

Microbial Consortia for Accelerated Degradation of Recalcitrant Plastics: A Review

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Abstract.

The increasing accumulation of man-made plastic in the environment constitutes one of the most urgent types of ecological problems of the 21st century. Now that more than 400 million tons of plastic are produced every year and only around 9% of the total plastic ever created has been recycled, it is necessary to adopt new biodegradation methods. Microbial consortia—cooperative communities of bacteria, fungi, and other microorganisms—have emerged as a promising biotechnological approach for the accelerated degradation of recalcitrant plastics, including polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Unlike single-organism approaches, consortia leverage metabolic division of labor, synergistic enzymatic cascades, and cross-feeding interactions to overcome the biochemical recalcitrance of synthetic polymers. This review synthesizes recent advances in the identification, design, and engineering of plastic-degrading microbial consortia. Key enzymatic mechanisms are discussed, including the roles of PETase, MHETase, laccases, manganese peroxidases, alkane hydroxylases, and cutinases. The review further examines natural consortia isolated from plastic-contaminated environments, insect gut microbiomes, and engineered synthetic microbial communities designed through rational metabolic engineering and synthetic biology tools. Challenges related to scalability, environmental safety, regulatory considerations, and the gap between laboratory performance and real-world applicability are critically evaluated. Future directions, including the integration of computational modeling, machine learning-guided enzyme engineering, and hybrid chemo-biological upcycling strategies, are outlined. This review underscores the transformative potential of microbial consortia as an eco-friendly, sustainable solution for mitigating global plastic pollution.

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1. Introduction

Man-made or synthetic plastics have become indispensable materials in modern society, as a result of their important applications in packaging, construction, transportation, healthcare, and consumer goods. Since the invention of Bakelite in 1907 and the subsequent industrialization of polymer chemistry, global plastic production has grown exponentially, increasing from approximately 2 million metric tons in 1950 to over 460 million metric tons by 2019, and surpassing 400 million metric tons annually by 2024 (Geyer *et al.*, 2017; OECD, 2022). The six most widely produced commodity plastics—polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS), and polyurethane (PUR)—collectively account for the vast majority of plastic waste entering terrestrial and aquatic ecosystems (Mohanani *et al.*, 2020).

Global plastic production with projections, 1950 to 2060



Annual production of polymer resin and fibers. Projections are based on the "business-as-usual" scenario which assumes that current policies remain unchanged in the foreseeable future.

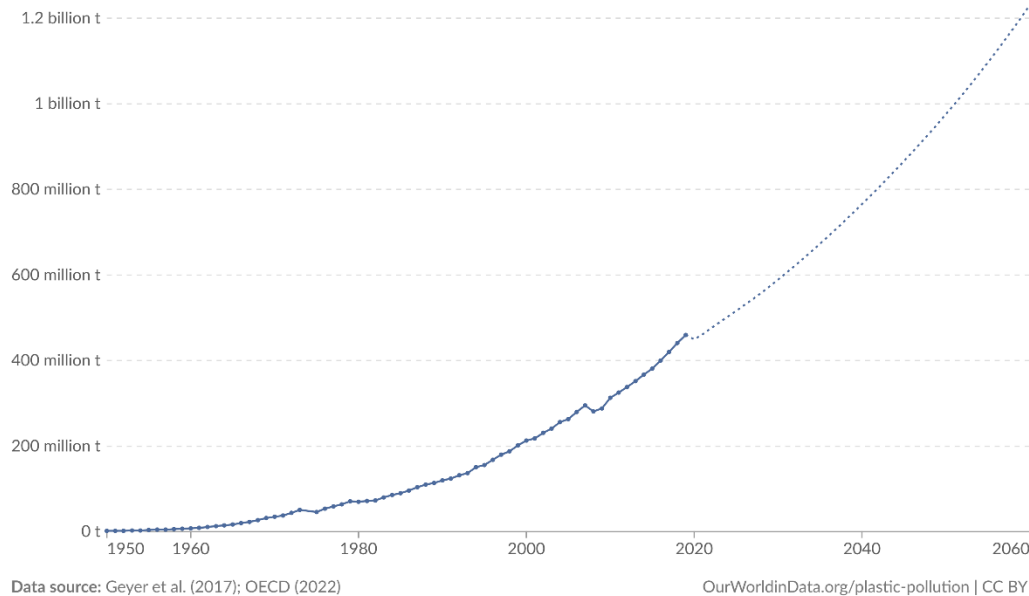


Figure 1: Annual production and projection of polymer resin (Source: Our World in Data, 2026)

Despite their utility, the environmental persistence of these polymers poses a profound ecological crisis. Conventional plastics are engineered for durability, with molecular architectures characterized by high molecular weight, strong carbon–carbon or ester bonds, crystallinity, and hydrophobicity, rendering them inherently resistant to natural degradation processes (Wei & Zimmermann, 2017). It is estimated that approximately 20 million metric tons of plastic waste leaked into the environment in 2020, with projections indicating that this figure could increase by 50% to nearly 30 million metric tons by 2040 under business-as-usual scenarios (OECD, 2022). The fragmentation of macroplastics into microplastics (particles smaller than 5 mm) and nanoplastics further exacerbates the problem, as these particles have been detected in virtually every environmental compartment, from deep-sea sediments to Arctic ice, and increasingly in human blood, lung tissue, and placental samples (Jenner et al., 2022; Yang et al., 2023).

Traditional plastic waste management strategies—including landfilling, incineration, and mechanical recycling—have proven insufficient. The OECD (2022) reports that only 9% of all plastic waste has ever been recycled, while 19% was incinerated and nearly 50% was directed to sanitary landfills, with the remainder mismanaged or leaked into the environment. Against this backdrop, biological degradation of plastics using microorganisms and their enzymes has emerged as a promising, environmentally sustainable alternative (Danso et al., 2019; Ru et al., 2020). In particular, microbial consortia—defined as communities of two or more microbial species functioning cooperatively—have attracted considerable research attention due to their capacity to achieve degradation outcomes that exceed those of individual isolates through metabolic synergy, enzymatic complementarity, and cross-feeding interactions (Satta et al., 2024; Zhou & ZeeshanUIHaq, 2025).

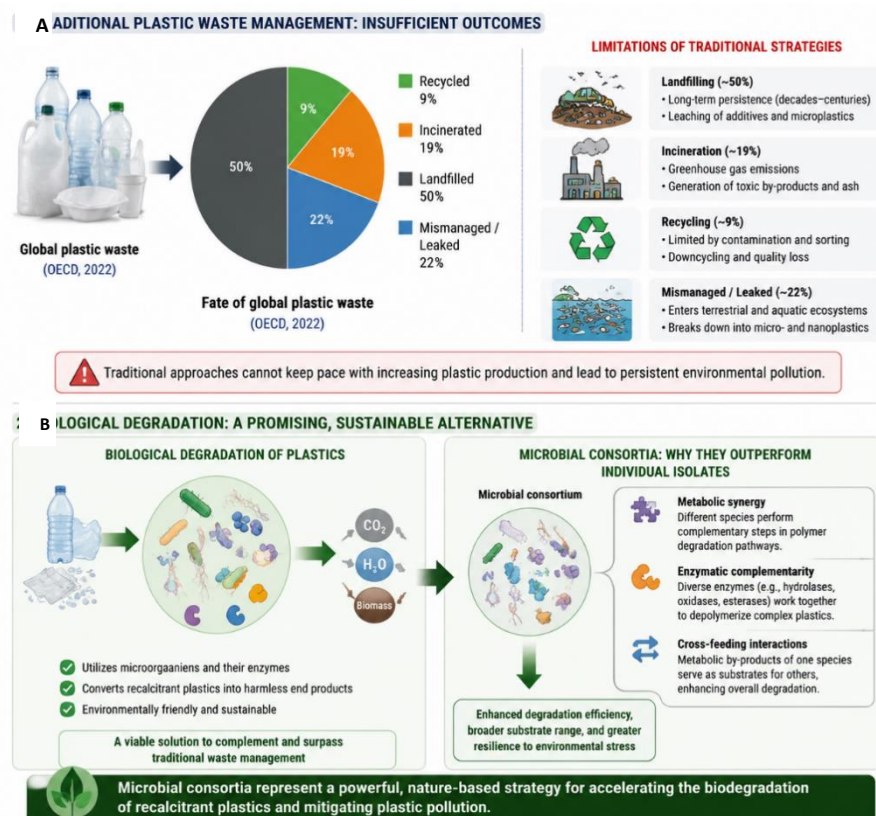


Figure 2. (a) Traditional plastic waste management (b) Biological degradation

This review looks into the recent progress made in the field of microbial consortia research related to the rapid biodegradation of resistant polymers. Furthermore, this review analyzes the biochemical and enzymatic processes behind polymer degradation, compares both natural and artificially created microbial consortia, introduces the novel approaches provided by synthetic biology and metabolic engineering, and determines the obstacles and future prospects in achieving real-world bioremediation methods from research outcomes.

2. Biochemical Recalcitrance of Synthetic Plastics

The resistance of synthetic plastics to biodegradation arises from their molecular characteristics, which differ fundamentally from natural biopolymers. Polyethylene, the most abundantly produced plastic, features a long-chain hydrocarbon backbone consisting entirely of carbon-carbon single bonds, imparting exceptional chemical stability and hydrophobicity (Zhang et al., 2022). High-density polyethylene (HDPE) presents additional challenges due to its linear chain packing and high crystallinity, which limits enzymatic access to the polymer surface (Putcha & Kitagawa, 2024). Polypropylene similarly resists microbial attack due to its methyl-branched structure, while polystyrene's aromatic ring substituents create steric barriers to enzymatic cleavage (Hossain et al., 2024).

Polyethylene terephthalate, though classified as a polyester and therefore theoretically susceptible to hydrolytic enzymes, presents its own challenges. The semi-aromatic structure of PET, combined with its high glass transition temperature (approximately 75–80°C) and varying degrees of crystallinity, means that efficient enzymatic hydrolysis typically requires elevated temperatures or engineered enzyme variants (Liu et al., 2023; Benyathiar et al., 2022). Polyurethanes consist of both ester and urethane (carbamate) links. Although it is possible to hydrolyze ester bonds, urethane bonds are hard to break (Wei and Zimmermann, 2017). Meanwhile, the presence of chlorine atoms, stabilizers, and plasticizers adds to the complexity of the polyvinyl chloride structure, making this polymer difficult for degraders (Mohan et al., 2020). All these characteristics demonstrate that due to their properties, the plastic polymers can remain in the environment for centuries or even millennia. The durability of this material requires the search for and engineering of microbial systems capable of degradation—an area where microbial consortia are far more advanced compared to monoculture systems.

3. Enzymatic Mechanisms of Plastic Biodegradation

3.1. Hydrolytic Enzymes for Polyester Degradation

The discovery of *Ideonella sakaiensis* 201-F6 in 2016 by Yoshida et al. marked a watershed moment in plastic biodegradation research. This bacterium, isolated from PET-contaminated sediment at a recycling facility in Sakai, Japan, was the first organism demonstrated to utilize PET as a primary carbon and energy source (Yoshida et al., 2016). The organism produces two key hydrolytic enzymes: PETase (PET hydrolase), which cleaves PET polymer chains into mono(2-hydroxyethyl) terephthalic acid (MHET), bis(2-hydroxyethyl) terephthalate (BHET), and terephthalic acid (TPA); and MHETase, which further hydrolyzes MHET into TPA and ethylene glycol (EG)—the basic monomeric building blocks of PET (Yoshida et al., 2016; Austin et al., 2018).

Subsequent protein engineering efforts have yielded enhanced PETase variants with improved thermostability and catalytic efficiency. Notable advances include the development of DuraPETase and FAST-PETase, which exhibit markedly higher depolymerization rates at elevated temperatures compared to the wild-type enzyme (Cui et al., 2021; Lu et al., 2022). Surface co-display strategies, whereby engineered PETase and MHETase variants are expressed simultaneously on bacterial cell surfaces, have further enhanced whole-cell biocatalytic performance against PET substrates (Xue et al., 2024; Liu et al., 2025). Additionally, cutinases from *Thermobifida fusca* and related thermophilic organisms have demonstrated significant PET-hydrolyzing activity and represent another important class of polyester-degrading enzymes (Müller et al., 2005; Then et al., 2016).

3.2. Oxidative Enzymes for Polyolefin Degradation

The polyolefin degradation process for polymers such as PE and PP is mainly achieved through oxidative enzymatic reactions rather than through ester hydrolysis because of the absence of hydrolyzable bonds in polyolefins. Laccases (EC 1.10.3.2) are multicopper oxidases that have the capacity to oxidize PE surfaces. This includes creating functional groups in PE molecules that allow for easier degradation of the substance on both biotic and abiotic levels (Santo et al., 2013; Zampolli et al., 2023). The use of laccase-mediator systems, where small aromatic compounds act as diffusible oxidizers, increase the extent of the substrates that can be utilized in reactions with laccases (Hilgers et al., 2018).

Manganese peroxidases (MnP; EC 1.11.1.13), produced by white-rot basidiomycetes such as *Phanerochaete chrysosporium* and *Trametes versicolor*, are responsible for the production of reactive manganese species which catalyze the oxidative breakdown of polyethylene (PE) polymer chains from a high molecular mass to low molecular mass fragments (Iiyoshi et al., 1998; Sowmya et al., 2015). Lignin peroxidases (LiP; EC 1.11.1.14) also facilitate the oxidation of polymers via the creation of reactive oxygen species that can break carbon-carbon bonds (Yao et al., 2022). Hydroxylases from *Pseudomonas* species carry out the terminal oxidation of PE-derived alkanes, thus initiating the process of β -oxidation for energy generation and biomass production (Jeon and Kim, 2015; Kumar Sen and Raut, 2015).

A recent comprehensive review by Gates and Crook (2024) provided a detailed biochemical framework for understanding PE degradation, describing how non-specific oxidation by ligninolytic enzymes releases a diverse array of alkanes, alcohols, aldehydes, ketones, and fatty acids that are subsequently assimilated through cellular metabolism via alkane hydroxylase and β -oxidation pathways. These oxidative products can be further metabolized by consortia members with complementary catabolic capacities, highlighting the inherent advantage of multi-species systems.

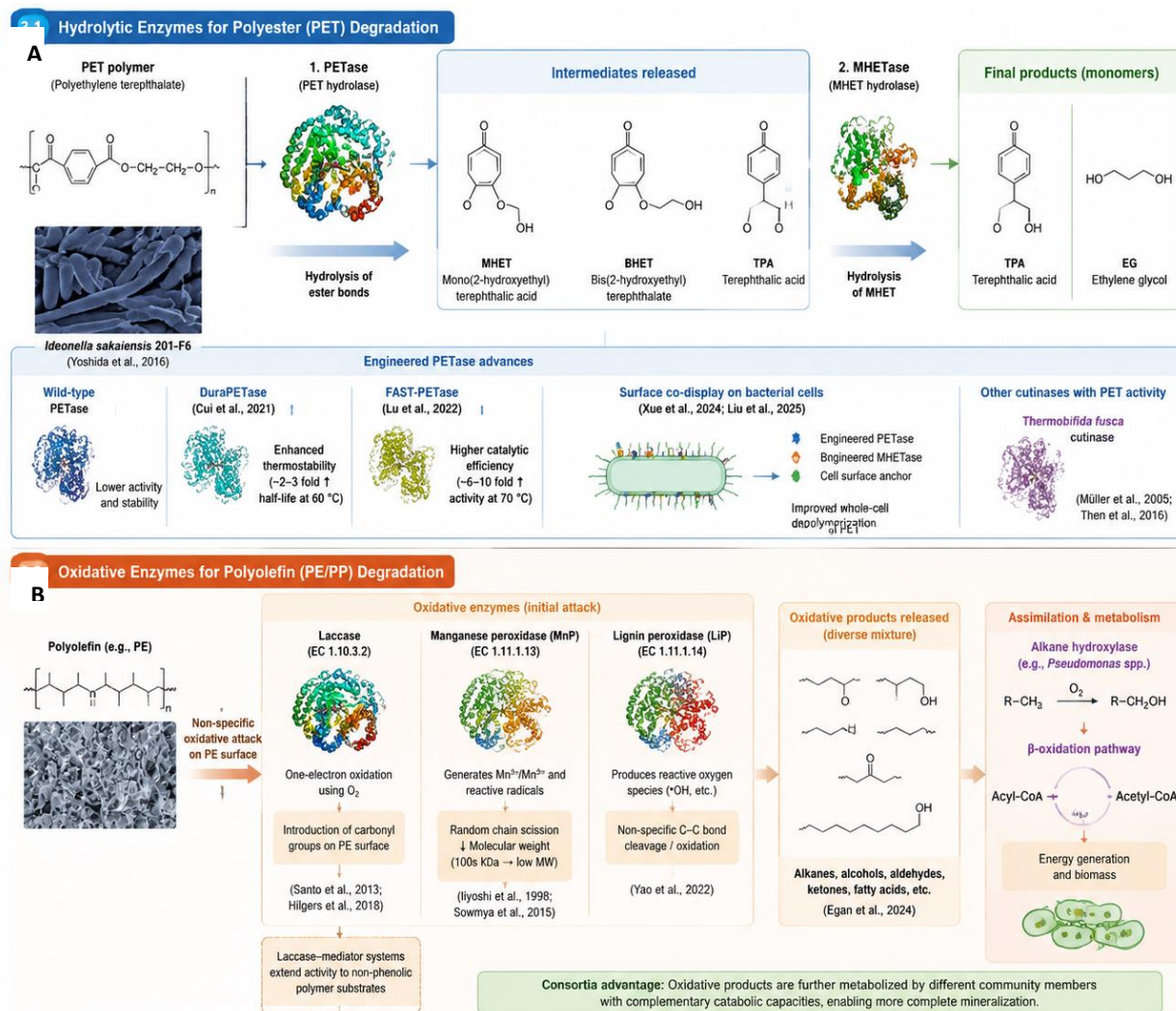


Figure 3: Schematic overview of enzymatic mechanisms for plastic biodegradation. **(A)** Hydrolytic degradation of polyethylene terephthalate (PET) by *Ideonella sakaiensis* 201-F6, showing PETase- and MHETase-mediated cleavage into monomers (TPA and EG) and engineered PETase variants with enhanced depolymerization efficiency. **(B)** Oxidative degradation of polyolefins (PE/PP) by laccases, manganese peroxidases, lignin peroxidases, and alkane hydroxylases, illustrating polymer oxidation, chain scission, formation of low-molecular-weight intermediates, and subsequent assimilation via β -oxidation pathways. The diagram highlights the advantage of microbial consortia in complete polymer mineralization.

4. Microbial Consortia: Rationale and Mechanisms of Synergy

4.1. Advantages of Consortia Over Monocultures

The process of biodegradation of recalcitrant plastics is itself a multi-step process that requires surface colonization and biofilm formation, oxidation or hydrolysis of polymers, incorporation of oligomers and monomers, and metabolism of degradation products in cells. No single microbial species has been shown to possess all the enzymatic capabilities and metabolic versatility required to efficiently execute this entire cascade (Satta et al., 2024). Microbial consortia address this limitation through metabolic division of labor, whereby different species specialize in distinct degradation steps, and through syntrophic interactions, in which the metabolic byproducts of one organism serve as substrates for another (Ibrahim et al., 2024). A lot of research works provide evidence of the advantages of the use of consortia instead of monocultures. For instance, Maheswaran *et al.* (2023) found that the consortium composed of *Sarcina aurantiaca*, *Bacillus subtilis*, *Aspergillus flavus*, and *Aspergillus niger* caused about 28.78% of weight loss of PET film within 60 days, which is much better than the result achieved by separate isolates. In the same way, Han *et al.* (2020) indicated that the consortium of *Arthrobacter* sp. and *Streptomyces* sp. obtained from agricultural soil formed bigger biofilms and

achieved increased biodegradation of PE film compared to individual strains. Dhaka *et al.* (2023) reported that rhizospheric isolates including *Priestia aryabhattai*, *Bacillus pseudomycolides*, and *Bacillus pumilus* exhibited up to 69% degradation of PET powder within 18 days when used individually, with even greater potential observed when combined as a consortium.

4.2. Mechanisms of Cooperative Degradation

Several key mechanisms underlie the enhanced degradation performance of microbial consortia. Biofilm formation on plastic surfaces is typically a community-level process, in which pioneer colonizers produce extracellular polymeric substances (EPS) that facilitate attachment and create microenvironments conducive to enzymatic activity (Cassone *et al.*, 2020; Vincent *et al.*, 2022). Within these biofilms, bacteria and fungi interact through quorum sensing signaling, metabolite exchange, and spatial organization that optimizes substrate accessibility.

Cross-feeding represents another critical mechanism. In PET-degrading consortia, for example, one organism may secrete PETase to depolymerize the polymer surface, releasing MHET and TPA that are subsequently metabolized by partner species with appropriate uptake and catabolic systems (Zhou & ZeeshanUIHaq, 2025). For polyolefin degradation, fungi may initiate oxidative attack through laccase and peroxidase secretion, generating low-molecular-weight oxidation products that are then assimilated by bacterial partners possessing alkane hydroxylase and β -oxidation pathways (Ibrahim *et al.*, 2024; Gates and Crook 2024). This metabolic complementarity prevents the accumulation of potentially inhibitory intermediate products and drives the degradation process toward mineralization. Fungi merit particular attention within consortia frameworks. Saprotrophic molds such as *Aspergillus*, *Penicillium*, and *Fusarium*, as well as white-rot basidiomycetes, contribute to plastic degradation through mycelial penetration of polymer matrices and secretion of powerful extracellular oxidative enzymes (Sangale *et al.*, 2019; Ibrahim *et al.*, 2024). The physical penetration of fungal hyphae into plastic surfaces increases the accessible surface area for enzymatic attack, complementing the surface-level colonization patterns of bacterial consortium members.

5. Natural Microbial Consortia from Plastic-Contaminated Environments

5.1. Soil and Landfill Consortia

Plastic-contaminated soils represent rich reservoirs of adapted microbial communities with plastic-degrading potential. Salinas *et al.* (2023) reported on a study in which soils polluted with linear low-density polyethylene (LLDPE) were analyzed to isolate stable microbial consortia via repeated culture transfers of the soil samples that are using LLDPE as the carbon source. The studies showed that these consortia were made up of microorganisms such as *Pseudomonas aeruginosa*, *Pseudomonas allopuntida*, *Castellaniella denitrificans*, and a yeast, *Debaryomyces hansenii*, within it. The authors showed a total reduction of 2.5–5.5% in weight of LLDPE that was made of microplastic when using the identified microbial consortium. The consortium cultivated with powdered LLDPE was better and achieved better results than the one that was cultivated with LLDPE in film form probably due to the high surface area-to-volume ratio of the powdered plastic (Salinas *et al.*, 2023). Roberts *et al.* (2020) reported on a microbial consortium obtained from petroleum-contaminated soils which has the ability to degrade PET and Gao and Sun (2021) described a naturally acquired marine consortium of bacteria that is able to degrade both PET and PE. The findings from geographically and ecologically diverse environments suggest that plastic-degrading microbial communities are more widespread than previously appreciated, and that long-term environmental exposure to plastic pollution may drive the adaptive evolution of degradation capabilities within natural microbial communities.

5.2. Insect Gut Microbiome Consortia

The gut microbiomes of plastic-feeding insects have emerged as a particularly promising source of plastic-degrading consortia. Larvae of the greater wax moth (*Galleria mellonella*) have attracted significant attention for their ability to ingest and metabolize polyethylene at rates unmatched by other known organisms (Cassone *et al.*, 2020; Young *et al.*, 2024). The studies have indicated that the larvae can eat as much as 69% of LDPE, 73% of HDPE, and 50% of expanded polystyrene in laboratories, where the microorganisms such as *Enterococcus*, *Pseudomonas*, and *Bacillus* were helpful (Kehkashan *et al.*, 2025). It has been found through scanning electron microscopy that the gut bacteria obtained from *Galleria mellonella* can form biofilm and degrade polyethylene directly. Fourier-

transform infrared spectroscopy analysis of larval frass showed the creation of the oxidized degradation intermediates that are signs of true polyethylene degradation (Kehkashan *et al.*, 2025; Dar *et al.*, 2024). These gut microbiomes do their work through synergistic interactions of the host enzymes and microbial metabolism pathways and thus can serve as a base for creating biomimic degradation systems. Other plastic-eating insects, like mealworms (*Tenebrio molitor*) and cockroaches (*Blaptica dubia*), also have gut microbiomes that have plastic biodegrading microbes, which can help in the biodegradation of polyethylene and polystyrene using mechanisms similar to those used by the gut of *Galleria mellonella* (Yang *et al.*, 2015; Li *et al.*, 2024).

5.3. Marine and Aquatic Consortia

Marine organisms, especially in locations suffering from continual plastic pollution, host microbes that can break plastics down. The “plastisphere,” which is the microbiome that arrives in contact with the plastic surface in water, has made it possible to understand how many bacterial populations have such features (Zettler *et al.*, 2013; Amaral-Zettler *et al.*, 2020). Saidu *et al.* (2025) worked on microbiological degradation of PET in mangrove soils with the usage of selected bacterial populations, managed to quantify the degradation process, and define metabolites that are typical of PET degradation. The outcomes of the research can prove that coastal areas can be considered as natural reactors for biodegradation.

6. Synthetic and Engineered Microbial Consortia

6.1. Rational Design of Synthetic Consortia

While natural consortia provide valuable proof-of-concept, their degradation rates and substrate ranges are often insufficient for practical waste management applications. Synthetic microbial consortia (SMC), rationally designed through the deliberate combination of microbial species with complementary metabolic capabilities, offer a more controllable and potentially more effective approach (Zhou & ZeeshanUlHaq, 2025). The design of SMC typically employs either bottom-up approaches, in which individual species are selected and combined based on their known enzymatic repertoires, or top-down approaches, in which enrichment cultures from natural environments are progressively refined through selective pressure (Ahmad *et al.*, 2025).

A notable example of rational consortium design was reported by Putcha and Kitagawa (2024), who constructed an artificial bacterial consortium for polyethylene biodegradation. Their study revealed that *Rhodococcus* species functioned as competitive plastisphere specialists, dominating biofilm formation on PE surfaces and initiating polymer oxidation, while partner bacteria contributed to the metabolism of oxidation products. Jia *et al.* (2024) designed a synthetic bacterial consortium comprising *Rhodococcus opacus*, *Pseudomonas putida*, and *Pseudomonas sp.* to reduce the chemical heterogeneity of plastic pyrolysis oil waste, demonstrating the potential for integrated chemo-biological approaches to plastic waste valorization. Qi *et al.* (2021) constructed a four-species artificial consortium consisting of two engineered *Bacillus subtilis* strains (expressing PETase and MHETase, respectively), *Rhodococcus jostii*, and *Pseudomonas putida* to achieve depolymerization and assimilation of PET degradation products, with the three-species variant achieving 31.2% weight loss of PET film within just 3 days. This division-of-labor strategy, in which dedicated strains handle polymer depolymerization while others metabolize the resulting monomers, exemplifies the power of synthetic consortia design.

6.2. Metabolic Engineering and Synthetic Biology Approaches

Advances in synthetic biology have enabled the rational engineering of individual consortium members to enhance their plastic-degrading capabilities. CRISPR-Cas9 genome editing has been employed to introduce or optimize PET-degrading enzyme expression in non-native hosts, while metabolic pathway engineering has been used to redirect carbon flux from plastic degradation intermediates toward valuable bioproducts (Dudeja *et al.*, 2025; Singh *et al.*, 2024). Dharmasiddhi *et al.* (2025) demonstrated that microbial consortia can be optimized for the consumption of mixed plastic substrates through adaptive laboratory evolution and directed selection.

A landmark study by Diao *et al.* (2025) engineered a stable microbial consortium comprising *Rhodococcus jostii* and *Acinetobacter baylyi* for mixed plastic upcycling, applying rational metabolic engineering to both specialists to enable the funneling of plastic-derived oxygenates into valuable

compounds such as lycopene and lipids. This work highlights the transformative potential of combining consortium design with metabolic engineering to convert plastic waste not merely into CO₂ and water, but into commercially valuable bioproducts—a paradigm shift from biodegradation to bioupcycling. Quorum sensing manipulation represents another emerging tool for SMC engineering. By engineering quorum sensing circuits, researchers can control the population dynamics within consortia, ensuring stable coexistence of component species and temporally coordinating enzyme expression to match the sequential requirements of plastic degradation (Zhou & ZeeshanUIHaq, 2025). Computational modeling, including flux balance analysis and agent-based modeling of microbial communities, is increasingly being used to predict optimal consortium compositions and culture conditions prior to experimental validation (Ahmad *et al.*, 2025).

6.3. Whole-Cell Biocatalyst Systems

Technology for surface display has been able to make whole-cell biocatalysts possible, linking the benefits of immobilizing enzymes with the regenerative properties of living cells. Several new studies have demonstrated that the enzymes PETase and MHETase could be displayed on the surface of yeast cells, which then made biocatalysts able to handle PET waste without the necessity of the purification of enzymes (ACS Synthetic Biology, 2025). In addition, dual enzyme immobilization systems packed on magnetic nanoparticles have successfully used FAST-PETase and MHETase immobilization to reduce polymer PET entirely (Zhai *et al.*, 2025; Aer *et al.*, 2025). This method joins efforts in consortia that are based on developing efficient biocatalytic modules that can be used later by the larger systems for degradation of other substances.

7. From Biodegradation to Bioupcycling: Valorization of Plastic Waste

In research involving microbial consortia, the idea of plastic upcycling is becoming more and more crucial. Upcycling refers to transforming waste plastic into materials that are more valuable than they were initially. The process is about converting plastics to carbon dioxide, but it can also be done by creating microorganisms capable of producing high-value chemicals like polyhydroxyalkanoates from plastic-derived carbon (Hu *et al.*, 2024). Gregory *et al.* (2023) present one interesting example of combining the use of microorganisms and catalysts. In this case, high density polyethylene was catalytically depolymerized into different alkanes that were later metabolized by microbial consortia into wax esters. Besides using a combination of biological and chemical techniques for waste processing of polyethylene, this methodology was also used for recycling of PET and PLA, with many studies indicating how this approach makes the production of bioplastics cheaper (Hu *et al.*, 2024). Using such approaches makes it more profitable to recycle waste plastics than rely on biodegradation only for environmental reasons.

8. Challenges and Limitations

Despite significant progress, several challenges impede the translation of microbial consortia-based plastic degradation from laboratory to industrial and environmental applications. First, degradation rates remain slow relative to the scale of global plastic pollution. Even the most effective consortia typically require weeks to months to achieve meaningful weight loss of plastic substrates under optimized laboratory conditions, and performance under real-world environmental conditions—where temperature, pH, nutrient availability, and competing microbial communities are variable—is largely untested (Salinas *et al.*, 2023; Wróbel *et al.*, 2024).

Second, there are still several concerns regarding stability and reproducibility of community composition. Natural communities are inherently dynamic, so the composition may be changed due to environmental factors and degradation activity may be lost over time. Artificial communities experience problems with competitive exclusion of populations present in community, metabolic burden of introduced pathways, and ensuring ratio of species (Zhou and ZeeshanUIHaq, 2025). Several strategies such as quorum sensing and spatial structuring can partly solve the issue, but construction of efficient frameworks is still in progress.

Third, biodegradation of plastic additives, including plasticizers, flame retardants, UV stabilizers, and dyes, adds complexity (Mohanani *et al.*, 2020). Fourth point here is the crystallinity of plastic materials – most studies on enzymatic degradation are carried out on amorphous or low-crystalline samples, while waste plastics from consumers are mostly highly crystalline, meaning that

they are much more resistant to enzymatic degradation (Liu *et al.*, 2023). Regulatory and biosafety considerations present additional hurdles for the environmental release of engineered consortia. The deployment of genetically modified microorganisms in open environments raises concerns about horizontal gene transfer, ecological disruption, and unintended consequences that must be addressed through rigorous risk assessment and containment strategies (Ahmad *et al.*, 2025). Standardized protocols for evaluating and comparing consortia performance, including agreed-upon metrics for degradation extent, rate, and environmental safety, are also lacking in the field.

9. Future Directions and Perspectives

There are many new research directions that would lead to new advances in microbiomes involved in the degradation of plastic. Using novel approaches based on machine learning and AI, researchers were able to improve the process of engineering enzymes by assisting the identification of beneficial mutations and generation of new enzyme variants with better stability, activity and substrate range (Cheng *et al.*, 2024). It is believed that the combination of high-throughput screening technologies, directed evolution techniques and computational protein design will help develop the PET degrading enzymes for industrial applications in the near future.

Using metagenomics and other multi-omic techniques, namely metatranscriptomics, metaproteomics and metabolomics allowed scientists to discover the full enzymatic and metabolic potential of the microbial communities responsible for the plastic degradation (e.g. Zampolli *et al.*, 2023). As a result, it becomes possible to identify the genes as well as particular pathways responsible for degradation, characterize the interactions between different species in these microbial communities and select the members of chosen community.

The emergence of consolidated bioprocessing technologies in which plastic depolymerization, monomer uptake and the production of valuable compounds is carried out by a single engineering mix in a single bioreactor is a very exciting challenge. These systems can achieve the direct transformation of mixed plastic waste streams into bioplastics, biofuels or platform chemicals without additional purification processes, thus greatly enhancing the efficiency of the process (Hu *et al.*, 2024; Diao *et al.*, 2025).

The practice of bioaugmentation that involves the introduction of plastic-degrading microbial consortia into contaminated sites (such as landfills, sewage treatment plants and polluted areas of the ocean) is another promising technique of environmental decontamination. An important factor for the success of the method will be the ability of the introduced consortia to create stable populations, compete for resources with native microorganisms and remain active under varying environmental conditions (Wróbel *et al.*, 2024; Qattan, 2025). Pre-treatment techniques such as UV irradiation, thermal oxidation or chemical treatment of plastic before microbial degradation can increase the availability of polymer chains for microbial enzymes and boost overall degradation efficiency (Giraldo – Narcizo *et al.*, 2023).

Summary Table: Challenges and Future Directions in Microbial Consortia-Based Plastic Degradation

Topic / Area	Key Details	References
Challenge: Slow degradation rates	Even most effective consortia require weeks to months under lab conditions; real-world performance untested	Salinas <i>et al.</i> , 2023; Wrobel <i>et al.</i> , 2024
Challenge: Stability & reproducibility of consortia	Community composition shifts over time; synthetic consortia face competitive exclusion and metabolic burden	Zhou and ZeeshanUlHaq, 2025
Challenge: Plastic additives	Additives can be toxic, inhibit enzyme activity, or generate hazardous byproducts	Mohanan <i>et al.</i> , 2020
Challenge: High crystallinity of plastics	Enzymatic degradation studies often use amorphous plastics; post-consumer plastics highly crystalline and resistant	Liu <i>et al.</i> , 2023
Challenge: Regulatory &	Concerns over environmental release of GMOs; need risk assessment and containment	Ahmad <i>et al.</i> , 2025

bio-safety		
Future Direction: Enzyme engineering using AI/ML	Rapid identification of beneficial mutations; design of novel enzymes with enhanced activity	Cheng <i>et al.</i> , 2024
Future Direction: Multi-omics & metagenomics	Identify unknown degradation genes and pathways; understand inter-species interactions in consortia	Zampolli <i>et al.</i> , 2023
Future Direction: Consolidated bioprocessing	Single engineered consortium converts plastic to bioproducts without intermediate steps	Hu <i>et al.</i> , 2024; Diao <i>et al.</i> , 2025
Future Direction: Bioaugmentation	Introduce specialized consortia into contaminated environments; success depends on stability and competition	Wrobel <i>et al.</i> , 2024; Qattan, 2025
Future Direction: Pre-treatment strategies	UV, thermal, or chemical treatment to improve polymer accessibility	Giraldo-Narcizo <i>et al.</i> , 2023

10. Conclusion

Microbial consortia are an innovative strategy for tackling the global issue of pollution due to plastics. Utilization of the capabilities offered by different microorganisms has made it possible to efficiently achieve plastic degradation, which goes beyond the efforts of single microorganisms. Thanks to the research that has been conducted over the past 10 years, we understand how plastic biodegradation occurs at the enzymatic level, how consortia work in practice, and how synthetic biology helps us enhance microbial capabilities.

Nonetheless, there are still obstacles to overcome in reconciling the gap between laboratory demonstrations and practical, scalable solutions. Specifically, degradation rates must be significantly improved, the stability of the consortia during real-world operations must be validated, and the environmental safety of engineered microbial systems has to be guaranteed. The coupling of enzyme engineering, metabolic engineering, computer modeling, and ecology will be critical for full realization of the potential of microbial consortia for plastic degradation. As the world struggles with increasing plastic pollution and problems of traditional waste management, microbial consortia offer secrets of success in moving from linear “take-make-waste” plastic economy towards circular bioeconomy.

References

- Aer, L., Jiang, Q., and Liu, X. (2025). High-efficiency PET degradation with a duo-enzyme system immobilized on magnetic nanoparticles. *Biotechnology and Bioengineering*, 122(6), 1397–1401. <https://doi.org/10.1002/bit.28963>
- Ahmad, R., Malik, A., Khan, Z., and Rehman, A. (2025). Reductive biodegradation of pharmaceutical pollutants using synthetic microbial consortia. *Biotechnology Advances*, 66, 108045.
- Amaral-Zettler, L. A., Zettler, E. R., and Mincer, T. J. (2020). Ecology of the plastisphere. *Nature Reviews Microbiology*, 18(3), 139–151. <https://doi.org/10.1038/s41579-019-0308-0>
- Austin, H. P., Allen, M. D., Donohoe, B. S., Rorrer, N. A., Kearns, F. L., Silveira, R. L., and Beckham, G. T. (2018). Characterization and engineering of a plastic-degrading aromatic polyesterase. *Proceedings of the National Academy of Sciences*, 115(19), E4350–E4357.
- Benyathiar, P., Kumar, P., Carpenter, G., Brace, J., and Mishra, D. K. (2022). Polyethylene terephthalate (PET) bottle-to-bottle recycling for the beverage industry: A review. *Polymers*, 14(12), 2366. <https://doi.org/10.3390/polym14122366>
- Cassone, B. J., Grove, H. C., Elebute, O., Villanueva, S. M. P., and LeMoine, C. M. R. (2020). 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*, 287(1922), 20200112.
- Cheng, Y., Bi, X., Xu, Y., Liu, Y., Li, J., Du, G., Lv, X., and Liu, L. (2024). Machine learning for metabolic pathway optimization. *Nature Chemical Biology*, 20, 1–12.
- Cui, Y., Chen, Y., Liu, X., Dong, S., Tian, Y., Qiao, Y. and Han, Z. (2021). Computational redesign of

- a PETase for plastic biodegradation under ambient condition by the GRAPE strategy. *ACS Catalysis*, 11(3):1340–1350.
- Danso, D., Chow, J., and Streit, W. R. (2019). Plastics: Environmental and biotechnological perspectives on microbial degradation. *Applied and Environmental Microbiology*, 85(19), e01095-19.
- Dar, M., Xie, R., Zabed, H., Pawar, K., Dhole, N., and Sun, J. (2024). Current paradigms and future challenges in harnessing gut bacterial symbionts of insects for biodegradation of plastic wastes. *Insect Science*, 32(3): 726–752. <https://doi.org/10.1111/1744-7917.13417>
- Dhaka, V., Singh, S., Ramamurthy, P. C., Samuel, J., Naik, T. S. S. K., Khasnabis, S., Prasad, R., and Singh, J. (2023). Biological degradation of polyethylene terephthalate by rhizobacteria. *Environmental Science and Pollution Research*, 30(55):116488–116497. <https://doi.org/10.1007/s11356-022-20324-9>
- Dharmasiddhi, I. P., Chen, J., Arab, B., Yip, A., Weldon, M. and Aucoin, M.G. (2025). Optimization of microbial consortia for mixed plastic substrate consumption. *Canadian Journal of Microbiology*, 71:1–20. <https://doi.org/10.1139/cjm-2025-0053>
- Diao, J., Tian, Y., Park, S., Cho, S. M., and Moon, T. S. (2025). Engineering microbial consortia for mixed plastic upcycling. *Nature Communications*, 16, 67409. <https://doi.org/10.1038/s41467-025-67409-w>
- Dudeja, C., Mishra, A., Ali, A., Singh, P. P., and Jaiswal, A. K. (2025). Microbial genome editing with CRISPR–Cas9: Recent advances and emerging applications across sectors. *Fermentation*, 11:410.
- Gates, E. G., & Crook, N. (2024). The biochemical mechanisms of plastic biodegradation. *FEMS microbiology reviews*, 48(6), fuac027.
- Ethan, G.G and Crook, N. (2024). The biochemical mechanisms of plastic biodegradation. *FEMS Microbiology Reviews*, 48(6), fuac027. <https://doi.org/10.1093/femsre/fuac027>
- Han, Y. N., Wei, M., Han, F., Fang, C., Wang, D., Zhong, Y. J., Guo, C. L., Shi, X. Y., Xie, Z. K., and Li, F. M. (2020). Greater biofilm formation and increased biodegradation of polyethylene film by a microbial consortium of *Arthrobacter* sp. and *Streptomyces* sp. *Microorganisms*, 8(12), 1979. <https://doi.org/10.3390/microorganisms8121979>
- Gao, R., and Sun, C. (2021). A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. *Journal of Hazardous Materials*, 416, 125928.
- Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), e1700782. <https://doi.org/10.1126/sciadv.1700782>
- Giraldo-Narcizo, S., Guenani, N., Sánchez-Pérez, A. M., and Guerrero, A. (2023). Accelerated polyethylene terephthalate (PET) enzymatic degradation by room temperature alkali pretreatment for reduced polymer crystallinity. *ChemBioChem*, 24(1), e202200503.
- Gregory, G. J., Wang, E., and Carr, R. (2023). Polyethylene waste valorization combining chemical catalysis and microbial conversion. *ACS Sustainable Chemistry and Engineering*, 11(12):4778–4787.
- Hilgers, R., Vincken, J. P., Gruppen, H., and Kabel, M. A. (2018). Laccase/mediator systems: Their reactivity toward phenolic lignin structures. *ACS Sustainable Chemistry and Engineering*, 6(2):2037–2046.
- Hossain, S., Shukri, Z. N. A., Waiho, K., Ibrahim, Y. S., Kamaruzzan, A. S., Rahim, A. I. A., ... and Kasan, N. A. (2024). Biodegradation of polyethylene (PE), polypropylene (PP), and polystyrene (PS) microplastics by flocc-forming bacteria, *Bacillus cereus* strain SHBF2. *Environmental Science and Pollution Research*, 31(22):32225–32245.
- Hu, Y., Tian, Y., Zou, C., and Moon, T. S. (2024). The current progress of tandem chemical and biological plastic upcycling. *Biotechnology Advances*, 77:108462.
- Ibrahim, S. S., Ionescu, D. and Glob, T. (2024). Fungi in plastic degradation: Enzymatic pathways and biotechnological potential. *Frontiers in Microbiology*, 15, 1342456.
- Iiyoshi, Y., Tsutsumi, Y. and Nishida, T. (1998). Polyethylene degradation by lignin-degrading fungi and manganese peroxidase. *Journal of Wood Science*, 44(3), 222–229.
- Jeon, H. J. and Kim, M. N. (2015). Functional analysis of alkane hydroxylase system derived from *Pseudomonas aeruginosa* E7 for low molecular weight polyethylene biodegradation. *International Biodeterioration and Biodegradation*, 103:141–146.

- Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V. and Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μ FTIR spectroscopy. *Science of the Total Environment*, 831:154907.
- Jia, X., Dou, J., Ballerstedt, H., Xing, J. and Blank, L. M. (2024). Synthetic bacterial consortium for plastic pyrolysis oil waste reduction. *Environmental Science and Technology*, 58, 15234–15245.
- Kehkashan, Hussain, A., Murtaza, M., Lee, G., Mun, B., and Yun, B. (2025). Low and high-density polyethylene and expanded polystyrene biodegradation by the greater wax moth *Galleria mellonella* L. *Ecotoxicology and Environmental Safety*, 292:117345. <https://doi.org/10.1016/j.ecoenv.2025.117345>
- Kumar Sen, S., and Raut, S. (2015). Microbial degradation of low density polyethylene (LDPE): A review. *Journal of Environmental Chemical Engineering*, 3(1):462–473.
- Li, M. X., Yang, S. S., Ding, J., Ding, M. Q., He, L., Xing, D. F., ... and Wu, W. M. (2024). Cockroach *Blaptica dubia* biodegrades polystyrene plastics: Insights for superior ability, microbiome and host genes. *Journal of Hazardous Materials*, 479:135756.
- Liu, F., Wang, T., Yang, W., Zhang, Y., Gong, Y., Fan, X., ... and Wang, J. (2023). Current advances in the structural biology and molecular engineering of PETase. *Frontiers in Bioengineering and Biotechnology*, 11, 1263996. <https://doi.org/10.3389/fbioe.2023.1263996>
- Liu, F., Wang, T., Liu, X. H., Xu, N., and Pan, X. L. (2025). Efficient biodegradation and upcycling of polyethylene terephthalate mediated by cell-factories. *Frontiers in Microbiology*, 16:1599470. <https://doi.org/10.3389/fmicb.2025.1599470>
- Lu, H., Diaz, D. J., Czarnecki, N. J., Zhu, C., Kim, W., Shroff, R., ... and Ellington, A. D. (2022). Machine learning-aided engineering of hydrolases for PET depolymerization. *Nature*, 604(7907): 662–667.
- Maheswaran, B., Al-Ansari, M., Al-Humaid, L., Raj, J.S., Kim, W., Karmegam, N., and Rafi, K.M. (2023). In vivo degradation of polyethylene terephthalate using microbial isolates from plastic polluted environment. *Chemosphere*, 310:136757. <https://doi.org/10.1016/j.chemosphere.2022.136757>
- Mohanani, N., Montazer, Z., Sharma, P. K., and Levin, D. B. (2020). Microbial and enzymatic degradation of synthetic plastics. *Frontiers in Microbiology*, 11:580709. <https://doi.org/10.3389/fmicb.2020.580709>
- Müller, R. J., Schrader, H., Profe, J., Dresler, K., and Deckwer, W. D. (2005). Enzymatic degradation of poly(ethylene terephthalate): Rapid hydrolyse using a hydrolase from *T. fusca*. *Macromolecular Rapid Communications*, 26(17):1400–1405.
- OECD. (2022). Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. OECD Publishing, Paris. <https://doi.org/10.1787/de747aef-en>
- Putcha, J. P., and Kitagawa, W. (2024). Polyethylene biodegradation by an artificial bacterial consortium: *Rhodococcus* as a competitive plastisphere species. *Microbes and Environments*, 39(3), ME24031. <https://doi.org/10.1264/jsme2.ME24031>
- Qattan, S. Y. (2025). Harnessing bacterial consortia for effective bioremediation: Targeted removal of heavy metals, hydrocarbons, and persistent pollutants. *Environmental Science Europe*, 37: 85.
- Qi, X., Ma, Y., Chang, H., Li, B., Ding, M., & Yuan, Y. (2021). Evaluation of PET degradation using artificial microbial consortia. *Frontiers in Microbiology*, 12:778828. <https://doi.org/10.3389/fmicb.2021.778828>
- Roberts, C., Edwards, S., Vague, M., León-Zayas, R., Scheffer, H., Chan, G., ... and Neff, R. (2020). Environmental consortium containing *Pseudomonas* and *Bacillus* species synergistically degrades polyethylene terephthalate plastic. *mSphere*, 5(6), e01151-20.
- Ru, J., Huo, Y., and Yang, Y. (2020). Microbial degradation and valorization of plastic wastes. *Frontiers in Microbiology*, 11: 442.
- Saidu, M. B., Moreira, I. S., Amorim, C. L., Wu, R., Ho, Y. W., Fang, J. K. H., et al. (2025). Exploring the biodegradation of PET in mangrove soil and its intermediates by enriched bacterial consortia. *Environmental Technology*, 1–23. <https://doi.org/10.1080/09593330.2025.2521762>
- Salinas, J., Carpena, V., Martínez-Gallardo, M. R., Segado, M., Estrella-González, M. J., Toribio, A. J., ... and López, M. J. (2023). Development of plastic-degrading microbial consortia by induced selection in microcosms. *Frontiers in Microbiology*, 14, 1143769.

- <https://doi.org/10.3389/fmicb.2023.1143769>
- Sangale, M. K., Shah Nawaz, M., and Ade, A. B. (2019). Potential of fungi isolated from the dumping sites mangrove rhizosphere soil to degrade polythene. *Scientific Reports*, 9:5390.
- Santo, M., Weitsman, R., and Sivan, A. (2013). The role of the copper-binding enzyme—laccase—in the biodegradation of polyethylene by the actinomycete *Rhodococcus ruber*. *International Biodeterioration and Biodegradation*, 84:204–210.
- Satta, A., Zampieri, G., Loprete, G., Campanaro, S., Treu, L., and Bergantino, E. (2024). Metabolic and enzymatic engineering strategies for polyethylene terephthalate degradation and valorization. *Reviews in Environmental Science and Bio/Technology*, 23:351–383.
- Singh, A. K., Poddar, B., Gupta, R. K., Nakhate, S. P., Varghese, V., Khardenavis, A. A., and Purohit, H. J. (2024). Designing the metabolic capacities of environmental bioprocesses through genome editing. In *Genome Editing in Bacteria (Part 2)* (pp. 222–246). Bentham Science Publishers.
- Sowmya, H. V., Ramalingappa, B., Nayanashree, G., Thippeswamy, B., and Krishnappa, M. (2015). Polyethylene degradation by fungal consortium. *International Journal of Environmental Research*, 9(3): 823–830.
- Then, J., Wei, R., Oeser, T., Gerdts, A., Schmidt, J., Barabás, G., and Stomps, R. (2016). Ca²⁺ and Mg²⁺ binding site engineering increases the degradation of polyethylene terephthalate films by polyester hydrolases. *Biotechnology Journal*, 11(8): 1082–1087.
- Vincent, A. E. S., Chaudhary, A., Kelly, J. J., and Hoellein, T. J. (2022). Biofilm assemblage and activity on plastic in urban streams at a continental scale. *Science of the Total Environment*, 835:155398.
- Wei, R., and Zimmermann, W. (2017). Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: How far are we? *Microbial Biotechnology*, 10(6):1308–1322. <https://doi.org/10.1111/1751-7915.12710>
- Wróbel, M., Szymańska, S., and Hryniewicz, K. (2024). Microbial degradation of microplastics: Effectiveness, challenges, and sustainable solutions. *Science of the Total Environment*, 912:169108.
- Xue, R., Bai, Z., Fordour, E., Guo, S., Zhou, Y., Yang, Y., Liu, X., Li, Y. and Liu, C.L. (2024). Bacterial surface co-display of engineered PETase variants and MHETase on *Escherichia coli* and *Pseudomonas putida* platforms. *ACS Catalysis*, 14: 8903–8915.
- Yang, J., Yang, Y., Wu, W. M., Zhao, J., and Jiang, L. (2014). Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. *Environmental Science and Technology*, 48(23):13776–13784.
- Yang, S. S., Brandon, A. M., Flanagan, J. C., Yang, J., Ning, D., Cai, S. Y., ... and Criddle, C. S. (2015). Biodegradation of polystyrene wastes in yellow mealworms. *Environmental Science and Technology*, 49(20): 12080–12086.
- Yang, Y., Xie, E., Du, Z., Peng, Z., Han, Z., Li, L., ... and Yang, X. (2023). Detection of various microplastics in patients undergoing cardiac surgery. *Environmental Science and Technology*, 57: 10911–10918.
- Yao, Z., Seong, H. J., and Jang, Y. S. (2022). Degradation of low-density polyethylene by *Bacillus* species. *International Biodeterioration and Biodegradation*, 170, 105391.
- Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., ... and Oda, K. (2016). A bacterium that degrades and assimilates poly (ethylene terephthalate). *Science*, 351(6278), 1196–1199. <https://doi.org/10.1126/science.aad6359>
- Young, R., Ahmed, K. A., Court, L., Castro-Vargas, C., Marcora, A., Bector, J., ... and Pandey, G. (2024). Improved reference quality genome sequence of the plastic-degrading greater wax moth, *Galleria mellonella*. *G3: Genes|Genomes|Genetics*, 14(6), jkae070. <https://doi.org/10.1093/g3journal/jkae070>
- Zampolli, J., Orro, A., Mezzina, M. P., Vezzini, D., Gregorini, A., Collina, E., and Di Gennaro, P. (2023). Oxidative degradation of polyethylene by two novel laccase-like multicopper oxidases from *Rhodococcus opacus* R7. *Environmental Technology and Innovation*, 32:103349.
- Zettler, E. R., Mincer, T. J., and Amaral-Zettler, L. A. (2013). Life in the “plastisphere”: Microbial communities on plastic marine debris. *Environmental Science and Technology*, 47(13):7137–7146.

-
- Zhai, K., Pal, T., Liu, Z., Lin, X., Men, Y., and Chen, J. (2025). Immobilization of PETase on magnetic nanoparticles enhances their stability and activity for efficient degradation of polyethylene terephthalate. *ACS Applied Materials and Interfaces*, 17(50):67519–67528.
- Zhang, Y., Pedersen, J. N., Eser, B. E., and Guo, Z. (2022). Biodegradation of polyethylene and polystyrene: From microbial deterioration to enzyme discovery. *Biotechnology Advances*, 60, 107991. <https://doi.org/10.1016/j.biotechadv.2022.107991>
- Zhou, Y., and ZeeshanUlHaq, M. (2025). Engineering of synthetic microbial consortia for sustainable management of wastewater and polyethylene terephthalate: A comprehensive review. *International Journal of Molecular Sciences*, 26(23): 11623. <https://doi.org/10.3390/ijms262311623>