The Microbial Challenge to a Recalcitrant Polymer: A Critical Review of Polyethylene Biodegradation

Abstract
Polyethylene (PE) represents a modern paradox: a material of immense utility whose chemical inertness and durability have led to its accumulation as a persistent global pollutant. With annual production exceeding 100 million tons and conventional waste management strategies proving inadequate, there is an urgent need for sustainable end-of-life solutions. Microbial biodegradation has emerged as a critical research frontier, offering the potential to mineralize this recalcitrant polymer. This review critically examines the current state of PE biodegradation by microbial communities. We first dissect the molecular basis of PE's recalcitrance, rooted in its hydrophobic, high-molecular-weight, saturated hydrocarbon backbone and semi-crystalline structure. We then detail the essential multi-step biodegradation cascade, which begins with abiotic photo- and thermo-oxidation and proceeds through microbial colonization, enzymatic fragmentation, and metabolic assimilation. A comprehensive survey of key microbial players—including bacteria (Rhodococcus, Bacillus), fungi (Aspergillus, Penicillium), synergistic consortia, and the highly efficient microbiomes of "plastivore" insects—highlights the diverse biological machinery being co-opted for this task. We analyze the enzymatic toolkit, focusing on the catalytic mechanisms of oxidoreductases (laccases, peroxidases) and hydroxylases that initiate polymer cleavage, and trace the metabolic fate of breakdown products through pathways analogous to alkane degradation, such as β-oxidation. A critical assessment of analytical methodologies reveals a "hierarchy of evidence," underscoring the limitations of surface characterization techniques and the necessity of definitive mineralization assays, such as isotopic labeling, to combat conflicting reports in the literature. Key challenges, including slow degradation rates, the inhibitory effects of plastic additives, and the risk of secondary microplastic formation, are discussed as major barriers to practical application. Finally, we provide a forward-looking perspective on the next decade of research, emphasizing a paradigm shift from discovery to design. Systems biology approaches are elucidating novel enzymes and pathways, while synthetic biology and protein engineering are poised to create highly efficient, specialized microbial systems for PE degradation and upcycling, paving the way for a circular bio-economy.

1. Introduction: The Polyethylene Paradox—Ubiquity

and Persistence

The global scale of plastic production has reached staggering proportions, with annual output now exceeding 460 million metric tons. Polyethylene (PE), the world's most produced synthetic polymer, accounts for approximately one-third of this total volume, with an annual production of more than 100 million tons. Its widespread use in packaging, agriculture, construction, and consumer goods stems from a unique combination of desirable properties: it is lightweight, flexible, durable, and exhibits excellent chemical and water resistance.[3] However, this success has created a profound environmental challenge. Recent analyses reveal a direct, quantitative link between the scale of plastic production and environmental pollution, with studies indicating a near 1:1 correlation between a percentage increase in production and a corresponding increase in plastic waste leakage. This relationship frames the accumulation of PE not merely as a post-consumer waste management failure but as an intrinsic consequence of a linear production model. Global estimates of annual plastic pollution entering the environment range from 20 to 57 million metric tons, a significant fraction of which is PE from short-lifespan, single-use products like bags and packaging films.[1]

The very properties that make PE an indispensable material are the same ones that render it exceptionally persistent in the environment, a concept that can be termed the "Polyethylene Paradox".[3] Its robust, non-polar hydrocarbon structure, which provides excellent chemical stability during its use phase, also makes it highly resistant to natural degradation processes. Once discarded, PE persists for hundreds or even thousands of years.[4] In the environment, it is subjected to abiotic stressors such as ultraviolet (UV) radiation, thermal cycling, and mechanical abrasion. These forces do not lead to mineralization but instead cause the material to fragment into progressively smaller particles: first into mesoplastics (0.5–5 cm), then microplastics (MPs; 1 µm–5 mm), and ultimately nanoplastics (NPs; <1 µm).[10]

These secondary plastic particles are now ubiquitous across every global ecosystem, from the deepest oceanic trenches to the highest mountain peaks and polar ice caps.[6] Their small size and high surface-area-to-volume ratio make them potent environmental contaminants. They can adsorb persistent organic pollutants (POPs) and heavy metals from the surrounding environment, acting as vectors for toxic chemicals.[7] Furthermore, they are readily ingested by a vast array of organisms, from plankton to mammals, leading to physical blockages, internal injuries, and reproductive issues.[7] This ingestion facilitates the transfer of plastics and their associated toxins through the food web, ultimately posing a potential risk to human health through the consumption of contaminated seafood, water, and salt.[13]

Conventional waste management strategies are ill-equipped to handle the sheer volume and persistence of PE waste. Global recycling rates for plastics remain dismally low, at

approximately 9%.[17] Mechanical recycling often results in downcycling to lower-quality materials and is hampered by contamination. Incineration, while recovering energy, releases greenhouse gases and toxic byproducts such as dioxins and furans.[10] Landfilling merely sequesters the problem, creating long-term sources of plastic leakage and pollution. This context establishes the urgent need for innovative and sustainable end-of-life solutions. Microbial biodegradation, the process by which microorganisms metabolize polymers into simple, benign products like carbon dioxide, water, and biomass, represents a critical frontier of research. Harnessing the metabolic potential of microbial communities offers a pathway to mineralize PE waste, potentially closing the material loop within a circular bio-economy and addressing one of the most pressing environmental challenges of our time.

2. The Molecular Basis of Polyethylene Recalcitrance

The profound resistance of polyethylene to biodegradation is not a singular property but a multi-layered defense system rooted in its fundamental chemical structure and physical organization. Understanding these barriers is essential for developing effective biological degradation strategies.

The Inert Carbon-Carbon Backbone

At the most fundamental level, PE's recalcitrance stems from its chemical makeup. It is a simple polyolefin with the general formula $(C_2H_4)_n$, consisting of a long, saturated hydrocarbon backbone composed exclusively of strong, non-polar carbon-carbon (C-C) and carbon-hydrogen (C-H) single bonds.[2] The high bond dissociation energy of these C-C bonds, reported to be in the range of 101–118 kcal mol^{-1}, presents a formidable thermodynamic and kinetic barrier to enzymatic cleavage.[2] This stability contrasts sharply with that of other polymers like polyesters (e.g., PET) or natural polymers like lignin, which contain more chemically labile heteroatom bonds (e.g., ester C-O or aryl ether C-O bonds) with significantly lower bond dissociation energies (49–72 kcal mol^{-1}).[22] Most microbial hydrolases have evolved to target these weaker, polar linkages, and there are no known naturally evolved enzyme systems specifically designed to efficiently cleave the inert, non-polar C-C backbone of PE at ambient temperatures.

High Molecular Weight and Hydrophobicity

The long polymer chains of commercial PE result in high molecular weights, typically ranging from 20,000 to over 1,000,000 g/mol. This large size, combined with the non-polar nature of the hydrocarbon chain, renders PE insoluble in water and highly hydrophobic.[3] Hydrophobicity acts as a primary physical barrier to biodegradation. Most microbial degradative enzymes are extracellular hydrolases that function in an aqueous environment. The hydrophobic surface of PE repels these water-soluble enzymes, preventing the intimate contact required for catalysis.[8] Furthermore, this surface property hinders the initial and crucial step of microbial colonization, as microorganisms must first overcome repulsive forces to adhere and form a biofilm.

The Role of Crystallinity and Branching

Beyond its chemical composition, the physical arrangement of PE chains plays a decisive role in its biodegradability. PE is a semi-crystalline polymer, meaning it contains both highly ordered crystalline regions and disordered amorphous regions. The ratio and distribution of these phases are determined by the degree of branching in the polymer chains, which defines the different types of PE.[3] This structural variation directly correlates with recalcitrance, establishing a clear hierarchy of resistance to microbial attack. The general order of biodegradability is LDPE > LLDPE > HDPE.

Table 1: Physicochemical Properties of Common Polyethylene Types and their Implications for Biodegradation

Property	High-Density PE (HDPE)	Low-Density PE (LDPE)	Linear Low-Density PE (LLDPE)
Density (g/cm^3)	0.941–0.965	0.910–0.940	0.915–0.940
Typical Molecular Weight (g/mol)	50,000–200,000	20,000–500,000	50,000–500,000
Branching Structure	Linear chains, minimal branching	Highly branched (long and short	Linear chains with controlled short

		chains)	branches
Degree of Crystallinity (%)	High (typically > 70%)	Low (typically 50–60%)	Intermediate
Implication for Biodegradation	Tightly packed crystalline regions are physically inaccessible to enzymes. Most recalcitrant form.	Disordered amorphous regions increase enzyme accessibility. Most susceptible to degradation among the three.	Properties are intermediate, resulting in moderate susceptibility to degradation.

Data compiled from.[4]

As Table 1 illustrates, the linear nature of **HDPE** allows its chains to pack tightly into dense, highly ordered crystalline structures. These crystalline domains are physically impenetrable to microbial enzymes, which can only act on the polymer surface or within the more accessible amorphous regions.[25] In contrast, the extensive and irregular branching of **LDPE** disrupts this packing, resulting in a larger proportion of amorphous domains. These disordered regions have lower density and greater free volume, allowing for easier penetration of oxygen and microbial enzymes, thus making LDPE significantly more susceptible to biodegradation than HDPE.[27] The structural differences between PE types are therefore not minor variations but fundamental determinants of their environmental fate, creating a direct link between a material's physical properties (e.g., rigidity and strength derived from crystallinity) and its environmental persistence.

3. The Biodegradation Cascade: A Multi-Step Process

The biodegradation of polyethylene is not a singular event but a complex, sequential process that requires a combination of abiotic and biotic actions to overcome the polymer's formidable defenses. This process can be conceptualized as an "abiotic-biotic continuum," where environmental weathering is a non-negotiable prerequisite that primes the inert polymer for subsequent microbial attack. Following this initiation, the biological degradation proceeds through four canonical stages.

The Abiotic-Biotic Continuum: The Essential First Step

Pure, unweathered PE is almost entirely resistant to microbial degradation. The process must be initiated by abiotic factors, primarily UV radiation from sunlight (photo-oxidation) and heat (thermo-oxidation).[29] This abiotic weathering phase is the critical first step that breaches PE's molecular defenses. Exposure to UV light and heat generates free radicals within the polymer matrix, which then react with oxygen. This leads to a cascade of oxidative reactions, including chain scission and the introduction of oxygen-containing functional groups—such as carbonyls ($>C=O$), hydroxyls ($-OH$), and carboxylic acids ($-COOH$)—into the non-polar hydrocarbon backbone.[29]

This initial oxidation is crucial for two reasons. First, it increases the polymer's surface energy and hydrophilicity, creating polar sites that facilitate the attachment of microbial cells and the formation of biofilms.[30] Second, it introduces chemical "weak points" along the polymer chain, as the C-C bonds adjacent to these carbonyl groups are more susceptible to enzymatic cleavage than the original saturated backbone. Abiotic weathering thus acts as the essential bridge, transforming the biologically inert substrate into one that is recognizable and accessible to microbial enzymatic machinery.

The Four Canonical Stages of Biodegradation

Once the PE surface has been abiotically primed, microorganisms can begin the biological phase of degradation, which is typically described as a four-step process.[32]

1. **Biodeterioration (Colonization and Biofilm Formation)**: In this first stage, microorganisms adhere to the oxidized polymer surface and begin to colonize it. This process is not trivial, as the bulk material remains hydrophobic. Successful colonizers are often those with hydrophobic cell surfaces or the ability to produce biosurfactants. These pioneering microbes form a biofilm, a complex community embedded within a self-produced matrix of extracellular polymeric substances (EPS).[37] This biofilm, often referred to as the "plastisphere," creates a specialized microenvironment that traps moisture and nutrients and, most importantly, concentrates degradative enzymes directly at the polymer-water interface.[26] This strategy overcomes the problem of enzyme dilution in the bulk environment and functions as a form of "external digestion."
2. **Biofragmentation (Depolymerization)**: Within the biofilm, microorganisms secrete a battery of extracellular enzymes that attack the polymer chains. As discussed in Section 5, these are primarily oxidative enzymes like laccases and peroxidases. They act on the polymer, particularly at the sites of abiotic oxidation, cleaving the long polymer chains

into smaller, lower-molecular-weight fragments such as oligomers, dimers, and monomers.[30] This enzymatic depolymerization reduces the polymer's molecular weight and generates a pool of water-soluble organic molecules.

3. **Assimilation**: The small, soluble breakdown products generated during biofragmentation are then transported across the microbial cell membrane into the cytoplasm.[32] This step marks the transition from extracellular degradation to intracellular metabolism.
4. **Mineralization**: Inside the cell, the assimilated carbon compounds are channeled into central metabolic pathways. Through processes like β-oxidation and the tricarboxylic acid (TCA) cycle, they are completely catabolized to generate energy (in the form of ATP), produce new cellular components (biomass), and release simple inorganic end-products, primarily carbon dioxide (CO_2) and water (H_2O) under aerobic conditions.[36] The complete conversion of the polymer's carbon to CO_2 is the ultimate definition of biodegradation and provides definitive proof that the material has been removed from the environment.

4. Key Microbial Players in Polyethylene Degradation

The ability to degrade polyethylene is not widespread in the microbial world but has been identified in a diverse array of bacteria and fungi, often isolated from environments contaminated with plastic waste, such as landfills, marine ecosystems, and industrial sites.[25] The most effective degradation, however, appears to occur not by single organisms but by complex, synergistic communities, including those found in the guts of certain insects.

Bacteria

Several bacterial genera have been consistently implicated in PE degradation, leveraging their metabolic versatility, particularly their capacity to degrade hydrocarbons.

- ***Rhodococcus* spp.**: This genus stands out as one of the most promising bacterial candidates for PE biodegradation. Strains like *Rhodococcus ruber* exhibit high cell-surface hydrophobicity, a key trait that enables strong adhesion to the non-polar PE surface and facilitates the formation of dense, robust biofilms.[26] This biofilm-forming capacity is critical for concentrating degradative enzymes at the site of action. Studies have reported significant PE weight loss, up to 8% in 30 days, accompanied by surface erosion and changes in molecular weight.[19] Multi-omics studies on *Rhodococcus* have provided crucial insights, revealing the upregulation of genes involved in alkane

degradation and β-oxidation pathways during growth on PE, confirming the metabolic machinery being co-opted for this process.[45]

- ***Bacillus* spp.**: Members of this genus, including *B. subtilis*, *B. licheniformis*, and *B. cereus*, are frequently isolated from plastic-polluted soils and are known for their ability to produce a wide range of extracellular enzymes.[42] They have been shown to colonize PE surfaces, form biofilms, and cause measurable degradation. Reported efficiencies vary widely, from 1.5% weight loss in 60 days by a single strain to over 34% by a *Bacillus*-led consortium, highlighting the importance of microbial interactions.[42]
- ***Pseudomonas* spp.**: Known for their broad metabolic capabilities and role in bioremediation, species like *Pseudomonas aeruginosa* have demonstrated the ability to use PE as a carbon source.[50] Studies have reported weight loss of up to 11.5% in just 16 days, with evidence of surface pitting and chemical modification. Their well-characterized pathways for alkane and polycyclic aromatic hydrocarbon degradation are thought to be central to their action on PE.

Fungi

Fungi are particularly well-suited for degrading recalcitrant polymers like PE. Their filamentous mycelial growth allows them to physically penetrate the polymer matrix, increasing the surface area for enzymatic attack, while their powerful secretion of extracellular ligninolytic enzymes provides the necessary oxidative chemistry.[52]

- **Ligninolytic Fungi**: Genera such as ***Aspergillus***, ***Penicillium***, and ***Fusarium*** are prominent in the literature.[51] These fungi are natural decomposers of lignin, a complex aromatic polymer whose degradation also requires potent, non-specific oxidative enzymes. They co-opt this machinery to attack PE. For example, studies using *Aspergillus niger* and *Trichoderma harzianum* have reported remarkable PE weight loss of up to 45.6% in a 30-day liquid culture, accompanied by significant structural damage to the polymer surface.[54] The key enzymes involved are laccases and peroxidases, which initiate the oxidative cascade.[51]

Microbial Consortia: The Power of Synergy

In nature, biodegradation is a community effort. This principle holds true for PE, where microbial consortia consistently and significantly outperform single-strain cultures.[57] This enhanced efficiency is a direct result of synergistic interactions:

- **Metabolic Division of Labor**: Different species within the consortium specialize in distinct stages of the degradation process. One organism might produce biosurfactants to facilitate colonization, another may secrete the initial powerful oxidoreductases to fragment the polymer, and a third group could be responsible for metabolizing the resulting oligomers, potentially detoxifying inhibitory byproducts in the process.[37]
- **Complementary Enzymatic Activity**: A mixed community brings a broader and more diverse enzymatic toolkit to bear on the complex and heterogeneous substrate of weathered plastic. This allows for a more complete and rapid breakdown. For instance, a co-culture of a fungus and a bacterium was found to reduce the half-life of LDPE from 602 days (bacterium alone) to just 134 days, demonstrating a powerful synergistic effect.

Insect Gut Microbiomes: A Natural Bioreactor

A paradigm-shifting discovery in the field has been the identification of "plastivore" insect larvae that can rapidly consume and mineralize PE. The larvae of the greater wax moth (*Galleria mellonella*) and the mealworm (*Tenebrio molitor*) are the most studied examples.[60] The degradation process is a remarkable symbiosis between the host insect and its gut microbiome:

- **Host Contribution**: The insect provides crucial mechanical pre-treatment by chewing the plastic into small particles, vastly increasing the surface area available for microbial attack. Its gut acts as a highly efficient, temperature-controlled, anaerobic bioreactor.
- **Microbiome Contribution**: The dense and diverse microbial community within the gut performs the biochemical degradation. Strains of *Acinetobacter*, *Bacillus*, and *Pseudomonas* isolated from these guts have been shown to degrade PE.[60] The degradation rates observed in vivo (within the insect) are orders of magnitude higher than those typically seen in environmental isolates, suggesting that the gut environment provides optimal conditions and a highly adapted microbial consortium for this process. This natural system provides a powerful blueprint for designing future engineered bioremediation strategies.

Table 2: A Curated List of Key PE-Degrading Microorganisms and Consortia

Organism/Consortium	Isolation Source	PE Type & Pre-treatment	Incubation Time (days)	Degradation (% Weight Loss)	Key Enzymes Implicated	Reference(s)

Rhodococcus ruber C208	Soil	UV-photooxidized LDPE film	30	~8%	Laccase, Alkane Hydroxylase	[26]
Bacillus sp. ISJ55	Plastic-contaminated soil	LDPE film	60	1.5%	Not specified	
Bacillus licheniformis FMMA	Marine sediment	LDPE sheets	30	25.5%	Not specified	
Pseudomonas aeruginosa	Plastic-contaminated soil	Polythene material	16	11.5%	Not specified	
Aspergillus niger	Soil	LDPE film	30 (liquid)	45.6%	Laccase, Peroxidase	
Collectotrichum fructicola	Plant endophyte	LDPE film	90	48.8%	Laccase	
Fungal-Bacterial Consortium	Mangrove soil	LDPE film	60	26.3%	Not specified	
Bacillus cereus LDPE-DB2	Gut of *Achroia grisella* (waxworm)	LDPE film	45	19.8%	Lignin-modifying enzymes	
Galleria mellonell	N/A (in	PE film	0.5 (12	14.2% (92	Saliva enzymes,	[60]

a larvae	vivo)		hours)	mg)	Gut microbes	

This table represents a selection of reported values to illustrate the range of organisms and efficiencies. Direct comparison is challenging due to variations in experimental conditions, PE types, and analytical methods.

5. The Enzymatic Toolkit for Polyolefin Cleavage

The biodegradation of polyethylene hinges on the catalytic action of specific enzymes that can initiate the cleavage of its inert hydrocarbon backbone. Since PE lacks the hydrolysable ester or amide bonds found in other polymers like PET or nylon, the enzymatic strategy must be oxidative. The enzymes implicated in this process are not specialized for PE but are rather co-opted from pathways evolved for the degradation of other complex, recalcitrant natural polymers, namely lignin and long-chain alkanes.

The Oxidative First Strike: Ligninolytic Enzymes

The initial enzymatic attack on the weathered PE surface is thought to be carried out by powerful, non-specific oxidoreductases, primarily those involved in lignin degradation.

- **Laccases (EC 1.10.3.2)**: These are blue multi-copper oxidases that catalyze the one-electron oxidation of a broad range of substrates while reducing molecular oxygen to water.[68] While their primary substrates are phenols, their activity against non-phenolic polymers like PE is achieved through a **laccase-mediator system (LMS)**. In this mechanism, the laccase first oxidizes a small, diffusible redox mediator molecule, such as 1-hydroxybenzotriazole (HBT). This oxidized mediator becomes a potent, highly reactive oxidant that can then diffuse to the polymer surface and attack the C-H bonds of the PE backbone via a free radical mechanism, initiating chain scission.[21] The LMS has been shown to be highly effective, causing significant reductions in the molecular weight and tensile strength of PE films in a matter of days.
- **Manganese Peroxidases (MnP, EC 1.11.1.13)**: These are heme-containing peroxidases that are central to lignin degradation by white-rot fungi.[72] The catalytic cycle of MnP does not involve direct oxidation of the polymer. Instead, the enzyme uses hydrogen peroxide (H_2O_2) to oxidize manganese(II) ions (Mn^{2+}) to the highly reactive and unstable manganese(III) (Mn^{3+}).[72] The Mn^{3+} ion is stabilized by chelating

organic acids (e.g., oxalate) secreted by the fungus. This chelated Mn^{3+} complex then acts as a small, diffusible redox mediator, analogous to the mediator in the LMS. It attacks the polymer surface, abstracting electrons and generating free radicals that lead to depolymerization. The involvement of MnP has been identified as a key factor in PE degradation by several lignin-degrading fungi.[56] The use of these mediator-driven systems is a clever evolutionary strategy to overcome the steric hindrance and insolubility of a large, solid substrate; the enzyme uses a small-molecule "proxy" to deliver its oxidative power.

Functionalization for Metabolism: Alkane Hydroxylase Systems

Once the initial oxidative attack has fragmented the PE into shorter, alkane-like oligomers, a different set of more specific enzymes is required to functionalize these chains for entry into cellular metabolism. Given PE's chemical structure as a long-chain alkane, enzymes from alkane degradation pathways are prime candidates.

- **Alkane Hydroxylases (e.g., AlkB, CYP153)**: These enzymes are responsible for the critical first step in aerobic alkane metabolism: the hydroxylation of an inert C-H bond to form an alcohol.[75] This is an activation step, converting the non-reactive alkane into a more reactive functional group.
    - **AlkB** is a membrane-bound, non-heme iron monooxygenase that typically acts on medium-chain alkanes (C_5-C_{17}).
    - **CYP153** is a cytochrome P450-type alkane hydroxylase that also targets medium-chain alkanes.
    - Other systems, like the AlmA monooxygenase, are specialized for long-chain alkanes ($>C_{18}$).77
      The genes encoding these enzymes (alkB, CYP153) are consistently found to be upregulated in metagenomic and transcriptomic studies of PE-degrading microbial communities, providing strong correlational evidence for their involvement.19 The proposed mechanism involves these hydroxylases acting on the ends of the PE oligomers, converting them into long-chain alcohols. This hydroxylation is the gateway step that commits the hydrocarbon fragment to a metabolic fate inside the cell. This suggests a two-phase enzymatic model: a non-specific, mediator-driven oxidative attack by ligninolytic enzymes to fragment the polymer, followed by a more specific functionalization of the resulting oligomers by alkane hydroxylases.

6. Metabolic Fate of Polyethylene Breakdown Products

Once the formidable PE polymer has been fragmented into smaller, soluble oligomers and assimilated by microbial cells, the subsequent catabolism relies on highly conserved and efficient central metabolic pathways. The process represents a remarkable example of metabolic funneling, where a xenobiotic, recalcitrant substrate is converted into intermediates that can be processed by the universal machinery of cellular metabolism. The metabolic route for PE breakdown products is understood to be analogous to the well-characterized pathways for long-chain alkane degradation.[77]

From Oligomer to Fatty Acid

The biofragmentation of PE yields a mixture of long-chain alkanes, alcohols, aldehydes, and carboxylic acids.[68] The primary entry point into intracellular metabolism begins with the functionalization of the alkane-like fragments.

1. **Terminal Hydroxylation**: As described in the previous section, alkane hydroxylase systems (e.g., AlkB) catalyze the initial and rate-limiting step, which is the oxidation of a terminal methyl group of a PE fragment to a primary alcohol ($R-CH_3 \rightarrow R-CH_2OH$).[75]
2. **Sequential Oxidation**: The resulting long-chain alcohol is then sequentially oxidized. First, an alcohol dehydrogenase converts the alcohol to an aldehyde ($R-CH_2OH \rightarrow R-CHO$). Second, an aldehyde dehydrogenase oxidizes the aldehyde to a carboxylic acid ($R-CHO \rightarrow R-COOH$).[46] The end product of this three-step enzymatic sequence is a molecule that is structurally identical to a natural fatty acid. The detection of fatty acids, such as palmitic acid (a C16 fatty acid), in the culture supernatants of *Rhodococcus* strains grown on PE provides strong experimental evidence for this conversion pathway.[19]

The Central Role of β-Oxidation

The long-chain fatty acid-like molecules derived from PE are then catabolized through the **β-oxidation pathway**, a core process in fatty acid metabolism found in virtually all aerobic organisms.[32] This pathway is a highly efficient spiral that systematically disassembles the fatty acid chain. In each cycle of β-oxidation, the fatty acid undergoes four enzymatic reactions that cleave a two-carbon unit from the carboxyl end of the chain, releasing it as acetyl-coenzyme A (acetyl-CoA). The cycle also produces the reducing equivalents $FADH_2$

and NADH. The shortened fatty acid chain then re-enters the cycle, and the process repeats until the entire chain has been converted into acetyl-CoA molecules.

Integration into Central Metabolism and Mineralization

The products of β-oxidation are universal metabolic currency that directly link the degradation of PE to the cell's energy-producing and biosynthetic machinery.

- **Tricarboxylic Acid (TCA) Cycle**: The acetyl-CoA generated from β-oxidation enters the TCA cycle (also known as the Krebs cycle or citric acid cycle). Here, it is completely oxidized to two molecules of CO_2.[46] This step represents the final mineralization of the carbon that originated from the PE polymer.
- **Energy Production**: The NADH and $FADH_2$ produced during both β-oxidation and the TCA cycle are fed into the electron transport chain, where they drive oxidative phosphorylation to generate large amounts of ATP, the cell's primary energy currency.
- **Biomass Synthesis**: Intermediates of the TCA cycle can be siphoned off as precursors for the biosynthesis of amino acids, nucleotides, and other essential cellular components, thus incorporating the carbon from PE into new microbial biomass.

Proteomic network analyses of PE-degrading *Rhodococcus* strains have confirmed the tight coupling between the expression of oxidative enzymes, the enzymes of the β-oxidation pathway, and the TCA cycle, providing a systems-level view of this entire metabolic funnel. This elegant strategy allows microorganisms to efficiently convert a complex, man-made polymer into energy and cellular building blocks by channeling it into one of the most fundamental pathways of life.

7. Methodological Challenges and the Hierarchy of Evidence

A significant impediment to progress in the field of polyethylene biodegradation is the widespread inconsistency in experimental methodologies and the frequent over-interpretation of results. The literature is replete with conflicting claims of degradation efficiency, a problem that stems largely from a lack of standardized protocols and a failure to apply a consistent "hierarchy of evidence" when assessing biodegradation.[8] Many studies report "biodegradation" based on evidence that only demonstrates surface colonization or partial chemical modification, rather than true polymer mineralization. To critically evaluate the

literature and guide future research, it is essential to categorize analytical techniques based on the level of proof they provide.

Tier 1: Evidence of Biodeterioration (Surface Interaction)

These methods are valuable for confirming that microorganisms can colonize and physically or chemically alter the polymer surface. However, they are insufficient on their own to prove that the polymer backbone is being broken down and metabolized.

- **Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM)**: These microscopic techniques are widely used to visualize changes in the surface morphology of PE after microbial incubation. They can reveal the formation of biofilms, cracks, pits, holes, and an increase in surface roughness, providing qualitative evidence of microbial activity on the surface.[83] The limitation is that these features do not definitively prove enzymatic cleavage of the polymer itself; they can also result from physical stress or the degradation of additives within the plastic matrix.
- **Water Contact Angle (WCA)**: This measurement quantifies changes in the surface hydrophobicity. A decrease in the contact angle indicates an increase in surface hydrophilicity, which is consistent with the introduction of polar, oxygen-containing functional groups by oxidative processes.[32] While indicative of chemical change, it does not measure chain scission or mineralization.

Tier 2: Evidence of Biofragmentation (Polymer Chain Alteration)

These methods provide stronger evidence by demonstrating that the polymer's chemical structure or molecular weight is changing, which is a prerequisite for biodegradation.

- **Fourier Transform Infrared (FTIR) Spectroscopy**: FTIR is a powerful tool for detecting changes in the chemical bonds of the polymer. In PE biodegradation, its primary use is to identify the appearance of new absorption bands corresponding to carbonyl ($C=O$, ~1715 cm^{-1}), hydroxyl ($-OH$, ~3300 cm^{-1}), and ether ($C-O$, ~1180 cm^{-1}) functional groups.[32] The formation of a carbonyl peak is a key indicator of oxidation. The "carbonyl index" (CI), often calculated as the ratio of the carbonyl peak area to a reference peak from the PE backbone (e.g., methylene scissoring at ~1465 cm^{-1}), is used to semi-quantify the extent of oxidation.[89] However, FTIR only probes chemical changes and does not directly measure chain cleavage or mineralization.
- **Weight Loss Measurement**: This is one of the most commonly reported metrics due to

its simplicity. However, it is notoriously prone to error and misinterpretation.[47] Apparent weight loss can be caused by the leaching of soluble additives (like plasticizers) rather than polymer degradation. Conversely, incomplete removal of the dense microbial biofilm from the polymer surface can mask true weight loss or even lead to a perceived weight gain.

- **Gel Permeation Chromatography (GPC)**: Also known as Size Exclusion Chromatography (SEC), GPC is a crucial technique for analyzing the molecular weight distribution of a polymer.[91] A decrease in the number-average (M_n) and weight-average (M_w) molecular weights, along with a broadening of the polydispersity index ($PDI = M_w/M_n$), provides strong evidence that the long polymer chains are being cleaved into shorter fragments (biofragmentation).[32]

Tier 3: Definitive Proof of Mineralization and Assimilation

These methods are the "gold standard" as they track the ultimate fate of the carbon atoms from the polymer backbone, providing unequivocal evidence of true biodegradation.

- **Respirometry (CO_2 Evolution)**: This technique measures the amount of CO_2 produced by the microbial community over time in a closed system.[95] When PE is the sole carbon source provided, the amount of CO_2 evolved above the background level of the inoculum can be used to calculate the percentage of the polymer's carbon that has been fully mineralized. This is a direct and quantitative measure of ultimate biodegradation.
- **^{13}C Isotopic Labeling**: This is the most rigorous and unambiguous method available. The experiment involves synthesizing PE using ^{13}C-enriched ethylene as the monomer. This ^{13}C-labeled PE is then supplied to the microbial culture. By using isotope-ratio mass spectrometry (IRMS) or nuclear magnetic resonance (NMR) spectroscopy, researchers can definitively track the ^{13}C label from the solid polymer into the gaseous phase (as $^{13}CO_2$), the aqueous phase (as dissolved intermediates), and into the microbial biomass itself (e.g., in lipids and proteins). This method proves not only mineralization but also assimilation, providing irrefutable evidence that the microorganisms are using the polymer's carbon for their metabolism and growth. The high cost and technical complexity of synthesizing labeled polymers and performing the analysis, however, limit its widespread use.

The field's reliance on lower-tier, less conclusive methods is a primary driver of the conflicting and often non-reproducible results in the literature. A move towards standardized protocols that require at least Tier 2 (e.g., GPC) and ideally Tier 3 (e.g., respirometry or isotopic labeling) evidence is essential for the maturation of PE biodegradation research.

Table 3: A Critical Comparison of Analytical Techniques for Assessing PE Biodegradation

Technique	Information Provided	Strengths	Critical Limitations / Potential for Misinterpretation	Tier of Evidence
SEM / AFM	Surface morphology (cracks, pits, erosion), roughness, biofilm formation.	High-resolution visualization of surface-microbe interactions.	Qualitative; does not prove polymer chain cleavage or mineralization. Changes can be due to physical effects or degradation of additives.	1 (Deterioration)
Weight Loss	Gross change in mass of the polymer sample.	Simple, inexpensive, and widely accessible.	Highly prone to error from additive leaching, water absorption, or incomplete removal of biofilm. Not specific to polymer degradation.	2 (Fragmentation)
FTIR Spectroscopy	Formation of new chemical functional groups (e.g., C=O, -OH).	Highly sensitive to chemical changes indicative of oxidation. Relatively fast and	Does not directly measure chain scission or molecular weight reduction. Provides no	2 (Fragmentation)

		accessible.	information on mineralization.	
Gel Permeation Chromatography (GPC)	Changes in molecular weight distribution (M_n, M_w, PDI).	Provides direct evidence of polymer chain scission (depolymerization).	Does not provide information on the ultimate fate of the fragments (assimilation or mineralization). Can be technically challenging for PE.	2 (Fragmentation)
Respirometry (CO_2 Evolution)	Quantification of carbon from the polymer converted to CO_2.	Direct, quantitative measure of ultimate mineralization. Standardized methods exist (e.g., ISO 14855).	Does not account for carbon incorporated into biomass. Can be sensitive to background CO_2 from the inoculum.	3 (Mineralization)
^{13}C Isotopic Labeling	Unambiguous tracking of polymer carbon into CO_2, biomass, and intermediates.	The "gold standard." Provides definitive proof of both mineralization and assimilation. Eliminates ambiguity from other carbon sources.	Technically complex, requires synthesis of labeled polymer, and expensive analytical equipment (e.g., IRMS).	3 (Mineralization)

Data compiled from.[8]

8. Critical Challenges and Knowledge Gaps

Despite decades of research and promising discoveries, the practical application of microbial polyethylene biodegradation remains a distant goal. The field is confronted by several fundamental challenges that must be addressed to bridge the gap between laboratory observations and real-world solutions. These hurdles range from the inherently slow kinetics of the process to the complexities of real-world plastic waste and the lack of standardized methodologies.

The Kinetic Barrier: Extremely Slow Degradation Rates

The primary and most formidable challenge is the exceptionally slow rate of PE biodegradation.[17] Even with promising microbial isolates and consortia, and after abiotic pre-treatment, the reported degradation rates are typically in the range of a few percent weight loss over several weeks or months.[25] For example, a polyethylene sheet buried in moist soil for over 30 years showed only partial degradation and negligible weight loss.[8] These rates are orders of magnitude too slow for any viable waste management process, which would need to handle tons of material on a timescale of days or weeks, not years. This kinetic barrier is a direct reflection of the polymer's intrinsic recalcitrance—the high energy required to break C-C bonds and the difficulty for enzymes to access the polymer chains.[103] Overcoming this will require not just better microbes, but fundamentally more efficient catalytic systems.

The Additive Problem: The Complexity of Commercial Plastics

A major blind spot in much of the current research is the focus on pure, virgin PE films or powders. Commercial plastics are complex formulations containing a variety of additives, such as plasticizers, UV stabilizers, antioxidants, flame retardants, and pigments, which can constitute a significant fraction of the material's weight.[101] These additives can profoundly influence, and often inhibit, microbial degradation.

- **Inhibition**: Some additives, particularly antioxidants and UV stabilizers, are designed to prevent oxidation, the very process that initiates biodegradation. Flame retardants, such as certain organophosphates, have been shown to be toxic to microbial communities or to directly inhibit the activity of degradative enzymes.[107]
- Preferential Consumption: Conversely, some additives, like certain plasticizers, may be more easily metabolized by microorganisms than the polymer backbone itself. This can lead to misleading results, such as apparent weight loss or CO_2 evolution that is due to the consumption of the additive, not the PE.25
  Furthermore, so-called "biodegradation-promoting" or "oxo-degradable" additives, which are designed to accelerate abiotic oxidation, have been shown in controlled studies to offer no significant enhancement of the ultimate biodegradation of PE in various environments.111 Research must therefore shift to address the complexity of real-world plastic waste, not just idealized laboratory polymers.

The Risk of Secondary Microplastic Formation

A critical and underappreciated risk of incomplete biodegradation is the accelerated formation of secondary micro- and nanoplastics.[11] The initial stages of biodegradation—biodeterioration and biofragmentation—inherently involve the breakdown of macroplastics into smaller fragments.[114] If the rate of this fragmentation significantly outpaces the rate of subsequent mineralization of those fragments, the net result is an accumulation of microplastics in the environment. These smaller particles may be more bioavailable and have different ecotoxicological profiles than the parent material, potentially representing a "cure worse than the disease." Any viable biodegradation strategy must therefore ensure that the entire process goes to completion, with the rate of mineralization keeping pace with the rate of fragmentation to avoid the transient accumulation of harmful intermediates.

Lack of Standardization and Reproducibility

The field is critically hampered by a lack of standardized methods and reporting, which makes comparing results across different studies nearly impossible and contributes to a literature filled with conflicting and often non-reproducible claims.[17] Key areas of inconsistency include:

- **Substrate Heterogeneity**: Studies use a wide variety of PE types (LDPE, HDPE, LLDPE), forms (films, powders, pellets), molecular weights, and, most often, an undisclosed or unknown formulation of additives.[25]
- **Inoculum and Incubation Conditions**: The source of microorganisms (e.g., soil, marine,

insect gut), the composition of the culture medium, and physical parameters (temperature, pH, aeration) vary dramatically between experiments.
- **Ambiguous Definitions and Insufficient Evidence**: As detailed in Section 7, there is no universally accepted, biochemically-based definition of what constitutes "polyethylene biodegradation." Many claims are based on insufficient, Tier 1 evidence (e.g., SEM images), leading to ambiguity and controversy.[25] Establishing standardized testing protocols, akin to those developed by organizations like ASTM and ISO for other materials, and mandating the use of higher-tier evidence (GPC, respirometry, isotopic labeling) are essential for the field to mature.

9. Future Perspectives: Engineering Biological Solutions for a Circular Bio-Economy

Addressing the monumental challenge of polyethylene pollution requires a paradigm shift in research, moving from the passive discovery of naturally occurring degradation processes to the active design and engineering of robust, efficient biological systems. The next 5–10 years will be defined by the convergence of systems biology, synthetic biology, and metabolic engineering to create tailored microbial solutions for a circular bio-economy.

Systems Biology for Discovery and Mechanistic Understanding

A deep, molecular-level understanding of the PE degradation process is the foundation for rational engineering. Multi-omics approaches are indispensable for dissecting the complex interplay of genes, proteins, and metabolites involved.

- **Genomics and Metagenomics**: These tools are crucial for mining novel enzymatic diversity from underexplored environments. Sequencing the genomes of potent PE-degrading isolates (e.g., *Rhodococcus* spp.) or the metagenomes of entire communities (e.g., from insect guts or the "plastisphere") will continue to uncover new classes of oxidoreductases, hydroxylases, and other enzymes with potential activity on PE.[77]
- **Transcriptomics and Proteomics**: These functional genomics approaches provide a dynamic view of the cell's response to PE. By identifying which genes and proteins are upregulated when microbes are grown on PE as a sole carbon source, researchers can pinpoint the key enzymatic players and metabolic pathways involved. Seminal studies on *Rhodococcus ruber* have already used transcriptomics to definitively link PE consumption

to the upregulation of alkane degradation and β-oxidation pathways, providing a clear metabolic roadmap for engineering efforts.[45]

Synthetic Biology and Metabolic Engineering for Enhanced Performance

The ultimate goal is to move beyond the slow kinetics of natural systems by engineering microorganisms and enzymes for superior performance.

- **Protein Engineering**: The catalytic efficiency, stability (especially thermal stability), and substrate specificity of key enzymes are primary targets for improvement. The rapid progress in engineering PET-degrading enzymes like PETase provides a transferable roadmap. Strategies such as **rational design**, which uses structural information to make targeted mutations in an enzyme's active site or to introduce stabilizing features like disulfide bonds, and **directed evolution**, which uses high-throughput screening to select for improved variants from large mutant libraries, can be applied to PE-active enzymes like laccases and alkane hydroxylases.[124] Increasing an enzyme's thermostability is particularly attractive, as higher reaction temperatures can increase the mobility of PE polymer chains, making them more accessible to enzymatic attack.
- **Metabolic Engineering and Pathway Construction**: Rather than relying on the native metabolism of a single organism, synthetic biology allows for the construction of optimized degradation pathways in robust, genetically tractable chassis organisms like *E. coli* or *Pseudomonas putida*. This could involve assembling a synthetic operon containing genes for a surface-displaying biosurfactant, an extracellular laccase with its mediator, an alkane hydroxylase, and the necessary dehydrogenases. This would create a specialist microbe engineered to perform the entire extracellular degradation cascade efficiently.
- **Designing Synthetic Consortia**: Mimicking the division of labor observed in natural consortia and insect guts, a powerful strategy is to engineer synthetic communities. This could involve co-cultures of two or more specialist strains: one engineered for robust biofilm formation and initial oxidative attack, and another engineered to efficiently assimilate and metabolize the resulting oligomers, perhaps even converting them into a valuable product.[122]

From Degradation to Upcycling: A Circular Bio-Economy

The future vision for PE biodegradation should extend beyond simple mineralization to CO_2.

The metabolic breakdown of PE funnels carbon into acetyl-CoA, a central hub of cellular metabolism. This presents a powerful opportunity for **upcycling**. By engineering microbes with synthetic pathways that divert this PE-derived acetyl-CoA, it can be used as a feedstock for the production of high-value chemicals and materials. For example, it could be channeled into pathways for synthesizing biodegradable polymers like polyhydroxyalkanoates (PHAs), biofuels, or specialty chemicals.[123] This approach would transform plastic waste from an environmental burden into a valuable resource, creating a truly circular bio-economy where old plastic is biologically re-manufactured into new, sustainable materials.

The path from the laboratory to a landfill or recycling facility is long and fraught with challenges of scale, cost, and efficiency. However, by integrating systems-level understanding with powerful engineering tools, the scientific community is poised to develop biological systems that can finally meet the challenge posed by this recalcitrant polymer, offering a tangible hope for mitigating one of the defining environmental crises of our time.

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References

Wikipedia. (n.d.). Polyethylene. https://en.wikipedia.org/wiki/Polyethylene
Smart Turf. (n.d.). Polyethylene Explained. https://smartturf.com/polyethylene-explained
ResearchGate. (n.d.). Polyethylene structure. https://www.researchgate.net/figure/Polyethylene-structure-a-General-chemical-structure-b-Schematic-differences-between_fig3_338406283
RT Prototype. (n.d.). What is Polyethylene? https://www.rtprototype.com/what-is-polyethylene/
ACS Publications. (2023). Chemical Reviews. https://pubs.acs.org/doi/10.1021/acs.chemrev.3c00587
National Center for Biotechnology Information. (2022). Polyethylene terephthalate. https://pmc.ncbi.nlm.nih.gov/articles/PMC8755403/
PBS News. (2024). The world is producing 57 million tons of plastic pollution per year, new study finds. https://www.pbs.org/newshour/science/the-world-is-producing-57-million-tons-of-plastic-pollution-per-year-new-study-finds
Safe Food Advocacy Europe. (2024). Plastic Overshoot Day 2024: Global Waste Crisis Surpasses Management Capacity. https://www.safefoodadvocacy.eu/plastic-overshoot-day-2024-global-waste-crisis-surpasses

-management-capacity/
Beyond Petrochemicals. (2024). New Report Shows Global Plastic Production as Significant Source of Carbon Pollution.
https://www.beyondpetrochemicals.org/news/new-report-shows-global-plastic-production-as-significant-source-of-carbon-pollution
Earth Action. (2024). Plastic Overshoot Day Report 2024.
https://plasticovershoot.earth/report-2024/
IUCN. (2024). Plastic pollution issues brief.
https://iucn.org/sites/default/files/2024-05/plastic-pollution-issues-brief-may-2024-update.pdf
CSIRO. (2024). Plastic manufacturing and pollution.
https://www.csiro.au/en/news/All/Articles/2024/April/Plastic-manufacturing-and-pollution
United States Environmental Protection Agency. (n.d.). Impacts of Plastic Pollution.
https://www.epa.gov/plastics/impacts-plastic-pollution
Medium. (n.d.). The Harmful Impact of Polyethylene: Understanding the Plastic Predicament.
https://medium.com/@Eco_LifeMastery/the-harmful-impact-of-polyethylene-understanding-the-plastic-predicament-697eb4d60ab2
MDPI. (2023). Applied Sciences. https://www.mdpi.com/2076-3417/13/5/3045
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
Center for International Environmental Law. (n.d.). The Toxic Impacts of Plastic Across Its Lifecycle. https://www.ciel.org/the-toxic-impacts-of-plastic-across-its-lifecycle/
POM Material. (n.d.). Is Polyethylene Plastic?
https://pom-material.com/blog/is-polyethylene-plastic/
ResearchGate. (2020). Biodegradation of polyethylene: a brief review.
https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
ACS Publications. (2023). Environmental Science & Technology.
https://pubs.acs.org/doi/10.1021/acs.est.3c03778
Stanford University. (2024). Intersect.
https://ojs.stanford.edu/ojs/index.php/intersect/article/download/3458/1712/11239
National Center for Biotechnology Information. (2020). Microorganisms.
https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
ResearchGate. (2020). Biodegradation of polyethylene: a brief review.
https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
MDPI. (2024). International Journal of Molecular Sciences.
https://www.mdpi.com/2311-5637/10/9/441
MDPI. (2025). Polymers. https://www.mdpi.com/2073-4360/17/2/169
Taylor & Francis Online. (2023). Critical Reviews in Biotechnology.
https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861

Oxford Academic. (2024). FEMS Microbiology Reviews.
https://academic.oup.com/femsre/article/48/6/fuae027/7876491
ResearchGate. (2011). Kinetics of abiotic and biotic degradability of low-density polyethylene containing prodegradant additives and its effect on the growth of microbial communities.
https://www.researchgate.net/publication/251509163_Kinetics_of_abiotic_and_biotic_degradability_of_low-density_polyethylene_containing_prodegradant_additives_and_its_effect_on_the_growth_of_microbial_communities
ResearchGate. (n.d.). Proposed mechanism of PE degradation process.
https://www.researchgate.net/figure/Proposed-mechanism-of-PE-degradation-process-by-abiotic-and-biotic-systems-Four-stages_fig4_374917416
EPI Environmental Products Inc. (n.d.). Biodegradation of thermally oxidized fragmented low-density polyethylenes.
https://epi-global.org/wp-content/uploads/2023/04/Biodegradation-of-thermally-oxidized-fragmented-low-density-polyethylenes.pdf
National Center for Biotechnology Information. (2024). Polymers.
https://pmc.ncbi.nlm.nih.gov/articles/PMC10857199/
Royal Society of Chemistry. (2025). Environmental Science: Atmospheres.
https://pubs.rsc.org/en/content/articlehtml/2025/em/d5em00079c
Universiti Teknologi Malaysia. (n.d.). Bioprocessing.
https://bioprocessing.utm.my/index.php/bioprocessing/article/view/69
ResearchGate. (2004). Colonization, biofilm formation, and biodegradation of Polyethylene by a strain of Rhodococcus ruber.
https://www.researchgate.net/publication/8487558_Colonization_biofilm_formation_and_biodegradation_of_Polyethylene_by_a_strain_of_Rhodococcus_ruber
Frontiers. (2023). Frontiers in Microbiology.
https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1290441/full
Oxford Academic. (2024). The ISME Journal.
https://academic.oup.com/ismej/advance-article/doi/10.1093/ismejo/wraf223/8277623?searchresult=1
MDPI. (2022). Applied Sciences. https://www.mdpi.com/2076-3417/12/10/5245
bioRxiv. (2025). Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms. https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full.pdf
Frontiers. (2022). Frontiers in Environmental Science.
https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2022.875157/full
National Center for Biotechnology Information. (2022). Journal of Fungi.
https://pmc.ncbi.nlm.nih.gov/articles/PMC9230134/
ResearchGate. (n.d.). Enzyme activity of Laccase and Manganese peroxidase.
https://www.researchgate.net/figure/Enzyme-activity-of-Laccase-and-Manganese-peroxidase_fig3_274468802
MDPI. (2022). Microorganisms. https://www.mdpi.com/2076-2607/10/8/1537
ResearchGate. (2023). Enzymatic Degradation of Polyethylene and Polyethylene Terephthalate: A Mini Review.

https://www.researchgate.net/publication/373983620_Enzymatic_Degradation_of_Polyethylene_and_Polyethylene_Terephthalate_A_Mini_Review
Preprints.org. (2025). Enzymatic Degradation of Plastics.
https://www.preprints.org/manuscript/202504.0667/v1/download
ResearchGate. (n.d.). The metabolic pathways of polythene (PE) plastics.
https://www.researchgate.net/figure/The-metabolic-pathways-of-polythene-PE-plastics-a-b-x-y-represent-different-number_fig5_377104870
ACS Publications. (2023). Chemical Reviews.
https://pubs.acs.org/doi/10.1021/acs.chemrev.3c00587
Frontiers. (2025). Frontiers in Pharmacology.
https://www.frontiersin.org/journals/pharmacology/articles/10.3389/fphar.2025.1689522/pdf
NRC Research Press. (n.d.). Canadian Journal of Chemistry.
https://nrc-publications.canada.ca/fra/voir/td/?id=0ee355ab-e821-45fb-9dcd-8bcbace4ac6b
ResearchGate. (n.d.). Enzymatic degradation pathways of polyethylene (PE), polyethylene terephthalate (PET).
https://www.researchgate.net/figure/Enzymatic-degradation-pathways-of-polyethylene-PE-polyethylene-terephthalate-PET_fig1_383056300
YouTube. (n.d.). Does Polyethylene Degrade?
https://www.youtube.com/watch?v=7wfm7n0o3C4
National Center for Biotechnology Information. (2023). Polymers.
https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/#:~:text=Biodegradation%20processes%20decrease%20in%20the,and%20high%20branching%20promote%20biodegradation.
Frontiers. (2024). Frontiers in Microbiology.
https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2024.1510817/full
MDPI. (2024). Polymers. https://www.mdpi.com/2073-4360/16/21/3038
ResearchGate. (2006). Degradation of Polyethylene and Nylon-66 by the Laccase-Mediator System.
https://www.researchgate.net/publication/39970690_Degradation_of_Polyethylene_and_Nylon-66_by_the_Laccase-Mediator_System
National Center for Biotechnology Information. (2020). Frontiers in Microbiology.
https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/
National Center for Biotechnology Information. (2024). Catalysis Science & Technology.
https://pmc.ncbi.nlm.nih.gov/articles/PMC11189586/
MDPI. (2023). International Journal of Molecular Sciences.
https://www.mdpi.com/1422-0067/24/7/6368
Royal Society of Chemistry. (2024). Chemical Science.
https://pubs.rsc.org/en/content/articlepdf/2024/sc/d4sc00070f
Google Patents. (n.d.). Method for degrading polyethylene by using bacillus extracellular laccase. https://patents.google.com/patent/CN103980535A/en
ResearchGate. (2003). Review: Lignin conversion by manganese peroxidase (MnP).
https://www.researchgate.net/publication/222915661_Review_Lignin_conversion_by_manganese_peroxidase_MnP
Frontiers. (2022). Frontiers in Environmental Science.

https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2022.875157/full
Kyushu University. (2000). Polyethylene degradation by manganese peroxidase in the absence of hydrogen peroxide. https://kyushu-u.elsevierpure.com/en/publications/polyethylene-degradation-by-manganese-peroxidase-in-the-absence-o
ResearchGate. (2000). Polyethylene degradation by manganese peroxidase in the absence of hydrogen peroxide. https://www.researchgate.net/publication/227202797_Polyethylene_degradation_by_manganese_peroxidase_in_the_absence_of_hydrogen_peroxide
Kyushu University. (1998). Polyethylene degradation by lignin-degrading fungi and manganese peroxidase. https://kyushu-u.elsevierpure.com/en/publications/polyethylene-degradation-by-lignin-degrading-fungi-and-manganese-
MDPI. (2021). Journal of Fungi. https://www.mdpi.com/2309-608X/7/8/594
ResearchGate. (2016). Functional analysis of alkane hydroxylase system derived from Pseudomonas aeruginosa E7 for low molecular weight polyethylene biodegradation. https://www.researchgate.net/publication/277338902_Functional_analysis_of_alkane_hydroxylase_system_derived_from_Pseudomonas_aeruginosa_E7_for_low_molecular_weight_polyethylene_biodegradation
Frontiers. (2013). Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2013.00058/full
Semantic Scholar. (2013). Structural insights into diversity and n-alkane biodegradation mechanisms of alkane hydroxylases. https://www.semanticscholar.org/paper/Structural-insights-into-diversity-and-n-alkane-of-Ji-Mao/2d75e2b7fd870cfd50d732ab433fa66575713a6a
National Center for Biotechnology Information. (2020). Microorganisms. https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
National Center for Biotechnology Information. (2022). mSystems. https://pmc.ncbi.nlm.nih.gov/articles/PMC8941889/
MDPI. (2022). Polymers. https://www.mdpi.com/2073-4360/14/23/5127
ResearchGate. (n.d.). A diagram of the microbial degradation processes of polyethylene (PE). https://www.researchgate.net/figure/A-diagram-of-the-microbial-degradation-processes-of-polyethylene-PE_fig2_370519387
ResearchGate. (2020). Biodegradation of polyethylene: a brief review. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
bioRxiv. (2025). Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms. https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full.pdf
National Center for Biotechnology Information. (2023). Environmental Science & Technology. https://pmc.ncbi.nlm.nih.gov/articles/PMC10515485/
MDPI. (2025). Polymers. https://www.mdpi.com/2073-4360/17/2/169
Frontiers. (2023). Frontiers in Microbiology.

https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full
Frontiers. (2013). Frontiers in Microbiology.
https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2013.00116/full
ResearchGate. (2007). Bacterial metabolism of long-chain n-alkanes.
https://www.researchgate.net/publication/6165374_Bacterial_metabolism_of_long-chain
Oxford Academic. (1998). FEMS Microbiology Reviews.
https://academic.oup.com/femsre/article/22/5/459/497338
PubMed. (2007). Bacterial metabolism of long-chain n-alkanes.
https://pubmed.ncbi.nlm.nih.gov/17673997/
Scispace. (2007). Bacterial metabolism of long-chain n-alkanes.
https://scispace.com/papers/bacterial-metabolism-of-long-chain-n-alkanes-11b9k1949p
National Center for Biotechnology Information. (2024). mSystems.
https://pmc.ncbi.nlm.nih.gov/articles/PMC11784139/
ResearchGate. (2021). Computational Study of Bond Dissociation Enthalpies for a Large Range of Native and Modified Lignins.
https://www.researchgate.net/publication/230766950_Computational_Study_of_Bond_Dissociation_Enthalpies_for_a_Large_Range_of_Native_and_Modified_Lignins
ACS Publications. (2021). ACS Materials Letters.
https://pubs.acs.org/doi/10.1021/acsmaterialslett.1c00490
National Center for Biotechnology Information. (2020). Microorganisms.
https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
ResearchGate. (2021). A Review: Plastics Waste Biodegradation Using Plastics-Degrading Bacteria.
https://www.researchgate.net/publication/357835311_A_Review_Plastics_Waste_Biodegradation_Using_Plastics-Degrading_Bacteria
ResearchGate. (2023). Polyethylene Degradation by Microbes (Bacteria, Fungus): A Review.
https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review
ACS Publications. (2023). Environmental Science & Technology.
https://pubs.acs.org/doi/10.1021/acs.est.3c03778
Egyptian Knowledge Bank. (2023). Egyptian Journal of Aquatic Biology and Fisheries.
https://ejabf.journals.ekb.eg/article_365569_c7ff969db8f79d226e63ffc74932e3d5.pdf
D-NB. (n.d.). Biodegradation of Plastics by Fungi: A Review. https://d-nb.info/1260915557/34
bioRxiv. (2021). A marine fungus Alternaria sp. FB1 mediated degradation of polyethylene.
https://www.biorxiv.org/content/10.1101/2021.11.19.469330.full
Technology Journal. (n.d.). Fungal Degradation of Plastic: A Comprehensive Review.
http://technologyjournal.net/wp-content/uploads/3-JOT1410.pdf
MDPI. (2024). Journal of Fungi. https://www.mdpi.com/1424-2818/16/12/759
National Center for Biotechnology Information. (2023). Journal of Fungi.
https://pmc.ncbi.nlm.nih.gov/articles/PMC10301175/
ResearchGate. (2024). Microbial Consortia: Synergistic Effects on Plastic Degradation and Enzyme Production.
https://www.researchgate.net/publication/392897680_Microbial_Consortia_Synergistic_Effects

_on_Plastic_Degradation_and_Enzyme_Production
National Center for Biotechnology Information. (2024). Polymers.
https://pmc.ncbi.nlm.nih.gov/articles/PMC12453932/
Stanford University. (2024). Intersect.
https://ojs.stanford.edu/ojs/index.php/intersect/article/download/3458/1712/11239
J-STAGE. (2024). Microbes and Environments.
https://www.jstage.jst.go.jp/article/jsme2/39/3/39_ME24031/_html/-char/en
MDPI. (2024). International Journal of Molecular Sciences.
https://www.mdpi.com/1422-0067/25/23/12747
ResearchGate. (2023). Polyethylene Degradation by Plastivores: Greater Wax Worms Larvae (Galleria mellonella).
https://www.researchgate.net/publication/372103961_Polyethylene_Degradation_by_Plastivores_Greater_Wax_Worms_Larvae_Galleria_mellonella
ResearchGate. (2024). Degradation of agricultural polyethylene film by greater wax moth (Galleria mellonella) larvae and screening of involved gut bacteria.
https://www.researchgate.net/publication/394757181_Degradation_of_agricultural_polyethylene_film_by_greater_wax_moth_Galleria_mellonella_larvae_and_screening_of_involved_gut_bacteria
National Center for Biotechnology Information. (2024). Polymers.
https://pmc.ncbi.nlm.nih.gov/articles/PMC12388499/
MDPI. (2025). Insects. https://www.mdpi.com/2075-4450/16/2/165
National Center for Biotechnology Information. (2020). Proceedings of the Royal Society B: Biological Sciences. https://pmc.ncbi.nlm.nih.gov/articles/PMC7126078/
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
ACS Publications. (2017). Environmental Science & Technology.
https://pubs.acs.org/doi/10.1021/acs.est.7b00846
National Center for Biotechnology Information. (2023). Environmental Science & Technology.
https://pmc.ncbi.nlm.nih.gov/articles/PMC10515485/
J-STAGE. (2024). Microbes and Environments.
https://www.jstage.jst.go.jp/article/jsme2/39/3/39_ME24031/_article
PubMed. (2006). Biofilm development of the polyethylene-degrading bacterium Rhodococcus ruber. https://pubmed.ncbi.nlm.nih.gov/16534612/
ResearchGate. (2019). Biodegradation of Low Density Polyethylene by Selected Bacillus sp..
https://www.researchgate.net/publication/335537760_Biodegradation_of_Low_Density_Polyethylene_by_Selected_Bacillus_sp
National Center for Biotechnology Information. (2015). 3 Biotech.
https://pmc.ncbi.nlm.nih.gov/articles/PMC4327746/
MDPI. (2024). Processes. https://www.mdpi.com/2227-9717/12/11/2516
EQA - International Journal of Environmental Quality. (2024). The biodegradation of low-density polyethylene by Bacillus species. https://eqa.unibo.it/article/view/20474

International Journal of Scientific Research and Analysis. (2024). Biodegradation of Polythene by Pseudomonas aeruginosa. https://ijsra.net/sites/default/files/IJSRA-2024-0507.pdf
D-NB. (n.d.). Biodegradation of Plastics by Fungi: A Review. https://d-nb.info/1260915557/34
ResearchGate. (2023). Polyethylene Degradation by Microbes (Bacteria, Fungus): A Review. https://www.researchgate.net/publication/371450494_Polyethylene_Degradation_by_Microbes_Bacteria_Fungus_A_Review
National Center for Biotechnology Information. (2022). Journal of Fungi. https://pmc.ncbi.nlm.nih.gov/articles/PMC9330918/
MDPI. (2021). Journal of Fungi. https://www.mdpi.com/2309-608X/7/8/594
National Center for Biotechnology Information. (2024). Journal of Fungi. https://pmc.ncbi.nlm.nih.gov/articles/PMC12114978/
Medvix Publications. (2024). Journal of Mycology and Clinical Cases Reports. https://medvixpublications.org/get/1-JMCCR2024091557FF%20Galley%20Proof-1724824598.pdf
Promega Connections. (2025). Bacteria From Insect Guts Could Help Degrade Plastic. https://www.promegaconnections.com/bacteria-degrade-plastic/
National Center for Biotechnology Information. (2024). Polymers. https://pmc.ncbi.nlm.nih.gov/articles/PMC12388499/
Royal Society Publishing. (2020). Proceedings of the Royal Society B: Biological Sciences. https://royalsocietypublishing.org/doi/10.1098/rspb.2020.0112
Frontiers. (2022). Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1001750/full
Preprints.org. (2024). Plastivore Larvae: A Novel Biotechnological Approach to Degrade Plastic. https://www.preprints.org/manuscript/202411.1632/v1
ResearchGate. (2024). Progress in polystyrene biodegradation by insect gut microbiota. https://www.researchgate.net/publication/379305081_Progress_in_polystyrene_biodegradation_by_insect_gut_microbiota
ResearchGate. (2020). Biodegradation of polyethylene: a brief review. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
ResearchGate. (2023). A Review of Degradation and Life Prediction of Polyethylene. https://www.researchgate.net/publication/368911555_A_Review_of_Degradation_and_Life_Prediction_of_Polyethylene
PubMed. (2021). Analytical methods for the investigation of enzyme-catalyzed degradation of polyethylene terephthalate. https://pubmed.ncbi.nlm.nih.gov/33792200/
MDPI. (2025). Molecules. https://www.mdpi.com/1420-3049/30/11/2462
Dnipropetrovsk National University of Railway Transport. (n.d.). Analytical Methods for Biopolymer Analysis. https://ouci.dntb.gov.ua/en/works/4gBygk07/
Office of Scientific and Technical Information. (2024). Science of the Total Environment. https://www.osti.gov/pages/biblio/2438502
ResearchGate. (n.d.). The FTIR spectra of the degraded polyethylene (LDPE) strips and pellets by bacterial. https://www.researchgate.net/figure/The-FTIR-spectra-of-the-degraded-polyethylene-LDPE-

strips-and-pellets-by-bacterial_fig3_303872553
The Madison Group. (n.d.). Identifying Failures and Ensuring Quality of Plastics Using FTIR. https://madisongroup.com/identifying-failures-and-ensuring-quality-of-plastic-materials/
MDPI. (2023). Polymers. https://www.mdpi.com/2073-4360/15/4/911
Jordi Labs. (n.d.). Case Study: Degradation of PE by FTIR & HTGPC. https://jordilabs.com/wp-content/uploads/filebase/Case_Study_Degradation_of_PE_FTIR_HTGPC.pdf
National Center for Biotechnology Information. (2021). International Journal of Environmental Research and Public Health. https://pmc.ncbi.nlm.nih.gov/articles/PMC8585154/
Advanced Light Source. (2024). Use and misuse of FTIR spectroscopy for studying the bio-oxidation of plastics. https://als.lbl.gov/infrared-site/wp-content/uploads/sites/17/2024/03/Use-and-misuse-of-FTIR-spectroscopy-for-studying-the-bio-oxidation-of-plastics.pdf
Biotechnology Reports. (n.d.). Biodegradation of low-density polyethylene (LDPE) strips by marine-derived fungi. https://www.biotechrep.ir/article_219031_6d286171b4821cb4ead7945c34ab0dd8.pdf
National Center for Biotechnology Information. (2017). 3 Biotech. https://pmc.ncbi.nlm.nih.gov/articles/PMC5603451/
MDPI. (2024). Journal of Fungi. https://www.mdpi.com/1424-2818/16/12/759
Frontiers. (2021). Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2021.687118/full
ResearchGate. (2024). A Morphological Insight into Degradation of Polyethylene-Based Plastic Waste via SEM and AFM. https://www.researchgate.net/publication/392884289_A_Morphological_Insight_into_Degradation_of_Polyethylene-Based_Plastic_Waste_via_SEM_and_AFM
MDPI. (2022). Bioengineering. https://www.mdpi.com/2673-6209/3/2/23
PubMed. (2015). Biodegradation of Polystyrene by Mealworms. https://pubmed.ncbi.nlm.nih.gov/26390034/
Patsnap. (n.d.). Gel Permeation Chromatography for Polymer Molecular Weight Determination. https://eureka.patsnap.com/report-gel-permeation-chromatography-for-polymer-molecular-weight-determination
International Journal of Pharmaceutical Research and Applications. (n.d.). A Review on Gel Permeation Chromatography and Its Pharmaceutical Applications. https://ijprajournal.com/issue_dcp/A%20Review%20on%20Gel%20Permeation%20Chromatography%20and%20Its%20Pharmaceutical%20Applications.pdf
Agilent Technologies. (n.d.). A Guide to GPC/SEC. https://www.agilent.com/cs/library/primers/public/5990-6969EN%20GPC%20SEC%20Chrom%20Guide.pdf
National Center for Biotechnology Information. (2020). Journal of Analytical Methods in Chemistry. https://pmc.ncbi.nlm.nih.gov/articles/PMC7032192/
Ukaaz Publications. (n.d.). Advanced Gel Permeation Chromatography with Multi-Detection for Polymer Analysis. https://www.ukaazpublications.com/publications/?sdm_process_download=1&download_id=1

0709
ResearchGate. (2020). Biodegradation of polyethylene: a brief review.
https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
ResearchGate. (2004). Development and Evaluation of an Online CO2 Evolution Test and a Multicomponent Biodegradation Test System.
https://www.researchgate.net/publication/8415527_Development_and_Evaluation_of_an_Online_CO2_Evolution_Test_and_a_Multicomponent_Biodegradation_Test_System
ResearchGate. (2025). Comparing respirometric systems for standardized biodegradation testing.
https://www.researchgate.net/publication/394274724_Comparing_respirometric_systems_for_standardized_biodegradation_testing_a_case_study_with_polyethylene_glycol_and_activated_sludge_microbiomes
National Center for Biotechnology Information. (2005). Applied and Environmental Microbiology. https://pmc.ncbi.nlm.nih.gov/articles/PMC492337/
ChemRxiv. (2025). Comparing respirometric systems for standardized biodegradation testing.
https://chemrxiv.org/engage/chemrxiv/article-details/68864d7bfc5f0acb524418e3
MDPI. (2022). Bioengineering. https://www.mdpi.com/2673-6209/3/2/23
BPC Instruments. (n.d.). Biodegradability & Compostability.
https://bpcinstruments.com/biodegradability-compostability/
Frontiers. (2025). Frontiers in Environmental Science.
https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1677793/full
National Center for Biotechnology Information. (2020). Microorganisms.
https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
ResearchGate. (2024). Biodegradability of polyethylene: Challenges and future perspectives.
https://www.researchgate.net/publication/385077019_Biodegradability_of_polyethylene_Challenges_and_future_perspectives
Frontiers. (2024). Frontiers in Microbiology.
https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2024.1510817/full
ACS Publications. (2017). Environmental Science & Technology.
https://pubs.acs.org/doi/10.1021/acs.est.7b04051
MDPI. (2024). Sustainability. https://www.mdpi.com/2071-1050/16/21/9395
ResearchGate. (2023). Comparative study on the degradation of HDPE, LLDPE and LDPE during multiple extrusions.
https://www.researchgate.net/publication/372587394_Comparative_study_on_the_degradation_of_HDPE_LLDPE_and_LDPE_during_multiple_extrusions
ResearchGate. (2020). Biodegradation of polyethylene: a brief review.
https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
Frontiers. (2023). Frontiers in Microbiology.
https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1181967/full
MDPI. (2023). Polymers. https://www.mdpi.com/2073-4360/15/6/1540

National Center for Biotechnology Information. (2024). Microbes and Environments. https://pmc.ncbi.nlm.nih.gov/articles/PMC11427307/
National Center for Biotechnology Information. (2023). Polymers. https://pmc.ncbi.nlm.nih.gov/articles/PMC10386651/
ResearchGate. (2024). Microbial degradation and deterioration of polyethylene - A review. https://www.researchgate.net/publication/259995084_Microbial_degradation_and_deterioration_of_polyethylene_-_A_review
Frontiers. (2020). Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2020.580709/full
ACS Publications. (2014). Environmental Science & Technology. https://pubs.acs.org/doi/abs/10.1021/es504258u
MDPI. (2025). Polymers. https://www.mdpi.com/2073-4360/17/2/169
Science Publications. (2021). American Journal of Environmental Engineering and Science. https://pubs.sciepub.com/aees/9/7/8/index.html
National Center for Biotechnology Information. (2022). International Journal of Molecular Sciences. https://pmc.ncbi.nlm.nih.gov/articles/PMC9295099/
ResearchGate. (2022). Experimental investigations on polyethylene and polyethylene terephthalate microplastics' degradation: A review. https://www.researchgate.net/publication/364700841_Experimental_investigations_on_polyethylene_and_polyethylene_terephthalate_microplastics'_degradation_A_review
National Center for Biotechnology Information. (2021). Arhiv za higijenu rada i toksikologiju. https://pmc.ncbi.nlm.nih.gov/articles/PMC8016121/
MDPI. (2023). Journal of Composites Science. https://www.mdpi.com/2305-6304/11/9/747
Royal Society of Chemistry. (2025). Environmental Science: Advances. https://pubs.rsc.org/en/content/articlehtml/2025/va/d5va00064e
National Center for Biotechnology Information. (2020). Frontiers in Microbiology. https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/
ACS Publications. (2022). Environmental Science & Technology. https://pubs.acs.org/doi/10.1021/acs.est.2c01228
MDPI. (2020). Polymers. https://www.mdpi.com/2073-4360/12/1/123#:~:text=A%20significant%20problem%20when%20studying,is%20solid%20and%20highly%20hydrophobic.
National Center for Biotechnology Information. (2023). Frontiers in Microbiology. https://pmc.ncbi.nlm.nih.gov/articles/PMC10150012/
ResearchGate. (2021). Knowledge Gaps in Polymer Biodegradation Research. https://www.researchgate.net/publication/353814455_Knowledge_Gaps_in_Polymer_Biodegradation_Research
American Society for Microbiology. (2022). mSystems. https://journals.asm.org/doi/10.1128/msystems.01415-21
ResearchGate. (2024). Research Progress in Microbial Degradation of Plastics. https://www.researchgate.net/publication/388797947_Research_Progress_in_Microbial_Degradation_of_Plastics
MDPI. (2020). Polymers. https://www.mdpi.com/2073-4360/12/1/123

Kinam Park. (2021). Degradation of conventional plastic wastes in the environment- A review. http://kinampark.com/T-Polymers/files/All%20References/Ali%202021%2C%20Degradation%20of%20conventional%20plastic%20wastes%20in%20the%20environment-%20A%20review.pdf
ResearchGate. (2020). Biodegradation of polyethylene: a brief review. https://www.researchgate.net/publication/341433719_Biodegradation_of_polyethylene_a_brief_review
National Center for Biotechnology Information. (2020). Microorganisms. https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
MDPI. (2023). Applied Sciences. https://www.mdpi.com/2076-3417/13/5/3045
American Society for Microbiology. (2023). Applied and Environmental Microbiology. https://journals.asm.org/doi/10.1128/aem.01060-23
bioRxiv. (2025). Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms. https://www.biorxiv.org/content/10.1101/2025.04.01.646683v1.full.pdf
National Center for Biotechnology Information. (2023). Polymers. https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/
The Italian Association of Chemical Engineering. (2017). Chemical Engineering Transactions. https://www.aidic.it/cet/17/56/009.pdf
National Center for Biotechnology Information. (2020). Frontiers in Microbiology. https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/
Frontiers. (2024). Frontiers in Microbiology. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2024.1510817/full
ResearchGate. (2020). Study of the effect of additives on biodegradation of PVC materials. https://www.researchgate.net/publication/340881610_Study_of_the_effect_of_additives_on_biodegradation_of_PVC_materials
ResearchGate. (2021). Degradation of Polyethylene plastic in Soil and Effects on Microbial Community Composition. https://www.researchgate.net/publication/351808917_Degradation_of_Polyethylene_plastic_in_Soil_and_Effects_on_Microbial_Community_Composition
MDPI. (2023). Polymers. https://www.mdpi.com/2073-4360/15/1/140
MDPI. (2024). Sustainability. https://www.mdpi.com/2071-1050/17/20/9203
National Center for Biotechnology Information. (2020). Polymers. https://pmc.ncbi.nlm.nih.gov/articles/PMC7407105/
ResearchGate. (2023). Effects of Flame Retardants Additives on the Properties of Low-Density Polyethylene. https://www.researchgate.net/publication/367865134_Effects_of_Flame_Retardants_Additives_on_the_Properties_of_Low-Density_Polyethylene
ResearchGate. (2024). INVESTIGATING THE EFFECT OF FLAME-RETARDANTS ON THE THERMAL AGEING OF A HIGH-DENSITY POLYETHYLENE. https://www.researchgate.net/publication/392905015_INVESTIGATING_THE_EFFECT_OF_FLAME-RETARDANTS_ON_THE_THERMAL_AGEING_OF_A_HIGH-DENSITY_POLYETHYLENE
National Center for Biotechnology Information. (2020). Polymers. https://pmc.ncbi.nlm.nih.gov/articles/PMC7664228/

Frontiers. (2022). Frontiers in Chemistry. https://www.frontiersin.org/journals/chemistry/articles/10.3389/fchem.2022.1018998/full
Wikipedia. (n.d.). Plastic. https://en.wikipedia.org/wiki/Plastic
Britannica. (n.d.). Microplastic. https://www.britannica.com/technology/microplastic
ResearchGate. (2022). Biodegradation of Polyethylene Microplastic: A Review. https://www.researchgate.net/publication/365805733_Biodegradation_of_Polyethylene_Microplastic_A_Review
MDPI. (2023). Processes. https://www.mdpi.com/2227-9717/11/12/3445
PubMed. (2022). Environmental risk, toxicity, and biodegradation of polyethylene: a review. https://pubmed.ncbi.nlm.nih.gov/36205861/
ACS Publications. (2023). Environmental Science & Technology. https://pubs.acs.org/doi/10.1021/acs.est.3c03778
ResearchGate. (2023). Polyethylene-biodegrading Microbes and Their Future Directions. https://www.researchgate.net/publication/368256401_Polyethylene-biodegrading_Microbes_and_Their_Future_Directions
International Journal of Scientific Research and Analysis. (n.d.). Innovative Biotechnological Approaches for Plastic Degradation: A Pathway to Sustainable Waste Management. https://ijsra.net/content/innovative-biotechnological-approaches-plastic-degradation-pathway-sustainable-waste
National Center for Biotechnology Information. (2024). Metabolic Engineering Communications. https://pmc.ncbi.nlm.nih.gov/articles/PMC11647663/
Royal Society of Chemistry. (2025). Environmental Science: Advances. https://pubs.rsc.org/en/content/articlehtml/2025/va/d5va00058k
Diva Portal. (2024). Engineering of polyethylene-degrading synthetic microbial consortia. https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf
SciePublish. (n.d.). Synthetic Biology Boosts the Biological Depolymerization and Upcycling of Waste Plastic Resources. https://www.sciepublish.com/article/pii/440
Frontiers. (2024). Frontiers in Bioengineering and Biotechnology. https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2024.1349010/full

Works cited

1. PLASTIC POLLUTION - IUCN, accessed on October 23, 2025, https://iucn.org/sites/default/files/2024-05/plastic-pollution-issues-brief-may-2024-update.pdf
2. Synthesis and Deconstruction of Polyethylene-type Materials | Chemical Reviews, accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acs.chemrev.3c00587
3. Polyethylene - Wikipedia, accessed on October 23, 2025, https://en.wikipedia.org/wiki/Polyethylene
4. Understanding Polyethylene: Properties, Uses, and FAQs | Smart Turf® Artificial Grass, accessed on October 23, 2025, https://smartturf.com/polyethylene-explained

5. If plastic manufacturing goes up 10%, plastic pollution goes ... - CSIRO, accessed on October 23, 2025, https://www.csiro.au/en/news/All/Articles/2024/April/Plastic-manufacturing-and-pollution
6. The world is producing 57 million tons of plastic pollution per year, new study finds - PBS, accessed on October 23, 2025, https://www.pbs.org/newshour/science/the-world-is-producing-57-million-tons-of-plastic-pollution-per-year-new-study-finds
7. The Harmful Impact of Polyethylene: Understanding the Plastic Predicament - Medium, accessed on October 23, 2025, https://medium.com/@Eco_LifeMastery/the-harmful-impact-of-polyethylene-understanding-the-plastic-predicament-697eb4d60ab2
8. (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
9. Impacts of Plastic Pollution | US EPA, accessed on October 23, 2025, https://www.epa.gov/plastics/impacts-plastic-pollution
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. Experimental investigations on polyethylene and polyethylene terephthalate microplastics' degradation. A review - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/364700841_Experimental_investigations_on_polyethylene_and_polyethylene_terephthalate_microplastics'_degradation_A_review
12. From plastics to microplastics and organisms - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8016121/
13. 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/
14. Microplastics | Definition, Properties, & Plastic Pollution - Britannica, accessed on October 23, 2025, https://www.britannica.com/technology/microplastic
15. Biodegradation of Polyethylene Microplastic: A Review - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/365805733_Biodegradation_of_Polyethylene_Microplastic_A_Review
16. Environmental risk, toxicity, and biodegradation of polyethylene: a review - PubMed, accessed on October 23, 2025, https://pubmed.ncbi.nlm.nih.gov/36205861/
17. Plastic degradation in aquatic environments: a review of challenges and the need for standardized experimental approaches - Frontiers, accessed on October 23, 2025,

https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1677793/full
18. Plastic - Wikipedia, accessed on October 23, 2025, https://en.wikipedia.org/wiki/Plastic
19. 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
20. The biochemical mechanisms of plastic biodegradation - Oxford Academic, accessed on October 23, 2025, https://academic.oup.com/femsre/article/48/6/fuae027/7876491
21. Polyolefins and Polystyrene as Chemical Resources for a ..., accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acsmaterialslett.1c00490
22. Computational Study of Bond Dissociation Enthalpies for a Large Range of Native and Modified Lignins | Request PDF - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/230766950_Computational_Study_of_Bond_Dissociation_Enthalpies_for_a_Large_Range_of_Native_and_Modified_Lignins
23. Comparative biodegradation analysis of three compostable polyesters by a marine microbial community | Applied and Environmental Microbiology - ASM Journals, accessed on October 23, 2025, https://journals.asm.org/doi/10.1128/aem.01060-23
24. Polyethylene (PE) - What It Is, Properties, Types and Uses - Ruitai Mould, accessed on October 23, 2025, https://www.rtprototype.com/what-is-polyethylene/
25. Challenges with Verifying Microbial Degradation of Polyethylene - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7022683/
26. (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
27. pmc.ncbi.nlm.nih.gov, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10598529/#:~:text=Biodegradation%20processes%20decrease%20in%20the,and%20high%20branching%20promote%20biodegradation.
28. Effects of Crystallinity and Branched Chain on Thermal Degradation ..., accessed on October 23, 2025, https://www.mdpi.com/2073-4360/16/21/3038
29. A Review of Degradation and Life Prediction of Polyethylene - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-3417/13/5/3045
30. Full article: Enhancing plastic biodegradation process: strategies ..., accessed on October 23, 2025, https://www.tandfonline.com/doi/full/10.1080/07388551.2023.2170861
31. 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/
32. Polyethylene structure. (a) General chemical structure; (b) Schematic... | Download Scientific Diagram - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/figure/Polyethylene-structure-a-General-chemical-structure-b-Schematic-differences-between_fig3_338406283
33. Use and misuse of FTIR spectroscopy for studying the bio-oxidation of plastics - Advanced Light Source, accessed on October 23, 2025, https://als.lbl.gov/infrared-site/wp-content/uploads/sites/17/2024/03/Use-and-misuse-of-FTIR-spectroscopy-for-studying-the-bio-oxidation-of-plastics.pdf
34. Biodegradation of thermally-oxidized, fragmented low-density polyethylenes | EPI Global, accessed on October 23, 2025, https://epi-global.org/wp-content/uploads/2023/04/Biodegradation-of-thermally-oxidized-fragmented-low-density-polyethylenes.pdf
35. Biodegradation of Polymers: Stages, Measurement, Standards and Prospects - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2673-6209/3/2/23
36. Synergistic biodegradation of polyethylene by experimentally evolved bacterial biofilms | The ISME Journal | Oxford Academic, accessed on October 23, 2025, https://academic.oup.com/ismej/advance-article/doi/10.1093/ismejo/wraf223/8277623?searchresult=1
37. 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
38. Microbial colonization patterns and biodegradation of petrochemical and biodegradable plastics in lake waters: insights from a field experiment - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1290441/full
39. 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
40. Biodegradation of Low-Density Polyethylene Plastic Using Marine Bacterial Consortium - Egyptian Journal of Aquatic Biology and Fisheries, accessed on October 23, 2025, https://ejabf.journals.ekb.eg/article_365569_c7ff969db8f79d226e63ffc74932e3d5.pdf
41. (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
42. Biofilm development of the polyethylene-degrading bacterium Rhodococcus ruber - PubMed, accessed on October 23, 2025, https://pubmed.ncbi.nlm.nih.gov/16534612/
43. Transcriptomics and Lipidomics of the Environmental Strain Rhodococcus ruber Point out Consumption Pathways and Potential Metabolic Bottlenecks for Polyethylene Degradation - ACS Publications, accessed on October 23, 2025,

https://pubs.acs.org/doi/10.1021/acs.est.7b00846
44. Polyethylene Degradation by a Rhodococcous Strain Isolated from Naturally Weathered Plastic Waste Enrichment - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10515485/
45. (PDF) Biodegradation of Low Density Polyethylene by Selected ..., accessed on October 23, 2025, https://www.researchgate.net/publication/335537760_Biodegradation_of_Low_Density_Polyethylene_by_Selected_Bacillus_sp
46. Biodegradation of Polyethylene Using Bacillus tropicus Isolated from Sewage Wastewater Treatment Plant - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2227-9717/12/11/2516
47. The biodegradation of low-density polyethylene by Bacillus species | EQA, accessed on October 23, 2025, https://eqa.unibo.it/article/view/20474
48. Biodegradation of plastic by Pseudomonas aeruginosa, accessed on October 23, 2025, https://ijsra.net/sites/default/files/IJSRA-2024-0507.pdf
49. 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
50. Biodegradation of plastic polymers by fungi: a brief review, accessed on October 23, 2025, https://d-nb.info/1260915557/34
51. Biodegradation of Low Density Polyethylene by the Fungus Cladosporium sp. Recovered from a Landfill Site - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10301175/
52. Biodegradation Efficacy of Aspergillus niger and Trichoderma harzianum on Low-Density Polyethylene - PMC - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC12114978/
53. BIODEGRADATION OF PLASTICS BY FUNGI - Medvix Publications, accessed on October 23, 2025, https://medvixpublications.org/get/1-JMCCR2024091557FF%20Galley%20Proof-1724824598.pdf
54. Low-Density Polyethylene Film Biodegradation Potential by Fungal Species from Thailand, accessed on October 23, 2025, https://www.mdpi.com/2309-608X/7/8/594
55. Microbial Consortia-Mediated Degradation of Recalcitrant Plastics, accessed on October 23, 2025, https://ojs.stanford.edu/ojs/index.php/intersect/article/download/3458/1712/11239
56. (PDF) Microbial Consortia: Synergistic Effects on Plastic ..., accessed on October 23, 2025, https://www.researchgate.net/publication/392897680_Microbial_Consortia_Synergistic_Effects_on_Plastic_Degradation_and_Enzyme_Production
57. 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/_html/-char/en
58. Polyethylene Degradation by Plastivores Greater Wax Worms Larvae (Galleria

mellonella), accessed on October 23, 2025, https://www.researchgate.net/publication/372103961_Polyethylene_Degradation_by_Plastivores_Greater_Wax_Worms_Larvae_Galleria_mellonella
59. Degradation of agricultural polyethylene film by greater wax moth (Galleria mellonella) larvae and screening of involved gut bacteria - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/394757181_Degradation_of_agricultural_polyethylene_film_by_greater_wax_moth_Galleria_mellonella_larvae_and_screening_of_involved_gut_bacteria
60. Using Insect Larvae and Their Microbiota for Plastic Degradation, accessed on October 23, 2025, https://www.mdpi.com/2075-4450/16/2/165
61. Plastic biodegradation by in vitro environmental microorganisms and in vivo gut microorganisms of insects - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2022.1001750/full
62. Latest Trends on Insect Larvae, Their Enzymes and Their Gut Microbiota to Degrade PlasticLatest Trends on Insect Larvae, Their Enzymes and Their Gut Microbiota to Degrade Plastic - Preprints.org, accessed on October 23, 2025, https://www.preprints.org/manuscript/202411.1632/v1
63. Harnessing and Degradation Mechanism of Persistent Polyethylene Waste by Newly Isolated Bacteria from Waxworm and Termite Gut Symbionts - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC12388499/
64. Role of the intestinal microbiome in low-density polyethylene degradation by caterpillar larvae of the greater wax moth, Galleria mellonella - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7126078/
65. Role of the intestinal microbiome in low-density polyethylene degradation by caterpillar larvae of the greater wax moth, Galleria mellonella | Proceedings of the Royal Society B - Journals, accessed on October 23, 2025, https://royalsocietypublishing.org/doi/10.1098/rspb.2020.0112
66. Current Advances in Biodegradation of Polyolefins - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2076-2607/10/8/1537
67. 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
68. 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
69. (PDF) Degradation of Polyethylene and Nylon-66 by the Laccase ..., accessed on October 23, 2025, https://www.researchgate.net/publication/39970690_Degradation_of_Polyethylene_and_Nylon-66_by_the_Laccase-Mediator_System
70. Biotechnological Applications of Manganese Peroxidases for Sustainable Management, accessed on October 23, 2025,

https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2022.875157/full
71. (PDF) Review: Lignin conversion by manganese peroxidase (MnP), accessed on October 23, 2025, https://www.researchgate.net/publication/222915661_Review_Lignin_conversion_by_manganese_peroxidase_MnP
72. Polyethylene degradation by lignin-degrading fungi and manganese peroxidase, accessed on October 23, 2025, https://kyushu-u.elsevierpure.com/en/publications/polyethylene-degradation-by-lignin-degrading-fungi-and-manganese-
73. Functional analysis of alkane hydroxylase system derived from Pseudomonas aeruginosa E7 for low molecular weight polyethylene biodegradation - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/277338902_Functional_analysis_of_alkane_hydroxylase_system_derived_from_Pseudomonas_aeruginosa_E7_for_low_molecular_weight_polyethylene_biodegradation
74. Structural insights into diversity and n-alkane ... - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2013.00058/full
75. Microbial Consortiums of Putative Degraders of Low-Density ... - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8941889/
76. Regulation mechanism of the long-chain n-alkane monooxygenase gene almA in Acinetobacter venetianus RAG-1 - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11784139/
77. Enzymes and genes involved in aerobic alkane degradation - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2013.00116/full
78. (PDF) Bacterial metabolism of long-chain - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/6165374_Bacterial_metabolism_of_long-chain
79. A diagram of the microbial degradation processes of polyethylene (PE). - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/figure/A-diagram-of-the-microbial-degradation-processes-of-polyethylene-PE_fig2_370519387
80. The metabolic pathways of polythene (PE) plastics. a, b, x, y ..., accessed on October 23, 2025, https://www.researchgate.net/figure/The-metabolic-pathways-of-polythene-PE-plastics-a-b-x-y-represent-different-number_fig5_377104870
81. 1- Applied Biotechnology Reports Biodegradation of Low-density ..., accessed on October 23, 2025, https://www.biotechrep.ir/article_219031_6d286171b4821cb4ead7945c34ab0dd8.pdf

82. Biodegradation of thermally treated high-density polyethylene ..., accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5603451/
83. A Morphological Insight into Degradation of Polyethylene-Based Plastic Waste via SEM and AFM - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/392884289_A_Morphological_Insight_into_Degradation_of_Polyethylene-Based_Plastic_Waste_via_SEM_and_AFM
84. CN103980535A - Method of degrading polyethylene by extracellular laccase of bacillus - Google Patents, accessed on October 23, 2025, https://patents.google.com/patent/CN103980535A/en
85. The FTIR spectra of the degraded polyethylene (LDPE strips and pellets)... - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/figure/The-FTIR-spectra-of-the-degraded-polyethylene-LDPE-strips-and-pellets-by-bacterial_fig3_303872553
86. Identifying Failures and Ensuring Quality of Plastics Using FTIR - The Madison Group, accessed on October 23, 2025, https://madisongroup.com/identifying-failures-and-ensuring-quality-of-plastic-materials/
87. Fourier Transform Infrared Spectroscopy to Assess the Degree of ..., accessed on October 23, 2025, https://www.mdpi.com/2073-4360/15/4/911
88. Assessing the Biodegradation of Low-Density Polyethylene Films by Candida tropicalis SLNEA04 and Rhodotorula mucilaginosa SLNEA05 - MDPI, accessed on October 23, 2025, https://www.mdpi.com/1424-2818/16/12/759
89. Gel permeation chromatography for polymer molecular weight determination, accessed on October 23, 2025, https://eureka.patsnap.com/report-gel-permeation-chromatography-for-polymer-molecular-weight-determination
90. An Introduction to Gel Permeation Chromatography and Size Exclusion Chromatography - Agilent, accessed on October 23, 2025, https://www.agilent.com/cs/library/primers/public/5990-6969EN%20GPC%20SEC%20Chrom%20Guide.pdf
91. Degradation of Polyethylene by FTIR and High Temperature GPC CASE STUDY Degradation of Polyethylene by FTIR and High Temperatur - Jordi Labs, accessed on October 23, 2025, https://jordilabs.com/wp-content/uploads/filebase/Case_Study_Degradation_of_PE_FTIR_HTGPC.pdf
92. Molecular weight determination of a newly synthesized guanidinylated disulfide-containing poly(amido amine) by gel permeation chromatography - PMC - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7032192/
93. (PDF) Development and Evaluation of an Online CO2 Evolution Test and a Multicomponent Biodegradation Test System - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/8415527_Development_and_Evaluation_of_an_Online_CO2_Evolution_Test_and_a_Multicomponent_Biodegradation_Test_System

94. (PDF) Comparing respirometric systems for standardized biodegradation testing: a case study with polyethylene glycol and activated sludge microbiomes - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/394274724_Comparing_respirometric_systems_for_standardized_biodegradation_testing_a_case_study_with_polyethylene_glycol_and_activated_sludge_microbiomes
95. Development and Evaluation of an Online CO2 Evolution Test and a Multicomponent Biodegradation Test System - PMC, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC492337/
96. Biodegradability & Compostability - BPC Instruments, accessed on October 23, 2025, https://bpcinstruments.com/biodegradability-compostability/
97. Biodegradation and Mineralization of Polystyrene by Plastic-Eating ..., accessed on October 23, 2025, https://pubmed.ncbi.nlm.nih.gov/26390034/
98. Current Approaches to Microplastics Detection and Plastic Biodegradation - MDPI, accessed on October 23, 2025, https://www.mdpi.com/1420-3049/30/11/2462
99. Global perspectives on the biodegradation of LDPE in agricultural systems - Frontiers, accessed on October 23, 2025, https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2024.1510817/full
100. Status and Enhancement Techniques of Plastic Waste Degradation in the Environment: A Review - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2071-1050/16/21/9395
101. 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
102. Assembly strategies for polyethylene-degrading microbial consortia based on the combination of omics tools and the “Plastisphere” - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10150012/
103. Biological Degradation of Plastics and Microplastics: A Recent Perspective on Associated Mechanisms and Influencing Factors - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10386651/
104. Sustainable Bioremediation of Plastic Waste: How the Flame Retardant TCPP Affects Polyurethane Foam Biodegradation by Galleria mellonella Larvae - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2071-1050/17/20/9203
105. Biodegradable Flame Retardants for Biodegradable Polymer - PMC - NIH, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7407105/
106. Investigating the effect of flame-retardants on the thermal ageing of a high-density polyethylene | Request PDF - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/392905015_INVESTIGATING_THE_EFFECT_OF_FLAME-RETARDANTS_ON_THE_THERMAL_AGEING_OF_A_HIGH-DENSITY

_POLYETHYLENE
107. (PDF) Study of the effect of additives on biodegradation of PVC materials - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/340881610_Study_of_the_effect_of_additives_on_biodegradation_of_PVC_materials
108. 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
109. Evaluation of Biodegradation-Promoting Additives for Plastics ..., accessed on October 23, 2025, https://pubs.acs.org/doi/abs/10.1021/es504258u
110. Detection and degradation of microplastics in the environment: a review - RSC Publishing, accessed on October 23, 2025, https://pubs.rsc.org/en/content/articlehtml/2025/va/d5va00064e
111. Microbial and Enzymatic Degradation of Synthetic Plastics - PMC - PubMed Central, accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7726165/
112. Environmental Degradation of Microplastics: How to Measure Fragmentation Rates to Secondary Micro- and Nanoplastic Fragments and Dissociation into Dissolved Organics - ACS Publications, accessed on October 23, 2025, https://pubs.acs.org/doi/10.1021/acs.est.2c01228
113. Computational Exploration of Bio-Degradation Patterns of Various Plastic Types - MDPI, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/15/6/1540
114. Challenges with Verifying Microbial Degradation of Polyethylene, accessed on October 23, 2025, https://www.mdpi.com/2073-4360/12/1/123
115. Knowledge Gaps in Polymer Biodegradation Research | Request PDF - ResearchGate, accessed on October 23, 2025, https://www.researchgate.net/publication/353814455_Knowledge_Gaps_in_Polymer_Biodegradation_Research
116. Biodegradability of polyethylene: Challenges and future ..., accessed on October 23, 2025, https://www.researchgate.net/publication/385077019_Biodegradability_of_polyethylene_Challenges_and_future_perspectives
117. 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/
118. Cutting-edge developments in plastic biodegradation and upcycling ..., accessed on October 23, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11647663/
119. Polyethylene-biodegrading Microbes and Their Future Directions ..., accessed on October 23, 2025, https://www.researchgate.net/publication/368256401_Polyethylene-biodegrading_Microbes_and_Their_Future_Directions
120. Characterization and engineering of plastic-degrading ... - Frontiers, accessed on October 23, 2025,

https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2024.1349010/full
121. Innovative biotechnological approaches for plastic degradation: A ..., accessed on October 23, 2025, https://ijsra.net/content/innovative-biotechnological-approaches-plastic-degradation-pathway-sustainable-waste
122. Synthetic Biology Boosts the Biological Depolymerization and ..., accessed on October 23, 2025, https://www.sciepublish.com/article/pii/440
123. Polyethylene biodegradation: A multifaceted approach, accessed on October 23, 2025, https://ltu.diva-portal.org/smash/get/diva2:1955313/FULLTEXT01.pdf