using Systems Metabolic Engineering - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10607142/
79. Enzymatic Degradation of Polyethylene and Polyethylene Terephthalate: A Mini Review, accessed on October 23, 2025, https://www.researchgate.net/publication/373983620_Enzymatic_Degradation_of_Polyethylene_and_Polyethylene_Terephthalate_A_Mini_Review
80. Characterization and engineering of plastic-degrading polyesterases jmPE13 and jmPE14 from Pseudomonas bacterium - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2024.1349010/full