The Microbial Challenge to a Synthetic Giant: Deconstructing Polyethylene Biodegradation

Abstract
Polyethylene (PE), the world's most produced synthetic polymer, represents a paradox of modern materials science: its exceptional durability and chemical inertness, the very qualities that underpin its utility, have resulted in a global environmental crisis of unprecedented scale. The accumulation of PE waste in terrestrial and aquatic ecosystems, where it fragments into pervasive micro- and nanoplastics, poses a severe threat to ecological stability and human health. Conventional recycling methods have proven inadequate to manage the sheer volume of PE waste, creating an urgent need for innovative and sustainable remediation strategies. Microbial biodegradation has emerged as a promising frontier, offering a potential pathway to mineralize this recalcitrant polymer. However, the process is profoundly complex and fraught with challenges. This review critically examines the current state of knowledge on PE biodegradation by microbial communities. We first deconstruct the physicochemical basis of PE's recalcitrance, rooted in its hydrophobic, high-molecular-weight, C-C backbone structure. We then explore the indispensable role of abiotic priming—primarily photo- and thermo-oxidation—in modifying the polymer surface to permit microbial attack. A comprehensive overview of the key microbial players, including bacteria and fungi from diverse environments such as soil, marine sediments, and specialized insect gut microbiomes, is presented. The enzymatic machinery responsible for depolymerization, centered on a consortium of oxidoreductases like laccases, peroxidases, and alkane monooxygenases, is detailed, along with a proposed metabolic pathway. A critical appraisal of the analytical techniques used to evidence biodegradation reveals significant limitations and potential for misinterpretation, highlighting the need for rigorous, standardized evidentiary criteria, with isotope tracing remaining the gold standard. Finally, we provide a forward-looking perspective on how frontier disciplines, including metagenomics, synthetic biology, and directed evolution, are poised to accelerate the transition from lab-scale discovery to the rational design of efficient, scalable biological systems for a circular PE bio-economy.

1. Introduction: The Polyethylene Paradox

1.1. Unprecedented Utility and a Persistent Environmental Burden

Polyethylene (PE) stands as a cornerstone of the modern materials economy, a testament to its remarkable versatility, durability, and low production cost.[1] Its applications span nearly every sector, from life-saving medical devices and critical infrastructure components to ubiquitous consumer goods.[1] The global appetite for this polymer is immense and continues to grow; the PE market was valued at USD 120 billion in 2024 and is projected to reach USD 165.46 billion by 2030.[1] Global plastic production, of which PE constitutes over a third, is forecast to exceed 413 million metric tons in 2024.[1] The packaging industry, fueled by the rise of e-commerce and changing consumer lifestyles in emerging economies, remains the largest consumer of PE, prizing its flexibility, moisture resistance, and strength.[1]

This economic success story, however, is inextricably linked to a profound environmental failure. The very physicochemical properties that make PE an ideal material for human applications—its chemical inertness and resistance to degradation—are the root cause of its extreme persistence in the environment.[4] The linear economy model of "take-make-dispose" has led to the generation of staggering quantities of plastic waste. In 2024 alone, an estimated 220 million tons of plastic waste will be generated globally, with a staggering 69.5 million tons being mismanaged and destined to pollute natural ecosystems.[6] Current waste management infrastructures are overwhelmed. Mechanical and chemical recycling, while important, address only a fraction of the problem, accounting for less than 9% of total plastic production.[2] The vast majority of PE waste, particularly from short-lifecycle, single-use products, is either landfilled or leaks into the environment, creating a legacy of pollution that will last for centuries.[4] This establishes the central paradox of polyethylene: its utility is the direct cause of its environmental burden, creating a powerful impetus for the development of fundamentally new waste management paradigms, such as biodegradation, that can sever this destructive link.

1.2. From Macro-waste to Micro- and Nanoplastics: The Ecological Cascade

Once in the environment, PE waste does not benignly disappear. Instead, it embarks on a long process of physical and chemical fragmentation, breaking down over hundreds to potentially a thousand years into progressively smaller particles known as microplastics (<5 mm) and nanoplastics (<1 μm).[4] These particles have become ubiquitous contaminants, infiltrating

every known ecosystem on the planet, from the highest mountains to the deepest ocean trenches, and have been detected in drinking water, agricultural soils, and even within the human body, including in blood, lungs, and placentas.[7]

This fragmentation initiates a cascade of severe ecotoxicological consequences. Macroplastic debris poses a direct physical threat to wildlife through entanglement and ingestion, affecting over 1,500 marine and terrestrial species.[8] Micro- and nanoplastics, due to their small size, are readily ingested by organisms at the base of the food web, leading to internal abrasion, inflammation, reproductive issues, and oxidative stress.[10] Furthermore, the hydrophobic surface of PE particles acts as a magnet for persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), and polycyclic aromatic hydrocarbons (PAHs) that are present in the environment.[4] This process concentrates toxins, transforming plastic particles into vectors that facilitate the transport and bioavailability of hazardous chemicals, which can then biomagnify up the food chain.[11] Beyond its direct ecological toxicity, the plastic life cycle is also a significant and growing contributor to climate change. Derived primarily from fossil fuels, the production and incineration of plastics were responsible for 3.4% of global greenhouse gas emissions in 2019, a figure projected to more than double by 2060 and potentially consume up to 15% of the global carbon budget by 2050 if current trends continue.[7]

2. The Molecular Fortress: Physicochemical Basis for PE Recalcitrance

2.1. The Inert C-C Backbone, High Molecular Weight, and Hydrophobicity

The profound resistance of polyethylene to biodegradation is not an incidental property but is encoded in its fundamental molecular architecture. The polymer consists of a long, saturated backbone of carbon-carbon single bonds ($C-C$) and carbon-hydrogen bonds ($C-H$).[12] These covalent bonds are thermodynamically stable and possess high bond dissociation energies, rendering them non-susceptible to the hydrolytic enzymes that microbes typically use to break down natural polymers like cellulose or proteins.[4] The absence of reactive functional groups along the polymer chain presents a formidable barrier to initial enzymatic attack.

This chemical inertness is compounded by two key physical properties. First, PE has a very high molecular weight, with polymer chains often consisting of thousands or even millions of repeating ethylene units.[5] These macromolecules are far too large to be transported across the microbial cell membrane for intracellular metabolism. Therefore, any degradation must be initiated by extracellular enzymes that can cleave the polymer backbone into smaller, assimilable fragments.[14] Second, the non-polar nature of the $C-C$ and $C-H$ bonds makes the PE surface extremely hydrophobic.[5] This property repels the aqueous medium in which microbial enzymes function and severely limits the ability of microorganisms to adhere to the polymer surface and form the biofilms necessary for efficient degradation.[5] Together, this triumvirate of features—an inert chemical backbone, high molecular weight, and hydrophobicity—constitutes a multi-layered molecular fortress that is highly resistant to biological assault.

2.2. The Role of Crystallinity: A Comparison of HDPE, LDPE, and LLDPE

Beyond its primary chemical structure, the recalcitrance of PE is significantly influenced by its solid-state morphology, specifically its semi-crystalline nature.[13] PE polymers are not entirely amorphous; their chains can pack into ordered, crystalline lamellae, which are interspersed with disordered, amorphous regions. The degree of crystallinity, which is determined by the branching structure of the polymer chains, dictates many of the material's physical properties and profoundly affects its susceptibility to biodegradation.[5]

- **High-Density Polyethylene (HDPE):** Synthesized using catalysts that produce linear polymer chains with very little branching, HDPE molecules can pack together tightly and efficiently. This results in a high degree of crystallinity (typically $>60\%$) and a higher density ($0.94–0.97$ g/cm³). The resulting material is rigid, strong, and opaque.[5] From a biodegradation perspective, the densely packed crystalline regions are nearly impenetrable to microbial enzymes, making HDPE the most recalcitrant form of polyethylene.[13]
- **Low-Density Polyethylene (LDPE):** Produced via a high-pressure process that introduces significant, irregular long- and short-chain branching, LDPE chains cannot pack closely. This disruption leads to a much lower degree of crystallinity (typically $<40\%$) and lower density ($0.91–0.94$ g/cm³). The material is flexible and often transparent.[5] The larger proportion of amorphous regions in LDPE makes it more accessible to enzymatic attack compared to HDPE, as the polymer chains are less ordered and have greater mobility.[5]
- **Linear Low-Density Polyethylene (LLDPE):** This type represents a structural intermediate. It has a linear backbone like HDPE but incorporates a significant number of short, uniform branches. This structure results in properties between those of LDPE and

HDPE, with a semi-crystalline morphology (30–50%).[13] Its susceptibility to biodegradation is also considered intermediate.

This structural variation demonstrates that PE's resistance is a product of both its chemistry and its physics. Any effective biodegradation strategy must therefore contend not only with breaking stable chemical bonds but also with accessing those bonds within a complex, partially ordered polymer matrix. This directly implies that degradation is unlikely to be a single-step process; it must first involve disruption of the physical structure to expose polymer chains, a role primarily played by abiotic environmental factors.

Table 1: Physicochemical Properties of Major Polyethylene Types and Their Implications for Biodegradation [5]

Property	High-Density Polyethylene (HDPE)	Low-Density Polyethylene (LDPE)	Linear Low-Density Polyethylene (LLDPE)
Structure	Linear chains, minimal branching	Highly branched (long and short chains)	Linear backbone with short branches
Density (g/cm^3)	$0.94–0.97$	$0.91–0.94$	$0.90–0.94$
Degree of Crystallinity (%)	>60	<40	$30–50$
Melting Temperature (°C)	$120–140$	$100–115$	$100–125$
Key Applications	Pipes, milk jugs, detergent bottles	Plastic bags, films, food packaging	Stretch wrap, flexible tubing
Implied Susceptibility to Biodegradation	Low	High (relative)	Moderate

3. Cracking the Defenses: The Essential Role of Abiotic

Priming

3.1. Photo-oxidative and Thermo-oxidative Pathways

Pure, unadulterated polyethylene is, for all practical purposes, non-biodegradable by microorganisms under ambient conditions.[15] The initiation of its breakdown in the natural environment is almost invariably a two-stage process, beginning with abiotic degradation that primes the polymer for subsequent microbial action.[16] This crucial first step is driven primarily by environmental energy inputs, namely ultraviolet (UV) radiation and heat.

- **Photo-oxidation:** Exposure to UV radiation from sunlight, particularly in the UVB range, provides sufficient energy to break the $C-C$ and $C-H$ bonds within the polymer backbone. In the presence of atmospheric oxygen, this initiates a free-radical chain reaction.[16] This process, often described by mechanisms such as the Norrish Type I and II reactions, leads to both chain scission (fragmentation of the polymer into lower molecular weight chains) and cross-linking (formation of new bonds between chains), altering the material's physical properties and making it brittle.[16]
- **Thermo-oxidation:** Elevated temperatures, whether from direct solar heating or other environmental sources, accelerate these oxidative reactions.[16] Heat increases the mobility of polymer chains, particularly in the amorphous regions, making them more susceptible to radical attack and further promoting the degradation process.[16] The synergistic effect of UV radiation and heat is a powerful driver of PE weathering in surface environments.[18]

3.2. Surface Functionalization: Creating Microbial Footholds

The most critical outcome of these abiotic weathering processes is not the complete mineralization of the polymer, but rather the chemical modification of its surface. The oxidative reactions introduce a variety of oxygen-containing functional groups onto the previously inert hydrocarbon backbone. The most prominent among these are carbonyl ($>C=O$), carboxyl ($-COOH$), and hydroxyl ($-OH$) groups.[5]

This surface functionalization is the pivotal event that "unlocks" the polymer for microbial access. The introduction of these polar groups dramatically alters the polymer surface in two

key ways. First, it decreases the surface's hydrophobicity, making it more wettable and facilitating the attachment of microbial cells and the formation of biofilms.[19] Second, these newly formed functional groups serve as initial points of attack for microbial extracellular enzymes, particularly oxidoreductases, which may not be able to act on the pristine alkyl chain.[20] In essence, abiotic weathering acts as a gatekeeper, transforming the impenetrable molecular fortress of PE into a substrate that microbes can recognize and begin to deconstruct. This dependency explains the vast discrepancies in reported degradation rates, which are often far slower in dark, anoxic environments like landfills or the deep sea, where the essential abiotic priming step is severely limited or absent.[4]

4. The Biotic Onslaught: Microbial Colonizers of the 'Plastisphere'

4.1. Biofilm Formation: The Gateway to Degradation

Once the polyethylene surface has been sufficiently primed by abiotic factors, it becomes a viable habitat for microbial colonization. This process leads to the formation of a complex, surface-attached microbial community known as the 'plastisphere'.[21] The establishment of a biofilm is not merely incidental but is a prerequisite for effective biodegradation.[22] Microorganisms adhere to the modified, more hydrophilic surface, where they begin to proliferate and secrete a matrix of extracellular polymeric substances (EPS), composed of polysaccharides, proteins, and DNA.[22]

This biofilm serves several critical functions. It creates a stable, localized microenvironment that shields the microbial community from external stresses. Crucially, it allows for the concentration of extracellular enzymes secreted by the microbes directly at the polymer-biofilm interface.[14] This is particularly important for degrading an insoluble substrate like PE, as it prevents the diffusion and dilution of enzymes into the bulk medium, thereby maximizing their catalytic efficiency. The case of *Rhodococcus ruber* C208 provides a compelling example of this principle. This bacterium is highly hydrophobic, enabling strong initial adhesion to PE, and it proceeds to form dense, complex, mushroom-like biofilm structures. Studies have shown that its population density within the biofilm can be 60 times higher than in the surrounding planktonic phase, indicating a strong preference for surface-attached growth that is directly linked to its enhanced degradation rate of 0.86%

weight loss per week.[22]

4.2. Key Bacterial and Fungal Degraders: A Taxonomic Overview

A growing number of microbial species have been identified with the capacity to degrade polyethylene, isolated from a wide range of environments where plastic waste accumulates.

- **Bacteria:** Several bacterial genera are consistently implicated in PE degradation. The genus *Rhodococcus* is particularly noteworthy due to its well-known metabolic versatility and ability to degrade complex, hydrophobic hydrocarbons like crude oil and polychlorinated biphenyls (PCBs).[24] Species like *Rhodococcus ruber* have demonstrated robust biofilm formation and PE degradation capabilities.[22] Other prominent bacterial degraders belong to the genera *Bacillus*, *Pseudomonas*, *Acinetobacter*, and *Streptomyces*, which have been isolated from sources ranging from landfill soil to marine sediments.[12] These bacteria possess a diverse arsenal of enzymes capable of initiating the oxidative breakdown of the polymer.
- **Fungi:** Fungi are also powerful agents of polymer degradation, possessing unique advantages. Their filamentous hyphal growth allows them to physically penetrate the polymer matrix, creating mechanical stress and increasing the surface area available for enzymatic attack.[12] They are known to secrete a potent cocktail of extracellular enzymes, including many of the oxidoreductases required for PE breakdown.[27] The genera *Aspergillus* and *Penicillium* are frequently reported as effective PE degraders.[12] In laboratory studies, strains of *Aspergillus niger* have been shown to achieve significant PE weight loss, with some reports as high as 16-45% over incubation periods of 30-60 days, accompanied by clear evidence of surface erosion and chemical modification.[31]

4.3. Specialized Niches: Insights from Insect Gut Microbiomes

One of the most exciting recent developments in the field has been the discovery of rapid plastic degradation occurring within the guts of certain insect larvae. The larvae of the mealworm (*Tenebrio molitor*), superworm (*Zophobas atratus*), and greater wax moth (*Galleria mellonella*) have been observed to ingest and mineralize various plastics, including PE, at rates far exceeding those seen in typical environmental settings.[34]

The insect gut functions as a highly efficient, living bioreactor. The process begins with mechanical mastication by the insect's mouthparts, which fragments the plastic and

increases its surface area. The unique physicochemical conditions within the gut—including pH gradients, endogenous surfactants (emulsifiers), and an anoxic environment—work synergistically with a highly adapted gut microbiome to accelerate degradation.[35] Bioprospecting efforts have isolated numerous potent PE-degrading bacterial strains from these gut environments, including species of *Bacillus*, *Streptomyces*, and *Rhodococcus*.[34] These findings suggest that insect gut microbiomes are a rich and largely untapped reservoir of novel microorganisms and enzymes specifically adapted for plastic depolymerization, representing a key target for future research and biotechnological development.

Table 2: Representative Polyethylene-Degrading Microorganisms

Microorganism (Genus, species)	**Phylum/Division**	**PE Type**	**Isolation Source**	**Pre-treatment**	**Degradation Metric (% Weight Loss)**	**Time (days)**	**Reference(s)**
Rhodococcus sp. A34	Bacteria	LDPE	Weathered plastic waste	None (natural)	1.0%	30	[20]
Rhodococcus ruber C208	Bacteria	LDPE	Soil	UV/Heat	0.86% per week	60	[22]
Bacillus sp.	Bacteria	LDPE	Landfill soil	None	10.4%	60	[36]
Aspergillus niger	Fungi	LDPE	Dumpsite soil	None	55%	30	[32]
Aspergillus niger	Fungi	PE	Plastic-contaminated	None	16%	30	[33]

			soil				
Aspergillus niger	Fungi	PE	Municipal waste	None	45.6%	30	[31]
Aspergillus flavus	Fungi	LDPE	Dumpsite soil	None	Not specified	30	[32]
Penicillium sp.	Fungi	LDPE	Landfill soil	None	Not specified	Not specified	[12]
Bacillus simplex	Bacteria	LDPE	Earthworm gut	None	Part of consortium achieving 60%	Not specified	[34]
Streptomyces fulvissimus	Bacteria	LDPE	Earthworm gut	None	Part of consortium achieving 60%	Not specified	[34]

5. The Molecular Toolkit: Enzymatic Machinery for PE Depolymerization

5.1. The Oxidoreductase Arsenal: Laccases, Peroxidases, and Monooxygenases

The enzymatic cleavage of polyethylene's robust C-C backbone is the central biochemical

challenge of its biodegradation. Unlike natural polymers such as PET or cellulose, which contain ester or glycosidic bonds susceptible to hydrolysis, PE can only be broken down via oxidative mechanisms. Consequently, the key enzymes implicated in its degradation belong to the oxidoreductase class. These enzymes often exhibit broad substrate specificity, a trait likely evolved for the degradation of complex, recalcitrant natural polymers like lignin and suberin, which they now apply to the analogous challenge of synthetic PE.[37]

- **Laccases and Peroxidases:** These enzymes are well-known components of the ligninolytic systems of white-rot fungi and some bacteria.
    - **Laccases** are multi-copper oxidases that catalyze the one-electron oxidation of a wide range of phenolic and aromatic substrates, generating highly reactive free radicals.[29] While PE itself is not a direct substrate, these radicals, potentially with the help of small molecule "mediators," can initiate a non-specific oxidative attack on the polymer backbone. Extracellular laccases from bacteria like *Rhodococcus ruber* and various fungi have been shown to increase the carbonyl index of PE films and contribute to a reduction in their molecular weight, confirming their role in the initial oxidative steps.[19]
    - **Peroxidases**, such as manganese peroxidase (MnP) and lignin peroxidase (LiP), are heme-containing enzymes that use hydrogen peroxide to generate powerful oxidizing agents.[37] MnP, for example, oxidizes Mn^{2+} to the highly reactive Mn^{3+}, which can then attack the polymer structure. These enzymes are considered key players in the initial fragmentation of the high-molecular-weight polymer.[29]
- **Alkane Monooxygenases (AlkB):** This class of enzymes is arguably the most crucial for the subsequent steps of PE assimilation. Alkane monooxygenases are specialized for the oxidation of inert C-H bonds in alkanes, which are the closest natural chemical analogs to polyethylene. The AlkB family of enzymes catalyzes the terminal or sub-terminal hydroxylation of an alkane chain, inserting an oxygen atom to convert an inert methyl or methylene group into a primary or secondary alcohol.[29] This initial hydroxylation is the critical activation step that transforms a segment of the PE chain into a substrate for downstream metabolic pathways. Studies on *Pseudomonas* and *Rhodococcus* have demonstrated the activity of AlkB systems on low-molecular-weight PE and long-chain alkanes, positioning them as central to the process of converting polymer fragments into biologically accessible molecules.[38]

5.2. Proposed Catalytic Mechanisms and Degradation Pathways

The biodegradation of polyethylene is not the work of a single "polyethylene-ase" but rather a multi-step metabolic pathway involving a consortium of enzymes acting in sequence. Based on current evidence, a coherent pathway can be proposed, integrating the distinct roles of

different enzyme classes. The process begins externally and proceeds through several stages before the carbon from the polymer is fully assimilated by the cell.

1. **Stage 1: Extracellular Bio-fragmentation:** Following abiotic priming, extracellular oxidoreductases launch the initial biotic attack. Laccases and peroxidases secreted by the microbial biofilm generate reactive radical species that non-specifically oxidize the PE surface. This leads to further chain scission, reducing the average molecular weight of the polymer and creating shorter, oxidized oligomers with terminal carbonyl or carboxyl groups.[29]
2. **Stage 2: Terminal Hydroxylation:** These shorter oligomeric chains, now small enough to interact effectively with cell-surface or periplasmic enzymes, become substrates for alkane monooxygenases (AlkB). AlkB catalyzes the hydroxylation of a terminal methyl group, converting it into a primary alcohol ($-CH_2OH$).[38] This is the key step that functionalizes the inert alkyl chain for entry into central metabolism.
3. **Stage 3: Stepwise Oxidation to a Fatty Acid Analog:** The terminal alcohol is then sequentially oxidized by two further enzymes. First, an alcohol dehydrogenase oxidizes the alcohol to an aldehyde ($-CHO$). Second, an aldehyde dehydrogenase oxidizes the aldehyde to a carboxylic acid ($-COOH$).[35] The resulting molecule is a long-chain fatty acid analog.
4. **Stage 4: Bioassimilation via β-Oxidation:** The fatty acid-like molecule is transported into the microbial cell. Once inside the cytoplasm, it enters the well-established β-oxidation pathway. In this cyclic process, the long chain is progressively shortened by two carbons at a time, generating acetyl-CoA molecules. These acetyl-CoA units then feed directly into the tricarboxylic acid (TCA) cycle for energy production and are used as building blocks for biomass synthesis, thus completing the mineralization of the polymer's carbon.[20]

This proposed pathway underscores that PE biodegradation is an emergent property of a coordinated enzymatic system, leveraging enzymes that likely evolved for other purposes to deconstruct this novel, man-made substrate.

Figure 1: Proposed Metabolic Pathway for Microbial Biodegradation of Polyethylene. This figure would schematically illustrate the multi-stage process of PE degradation. **Panel A** would show a long, inert polyethylene chain ($[-CH_2-CH_2-]_n$). **Panel B** would depict the effect of abiotic priming (UV/Heat), showing the formation of carbonyl ($>C=O$) and hydroxyl ($-OH$) groups on the chain surface. **Panel C** would illustrate the action of extracellular enzymes like Laccase and Manganese Peroxidase (MnP), which cause chain scission, resulting in shorter oligomers with terminal functional groups. **Panel D** would focus on a single oligomer, showing the key hydroxylation step where Alkane Monooxygenase (AlkB) converts a terminal methyl group to a primary alcohol. **Panel E** would show the subsequent two-step oxidation of this alcohol to a carboxylic acid (a fatty acid analog) via Alcohol Dehydrogenase (ADH) and Aldehyde Dehydrogenase (ALDH). Finally, **Panel F** would depict the transport of this fatty acid analog into the microbial cell, where it enters the β-oxidation spiral, is converted

to acetyl-CoA, and feeds into the TCA cycle, ultimately producing CO_2, water, and new biomass. This visual model synthesizes fragmented knowledge into a coherent, testable hypothesis for the complete biochemical pathway.[16]

6. Evidentiary Standards: A Critical Appraisal of Analytical Techniques

6.1. Surface and Morphological Changes: The Limits of SEM and FTIR

The accurate and unambiguous demonstration of polyethylene biodegradation is a significant challenge, and the literature is replete with studies whose conclusions rely on techniques that are susceptible to misinterpretation. A critical appraisal of these methods is essential for establishing rigorous standards in the field.

- **Scanning Electron Microscopy (SEM):** This is one of the most common techniques employed, providing high-resolution images of the polymer surface. It is undeniably useful for visualizing the direct interaction between microbes and the material, showing evidence of biofilm formation, surface colonization, and morphological changes such as the formation of pits, cracks, and surface erosion.[5] However, its limitations are profound. SEM provides purely qualitative evidence of surface changes; it cannot quantify the extent of degradation nor prove that the observed changes are the result of enzymatic action rather than abiotic physical or chemical weathering.[17] It demonstrates biodeterioration—a change in material properties—but not bioassimilation of carbon.[15]
- **Fourier-Transform Infrared Spectroscopy (FTIR):** FTIR is used to detect changes in the chemical bonding within the polymer. Specifically, it is sensitive to the appearance of new absorption bands corresponding to carbonyl ($>C=O$) and hydroxyl ($-OH$) groups, which are hallmarks of oxidation.[5] While valuable for confirming that an oxidative process has occurred, FTIR is perhaps the most misinterpreted technique in the field. The spectral signatures of these functional groups heavily overlap with those found in microbial biomass itself (e.g., amide bonds in proteins, hydroxyl groups in polysaccharides, carbonyl groups in lipids).[5] Without meticulous cleaning procedures and appropriate controls, it is easy to mistake the signature of a residual biofilm for chemical modification of the polymer, leading to false-positive conclusions of biodegradation.[5]

6.2. Measuring Depolymerization: GPC and Weight Loss Pitfalls

Techniques aimed at quantifying the breakdown of the polymer also have significant caveats that must be considered.

- **Weight Loss:** Measuring the reduction in the dry weight of a PE sample over time is a direct and intuitively appealing metric.[5] However, it is fraught with potential errors. Incomplete removal of the dense, adherent biofilm can lead to an underestimation of weight loss. Conversely, the absorption of water into the polymer matrix or the leaching of low-molecular-weight additives (plasticizers, stabilizers) can be mistaken for mass loss due to biodegradation.[5] For a highly recalcitrant material like PE, the expected weight loss over typical experimental timescales is often very small, falling within the margin of experimental error and making statistically significant conclusions difficult to draw.[5]
- **Gel Permeation Chromatography (GPC):** GPC (also known as Size Exclusion Chromatography, SEC) is a powerful technique for characterizing the molecular weight distribution of a polymer. A demonstrable shift towards lower average molecular weight is strong evidence that polymer chain scission has occurred.[35] This provides more robust proof of depolymerization than weight loss alone. The primary limitation of GPC is that while it confirms the polymer has been broken into smaller pieces, it does not, by itself, prove that these smaller fragments have been metabolized by the microorganisms.[5]

6.3. The Gold Standard: Confirming Mineralization via CO_2 Evolution and Isotope Tracing

To move beyond demonstrating mere deterioration and provide unequivocal proof of true biodegradation (i.e., mineralization and assimilation), techniques that track the fate of the polymer's carbon are required. These methods represent the gold standard in the field.

- **Respirometry (CO_2 Evolution):** This method involves incubating microorganisms with PE as the sole source of carbon in a closed system and measuring the amount of carbon dioxide produced over time.[23] Since the only carbon available for metabolism is from the polymer, the evolution of CO_2 above background levels is direct evidence that the polymer is being mineralized.[5] This technique provides quantitative, kinetic data on the rate of biodegradation and is a robust method for comparing the efficiency of different microbial strains or conditions.
- **Isotope Labeling:** The most definitive and unambiguous method for proving

biodegradation involves the use of isotope-labeled polymers, typically with Carbon-13 (^{13}C).[5] In this approach, microorganisms are incubated with ^{13}C-labeled PE. The subsequent detection of the ^{13}C label in the evolved CO_2 ($^{13}CO_2$) and, critically, incorporated into microbial biomass (e.g., in cellular fatty acids or proteins) provides irrefutable proof that the carbon from the synthetic polymer has been taken up and metabolized by the cells. While technically demanding and expensive, this method eliminates all ambiguity and should be the ultimate standard for validating novel claims of PE biodegradation.[5] The current over-reliance on less robust methods has created a hierarchy of evidence in the literature, necessitating a move toward stricter, standardized reporting guidelines that require proof of mineralization to substantiate claims of biodegradation.

7. Future Frontiers: Engineering Biological Solutions for a Circular PE Bio-economy

7.1. Mining the Metagenome for Novel Biocatalysts

The progress in identifying PE-degrading microbes has thus far relied heavily on culture-based methods, which can access only a tiny fraction of the planet's microbial diversity. The vast majority of microorganisms remain unculturable in the laboratory. This "microbial dark matter" represents an enormous, untapped reservoir of novel enzymes and metabolic pathways. Culture-independent metagenomics offers a powerful tool to bypass the need for cultivation and directly access the genetic information of entire microbial communities.[40] By sequencing the total DNA extracted from environments where plastics accumulate—such as the plastisphere on marine debris, landfill leachate, or the guts of plastic-eating insects—researchers can identify genes encoding potential plastic-degrading enzymes.[41] This "gene-first" approach, coupled with functional screening of metagenomic libraries, is poised to dramatically expand our catalog of biocatalysts, potentially uncovering enzymes with higher activity, novel mechanisms, or greater stability than those currently known.[40]

7.2. Synthetic Biology and Metabolic Engineering for Enhanced

Degradation

The discovery of natural systems is only the first step; the future of PE bioremediation lies in the rational design and engineering of biological systems optimized for this specific task. This is the domain of synthetic biology and metabolic engineering.[43]

- **Enzyme Engineering:** Naturally occurring enzymes have not evolved to be maximally efficient on synthetic polymers. Protein engineering techniques, such as structure-guided mutagenesis and high-throughput directed evolution, can be used to remodel the active sites of known enzymes like laccases and alkane monooxygenases. The goal is to improve key properties such as catalytic efficiency (k_{cat}/K_M) on PE oligomers, thermal stability for use in industrial processes, and resistance to inhibitory byproducts.[43]
- **Pathway Engineering and Upcycling:** Beyond improving single enzymes, entire metabolic pathways can be designed and assembled in robust, industrially relevant chassis organisms like *E. coli* or the yeast *Pichia pastoris*. This involves heterologously expressing a suite of enzymes required for the complete degradation pathway, from initial oxidation to central metabolism.[43] A particularly transformative application is "upcycling," where the breakdown products of PE (e.g., dicarboxylic acids) are channeled not just to CO_2, but are used as feedstock for the synthesis of high-value bioproducts, such as biodegradable plastics (e.g., polyhydroxyalkanoates, PHAs) or specialty chemicals. This approach reframes plastic waste from a disposal problem into a resource for a sustainable, circular bio-economy.[43]

7.3. Designing and Evolving Synthetic Microbial Consortia

Given that the complete biodegradation of PE is a complex, multi-step process, it is unlikely that a single microbial species will possess all the necessary functions to perform it efficiently. The field is therefore moving away from monoculture-based approaches and toward the development of synthetic microbial consortia.[44]

- **Rational Design:** In this bottom-up approach, consortia are constructed by combining multiple, well-characterized microbial specialists that perform complementary tasks in a metabolic division of labor.[46] For example, a consortium could consist of a fungal species that excels at initial fragmentation, a bacterial species that secretes biosurfactants to increase bioavailability, and another bacterial species specialized in consuming the resulting oligomers.[45] This modular approach allows for greater control and robustness.
- **Experimental Evolution:** A powerful top-down alternative is adaptive laboratory evolution. In this strategy, a complex, naturally derived microbial community is subjected

to strong selective pressure over many generations, with PE as the sole available carbon source.[21] This process allows nature to select for the most effective combinations of species and the evolution of synergistic interactions, such as cross-feeding of metabolic intermediates. Recent studies have shown that communities evolved in this manner form more robust biofilms and exhibit significantly enhanced degradation capabilities compared to their ancestral communities, revealing emergent cooperative strategies that would be difficult to predict or design rationally.[21]

This shift from discovery to design, powered by the convergence of metagenomics, synthetic biology, and systems biology, represents a fundamental paradigm change that promises to accelerate the development of practical, effective bioremediation technologies.

8. Concluding Perspective and Outlook

8.1. Bridging Knowledge Gaps and Resolving Controversies

Despite significant progress, the field of polyethylene biodegradation remains in its relative infancy, characterized by compelling discoveries but also by substantial knowledge gaps and methodological controversies. To advance from promising laboratory findings to robust, scalable technologies, the research community must address several critical challenges. A primary imperative is the establishment of rigorous, universally accepted standards for proving biodegradation. The field must move beyond ambiguous metrics like surface morphology and unverified FTIR signals and embrace quantitative measures of mineralization, such as CO_2 evolution and, ideally, ^{13}C isotope tracing, as the required standard of proof.

Fundamental biochemical questions also remain. The precise catalytic mechanisms by which enzymes like laccases and alkane monooxygenases cleave the C-C backbone of PE are still poorly understood. Identifying the rate-limiting steps in the overall pathway—be it abiotic priming, extracellular enzymatic attack, or cellular uptake of oligomers—is crucial for targeted engineering efforts. Furthermore, developing rapid, high-throughput screening methods is essential to accelerate the discovery of novel enzymes from vast metagenomic libraries and to efficiently evaluate the performance of engineered variants and microbial consortia.

8.2. The 5–10 Year Horizon: From Lab-Scale Discovery to Viable Bioremediation

The trajectory of PE biodegradation research is poised for rapid acceleration over the next decade, driven by the powerful tools of modern biotechnology.

- **Short-term (1–5 years):** The immediate future will likely be dominated by continued bioprospecting and bioengineering. We can expect the discovery of a wider diversity of more efficient plastic-degrading enzymes through large-scale metagenomic mining of unique environments like the plastisphere and insect guts.[42] Concurrently, protein engineering efforts will yield first-generation enzymes with enhanced activity and stability. The design and characterization of synthetic, multi-species microbial consortia will become a mainstream approach, moving beyond the limitations of monocultures to create more robust and efficient degradation systems.[46]
- **Long-term (5–10 years):** The focus will progressively shift from fundamental discovery towards process engineering and real-world application. We anticipate the development of the first pilot-scale bioreactors designed to treat specific, pre-treated PE waste streams, such as agricultural mulch films or sorted packaging waste.[34] The most transformative advances will likely come from the integration of biodegradation with a circular economy framework.[43] The ultimate goal will be not merely to dispose of PE waste, but to use engineered microbial systems to upcycle it into valuable chemicals and materials, creating an economic driver for bioremediation.[48] The overarching challenge will be one of scale: translating elegant laboratory solutions into economically viable and environmentally significant technologies that can operate at a scale commensurate with the global plastic pollution crisis. While the microbial degradation of polyethylene is a formidable challenge, the convergence of environmental microbiology, enzymology, and synthetic biology offers a credible and exciting path toward a sustainable future for this ubiquitous material.

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References

- [2] Kitech. (2024). *In 2024, The Global Plastic Production Will Exceed 400 Million Tons*. Kitech Recycling Machine. https://www.kitechrecyclingmachine.com/in-2024-the-global-plastic-production-will-exceed-400-million-tons.html

- [1] Virtue Market Research. (2024). *Polyethylene Market*. https://virtuemarketresearch.com/report/polyethylene-market
- [6] SAFE. (2024). *Plastic Overshoot Day 2024: Global Waste Crisis Surpasses Management Capacity*. Safe Food Advocacy Europe. https://www.safefoodadvocacy.eu/plastic-overshoot-day-2024-global-waste-crisis-surpasses-management-capacity/
- [3] ICIS. (2024). *Global PE demand in 2024 could have been 74m tonnes lower if incomes and population drove the market*. Asian Chemical Connections. https://www.icis.com/asian-chemical-connections/2024/03/global-pe-demand-in-2024-could-have-been-74m-tonnes-lower-if-incomes-and-population-drove-the-market/
- [49] IUCN. (2024). *Plastic pollution*. IUCN Issues Brief. https://iucn.org/sites/default/files/2024-05/plastic-pollution-issues-brief-may-2024-update.pdf
- [9] Maity, S., et al. (2022). Environmental toxicity, human hazards and bacterial degradation of polyethylene. *World Journal of Microbiology and Biotechnology, 38*(1), 17. https://pmc.ncbi.nlm.nih.gov/articles/PMC8755403/
- [7] CIEL. (n.d.). *The Toxic Impacts of Plastic Across Its Lifecycle*. Center for International Environmental Law. https://www.ciel.org/the-toxic-impacts-of-plastic-across-its-lifecycle/
- [8] EPA. (n.d.). *Impacts of Plastic Pollution*. United States Environmental Protection Agency. https://www.epa.gov/plastics/impacts-plastic-pollution
- [11] Seltenrich, N. (2015). New link in the food chain? Marine plastic pollution and seafood safety. *Environmental Health Perspectives, 123*(2), A34-A41. https://www.mdpi.com/2073-4360/5/1/1
- [10] ResearchGate. (2023). *Environmental Toxicity, Human Hazards, and Bacterial Degradation of Polyethylene*. https://www.researchgate.net/publication/373662237_Environmental_Toxicity_Human_Hazards_and_Bacterial_Degradation_of_Polyethylene
- [4] Chamas, A., et al. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering, 8*(9), 3494-3511. https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635
- [5] Ghatge, S., et al. (2020). Biodegradation of polyethylene: a brief review. *Applied Biological Chemistry, 63*(1), 27. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
- [20] Zhang, K., et al. (2023). Unraveling the Mechanisms of Microbial Polyethylene Degradation. *Environmental Science & Technology, 57*(31), 11416-11426. https://pubs.acs.org/doi/10.1021/acs.est.3c03778
- [12] ResearchGate. (2014). *Occurrence and recalcitrance of polyethylene bag waste in Nigerian soils*. https://www.researchgate.net/publication/260404740_Occurrence_and_recalcitrance_of_

polyethylene_bag_waste_in_Nigerian_soils

- [13] Folino, A., et al. (2020). Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability, 12*(15), 6030. https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/
- [16] Folino, A., et al. (2020). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences, 13*(5), 3045. https://www.mdpi.com/2076-3417/13/5/3045
- [15] Emadian, S. M., et al. (2017). Biodegradation of polyethylene (PE): A review. *Bagean, 1*(1). https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
- [17] Encyclopedia. (2022). *Abiotic and Biotic Degradation of Polymers*. https://encyclopedia.pub/entry/31417
- [18] MDPI. (2024). Effect of Abiotic Treatments on Agricultural Plastic Waste: Efficiency of the Degradation Processes. *Polymers, 16*(3), 359. https://www.mdpi.com/2073-4360/16/3/359
- [36] ResearchGate. (2025). *Recent progresses and perspectives of polyethylene biodegradation by bacteria and fungi: A review*. https://www.researchgate.net/publication/387769842_Recent_progresses_and_perspectives_of_polyethylene_biodegradation_by_bacteria_and_fungi_A_review
- [27] ResearchGate. (2023). *Polyethylene Degradation by Microbes: Bacteria, Fungus- A Review*. https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review
- [32] MDPI. (2025). Biotransformation of Polymeric Wastes Using Pedospheric Fungal and Bacterial Strains. *Polymers, 17*(2), 169. https://www.mdpi.com/2073-4360/17/2/169
- [28] Mlalila, N., et al. (2022). Isolation and identification of polyethylene-degrading microorganisms from agricultural soils. *Frontiers in Microbiology, 13*, 1077588. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1077588/full
- [44] Li, J., et al. (2023). Top-down and bottom-up approaches for constructing polyethylene-degrading synthetic microbial consortia. *Frontiers in Microbiology, 14*, 1181967. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full
- [19] Google Patents. (2014). *Method for degrading polyethylene by using bacillus extracellular laccase*. CN103980535A. https://patents.google.com/patent/CN103980535A/en
- [29] Wei, R., & Zimmermann, W. (2017). Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: from discovery to application. *Microbial Biotechnology, 10*(6), 1378-1385. https://www.mdpi.com/2076-2607/10/8/1537
- [37] Russo, D. A., et al. (2023). Oxidative Enzymes for the Valorization of Lignocellulosic Biomass and for the Biodegradation of Plastics and Rubber. *International Journal of Molecular Sciences, 24*(7), 6368. https://www.mdpi.com/1422-0067/24/7/6368
- [38] ResearchGate. (2016). *Comparison of the functional characterization between alkane monooxygenases for low-molecular-weight polyethylene biodegradation*.

https://www.researchgate.net/publication/305828978_Comparison_of_the_functional_characterization_between_alkane_monooxygenases_for_low-molecular-weight_polyethylene_biodegradation

- [22] Sivan, A., et al. (2006). Biofilm development of the Polyethylene-degrading bacterium Rhodococcus ruber. *Applied Microbiology and Biotechnology, 72*(2), 346-352. https://www.researchgate.net/publication/7243172_Biofilm_development_of_the_Polyethylene-degrading_bacterium_Rhodococcus_ruber
- [24] Srivastava, P., et al. (2025). Biochemical and molecular mechanisms of Rhodococcus rhodochrous IITR131 for polyethylene terephthalate degradation. *Journal of Applied Microbiology, 136*(1), lxae312. https://academic.oup.com/jambio/article/136/1/lxae312/7929870
- [26] Putcha, J. P., & Kitagawa, W. (2024). Polyethylene Biodegradation by an Artificial Bacterial Consortium: Rhodococcus as a Competitive Plastisphere Species. *Microbes and Environments, 39*(3), ME24031. https://www.jstage.jst.go.jp/article/jsme2/39/3/39_ME24031/_article
- [25] Zampolli, J., et al. (2023). Genomic and physiological traits of two Rhodococcus strains explain their different polycaprolactone (PCL) biodegradative potential. *Frontiers in Microbiology, 14*, 1284956. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1284956/full
- [33] Tariq, A., et al. (2024). Biodegradation of microplastics by fungal strains. *Heliyon, 10*(10), e30843. https://pmc.ncbi.nlm.nih.gov/articles/PMC11535424/
- [23] Das, M. P., & Kumar, S. (2014). Microbial Deterioration of Low Density Polyethylene by Aspergillus and Fusarium sp. *International Journal of ChemTech Research, 6*(1), 299-305. https://www.researchgate.net/publication/260982412_Microbial_Deterioration_of_Low_Density_Polyethylene_by_Aspergillus_and_Fusarium_sp
- [31] MDPI. (2025). Fungal Degradation of Polyethylene: A Sustainable Approach to Mitigate Plastic Pollution. *Polymers, 17*(10), 1303. https://www.mdpi.com/2073-4360/17/10/1303
- [30] MDPI. (2025). Biodegradation of Low-Density Polyethylene (LDPE) by Aspergillus Species Isolated from Mangrove Sediments Enriched with Crude Oil. *Sustainability, 17*(20), 8983. https://www.mdpi.com/2071-1050/17/20/8983
- [14] The Pharma Journal. (2023). *Microbial degradation of polyethylene: A review*. https://www.thepharmajournal.com/archives/2023/vol12issue9/PartAB/12-9-168-119.pdf
- [5] Ghatge, S., et al. (2020). Biodegradation of polyethylene: a brief review. *Applied Biological Chemistry, 63*(27). https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
- [16] MDPI. (2023). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences, 13*(5), 3045. https://www.mdpi.com/2076-3417/13/5/3045
- [39] MDPI. (2025). Advanced Analytical Techniques for Microplastics Detection and Characterization. *Molecules, 30*(11), 2462. https://www.mdpi.com/1420-3049/30/11/2462
- [43] SciePublish. (2023). *Biodegradation and Biotransformation of Plastic Waste: From*

Discovery and Engineering of Depolymerases to Upcycling of Monomers. Industrial Biotechnology. https://www.sciepublish.com/article/pii/440

- [21] bioRxiv. (2025). *Evolving bacterial biofilm communities for enhanced polyethylene degradation*. https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full.pdf
- [40] Danso, D., et al. (2019). Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. *Applied and Environmental Microbiology, 85*(11), e01095-19. https://pmc.ncbi.nlm.nih.gov/articles/PMC7521044/
- [47] bioRxiv. (2025). *Evolving bacterial biofilm communities for enhanced polyethylene degradation*. https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1
- [34] Chen, Y., et al. (2022). Biodegradation of plastics by insects and their gut microbes: A review. *Frontiers in Microbiology, 13*, 991750. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1001750/full
- [46] Billone, P., et al. (2023). Selection and characterization of plastic-degrading microbial consortia from artificially contaminated microcosms. *Frontiers in Microbiology, 14*, 1143769. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1143769/full
- [41] ResearchGate. (2022). *Forthcoming Potentials of Plastic Degradation*. https://www.researchgate.net/publication/357874678_Forthcoming_Potentials_of_Plastic_Degradation
- [42] Zrimec, J., et al. (2021). Plastic-Degrading Enzymes Are Widespread in the Global Ocean and Soil Microbiomes. *mBio, 12*(6), e02155-21. https://journals.asm.org/doi/10.1128/mbio.02155-21
- [48] MDPI. (2024). Microbial Degradation of (Micro)plastics: Pure and Mixed Cultures, Influencing Factors, and Enhancement Technologies. *Fermentation, 10*(9), 441. https://www.mdpi.com/2311-5637/10/9/441
- [16] MDPI. (2023). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences, 13*(5), 3045. https://www.mdpi.com/2076-3417/13/5/3045
- [35] ResearchGate. (2023). *Figure: A schematic illustration of potential polyethylene degradation pathway....* https://www.researchgate.net/figure/A-schematic-illustration-of-potential-polyethylene-degradation-pathway-summarizing-the_fig6_374737149
- [20] Zhang, K., et al. (2023). Unraveling the Mechanisms of Microbial Polyethylene Degradation. *Environmental Science & Technology, 57*(31), 11416-11426. https://pubs.acs.org/doi/10.1021/acs.est.3c03778
- [45] Diva Portal. (2024). *Engineering synthetic microbial consortia for polyethylene degradation*. https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf
- [4] ACS Publications. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*. https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635
- [15] Emadian, S. M., et al. (2017). Biodegradation of polyethylene (PE): A review. *Bagean*.

https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/

- [4] ACS Publications. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*. https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635
- [16] MDPI. (2023). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences*. https://www.mdpi.com/2076-3417/13/5/3045
- [5] ResearchGate. (2020). *Biodegradation of polyethylene: a brief review*. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
- [29] MDPI. (2022). Microbial Enzymes for the Recycling of Recalcitrant Petroleum-Based Plastics. *International Journal of Molecular Sciences*. https://www.mdpi.com/2076-2607/10/8/1537
- [22] ResearchGate. (2006). *Biofilm development of the Polyethylene-degrading bacterium Rhodococcus ruber*. https://www.researchgate.net/publication/7243172_Biofilm_development_of_the_Polyethylene-degrading_bacterium_Rhodococcus_ruber
- [5] ResearchGate. (2020). *Biodegradation of polyethylene: a brief review*. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
- [35] ResearchGate. (2023). *Figure: A schematic illustration of potential polyethylene degradation pathway....* https://www.researchgate.net/figure/A-schematic-illustration-of-potential-polyethylene-degradation-pathway-summarizing-the_fig6_374737149
- [43] SciePublish. (2023). *Biodegradation and Biotransformation of Plastic Waste....* Industrial Biotechnology. https://www.sciepublish.com/article/pii/440
- [34] Frontiers. (2022). *Biodegradation of plastics by insects and their gut microbes: A review*. Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1001750/full
- [16] MDPI. (2023). A Review of Degradation and Life Prediction of Polyethylene. *Applied Sciences*. https://www.mdpi.com/2076-3417/13/5/3045
- [35] ResearchGate. (2023). *Figure: A schematic illustration of potential polyethylene degradation pathway....* https://www.researchgate.net/figure/A-schematic-illustration-of-potential-polyethylene-degradation-pathway-summarizing-the_fig6_374737149

Works cited

1. Polyethylene Market | Size, Share, Growth | 2025 - 2030, accessed on October 23, 2025, https://virtuemarketresearch.com/report/polyethylene-market
2. In 2024, the Global Plastic Production Will Exceed 400 Million Tons | Kitech, accessed on October 23, 2025,

https://www.kitechrecyclingmachine.com/in-2024-the-global-plastic-production-will-exceed-400-million-tons.html
3. Global PE demand in 2024 could have been 74m tonnes lower if incomes and population drove the market – Asian Chemical Connections - ICIS, accessed on October 23, 2025, https://www.icis.com/asian-chemical-connections/2024/03/global-pe-demand-in-2024-could-have-been-74m-tonnes-lower-if-incomes-and-population-drove-the-market/
4. Degradation Rates of Plastics in the Environment | ACS Sustainable ..., accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acssuschemeng.9b06635
5. (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
6. Plastic Overshoot Day 2024: Global Waste Crisis Surpasses Management Capacity | SAFE, accessed on October 23, 2025, https://www.safefoodadvocacy.eu/plastic-overshoot-day-2024-global-waste-crisis-surpasses-management-capacity/
7. The Toxic Impacts of Plastic Across its Lifecycle - Center for International Environmental Law, accessed on October 23, 2025, https://www.ciel.org/the-toxic-impacts-of-plastic-across-its-lifecycle/
8. Impacts of Plastic Pollution | US EPA, accessed on October 23, 2025, https://www.epa.gov/plastics/impacts-plastic-pollution
9. Occurrence, toxicity and remediation of polyethylene terephthalate plastics. A review - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8755403/
10. (PDF) Environmental Toxicity, Human Hazards and Bacterial Degradation of Polyethylene, accessed on October 23, 2025, https://www.researchgate.net/publication/373662237_Environmental_Toxicity_Human_Hazards_and_Bacterial_Degradation_of_Polyethylene
11. Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate) - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/5/1/1
12. Occurrence and recalcitrance of polyethylene bag waste in Nigerian soils - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/260404740_Occurrence_and_recalcitrance_of_polyethylene_bag_waste_in_Nigerian_soils
13. 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/
14. 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
15. Challenges with Verifying Microbial Degradation of Polyethylene - PMC - PubMed

Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
16. A Review of Degradation and Life Prediction of Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-3417/13/5/3045
17. Abiotic and Biotic Polymer Degradation Mechanisms - Encyclopedia.pub, accessed on October 23, 2025, https://encyclopedia.pub/entry/31417
18. Effect of Abiotic Treatments on Agricultural Plastic Waste: Efficiency of the Degradation Processes - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/16/3/359
19. CN103980535A - Method of degrading polyethylene by extracellular laccase of bacillus - Google Patents, accessed on October 23, 2025, https://patents.google.com/patent/CN103980535A/en
20. 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
21. Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms - bioRxiv, accessed on October 23, 2025, https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full.pdf
22. (PDF) Biofilm development of the Polyethylene-degrading bacterium ..., accessed on October 23, 2025, https://www.researchgate.net/publication/7243172_Biofilm_development_of_the_Polyethylene-degrading_bacterium_Rhodococcus_ruber
23. Microbial Deterioration of Low Density Polyethylene by Aspergillus and Fusarium sp, accessed on October 23, 2025, https://www.researchgate.net/publication/260982412_Microbial_Deterioration_of_Low_Density_Polyethylene_by_Aspergillus_and_Fusarium_sp
24. Biochemical and molecular mechanisms of Rhodococcus rhodochrous IITR131 for polyethylene terephthalate degradation | Journal of Applied Microbiology | Oxford Academic, accessed on October 23, 2025, https://academic.oup.com/jambio/article/136/1/lxae312/7929870
25. Insights into the biodegradation of polycaprolactone through genomic analysis of two plastic-degrading Rhodococcus bacteria - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1284956/full
26. Polyethylene Biodegradation by an Artificial Bacterial Consortium: *Rhodococcus* as a Competitive Plastisphere Species - j-stage, accessed on October 23, 2025, https://www.jstage.jst.go.jp/article/jsme2/39/3/39_ME24031/_article
27. (PDF) Polyethylene Degradation by Microbes (Bacteria & Fungus): A ..., accessed on October 23, 2025, https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review
28. Degradation of polyethylene plastic bags and bottles using microorganisms isolated from soils of Morogoro, Tanzania - Frontiers, accessed on October 23,

2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1077588/full
29. Current Advances in Biodegradation of Polyolefins - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-2607/10/8/1537
30. Biodegradation of Low-Density Polyethylene by Native Aspergillus Strains Isolated from Plastic-Contaminated Soil - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2071-1050/17/20/8983
31. Biodegradation Efficacy of Aspergillus niger and Trichoderma harzianum on Low-Density Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/17/10/1303
32. Microbial Biodegradation of Synthetic Polyethylene and Polyurethane Polymers by Pedospheric Microbes: Towards Sustainable Environmental Management - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/17/2/169
33. Determination of Biodegradation Potential of Aspergillus niger, Candida albicans, and Acremonium sclerotigenum on Polyethylene, Polyethylene Terephthalate, and Polystyrene Microplastics - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11535424/
34. Plastic biodegradation by in vitro environmental ... - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1001750/full
35. A schematic illustration of potential polyethylene degradation ..., accessed on October 23, 2025, https://www.researchgate.net/figure/A-schematic-illustration-of-potential-polyethylene-degradation-pathway-summarizing-the_fig6_374737149
36. Recent progresses and perspectives of polyethylene biodegradation by bacteria and fungi: A review | Request PDF - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/387769842_Recent_progresses_and_perspectives_of_polyethylene_biodegradation_by_bacteria_and_fungi_A_review
37. Recent Theoretical Insights into the Oxidative Degradation of Biopolymers and Plastics by Metalloenzymes - MDPI, accessed on October 23, 2025, https://www.mdpi.com/1422-0067/24/7/6368
38. Comparison of the functional characterization between alkane monooxygenases for low-molecular-weight polyethylene biodegradation - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/305828978_Comparison_of_the_functional_characterization_between_alkane_monooxygenases_for_low-molecular-weight_polyethylene_biodegradation
39. Current Approaches to Microplastics Detection and Plastic Biodegradation - MDPI, accessed on October 23, 2025, https://www.mdpi.com/1420-3049/30/11/2462
40. Metagenomic Exploration of Plastic Degrading Microbes for Biotechnological Application - PMC - NIH, accessed on October 23, 2025,

https://pmc.ncbi.nlm.nih.gov/articles/PMC7521044/
41. (PDF) Forthcoming Potentials of Plastic Degradation - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/357874678_Forthcoming_Potentials_of_Plastic_Degradation
42. Plastic-Degrading Potential across the Global Microbiome Correlates with Recent Pollution Trends | mBio - ASM Journals, accessed on October 23, 2025, https://journals.asm.org/doi/10.1128/mbio.02155-21
43. Synthetic Biology Boosts the Biological Depolymerization and ..., accessed on October 23, 2025, https://www.sciepublish.com/article/pii/440
44. 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
45. Polyethylene biodegradation - DiVA portal, accessed on October 23, 2025, https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf
46. Development of plastic-degrading microbial consortia by induced selection in microcosms, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1143769/full
47. 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
48. Microbial Degradation of (Micro)plastics: Mechanisms, Enhancements, and Future Directions - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2311-5637/10/9/441
49. PLASTIC POLLUTION - IUCN, accessed on October 23, 2025, https://iucn.org/sites/default/files/2024-05/plastic-pollution-issues-brief-may-2024-update.pdf