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Breaking Down Barriers: Innovative Pathways and Biotechnological Frontiers in Plastic Degradation

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Abstract

Plastic pollution is one of the most significant environmental issues of the 21st century, with annual production spanning over 415 million tons and only 9% being successfully recycled (Cai et al., 2023). Here, we review different mechanisms of degradation of plastics such as photodegradation, thermal degradation, biodegradation, and chemical degradation while underscoring their environmental consequences and plausible remedial measures (Yousif & Haddad, 2013; Peterson et al., 2001; Kale et al., 2015). Plastic degradation follows various routes involving UV light, high temperatures, microbial activity, and chemical reactions. The procedure culminates in microplastic and nanoplastic formation through fragmentation, remaining in aquatic and terrestrial ecosystems for decades to centuries (Bajt, 2021; Maddison et al., 2023). Recent breakthroughs in enzymatic digestion utilizing plastic-digesting microorganisms such as *Ideonella sakaiensis* and engineered PETases hold high biotechnology promise (Sevilla et al., 2023; Zhu et al., 2022; Suresh et al., 2025). However, environmental conditions such as temperature, pH, humidity, and available oxygen play a huge impact in determining the rates and routes of degradation (Cai et al., 2023; Yang et al., 2023; Zhai et al., 2023). Elucidation of such mechanisms remains invaluable in formulating potent strategies for waste disposal of plastics as well as remediation of the environment (Urbanek et al., 2018; Xu et al., 2023).

Keywords: Plastic Degradation, Photodegradation, Microplastics, Enzymatic Degradation, Bioremediation

Introduction

Unparalleled growth in production and consumption of plastics has led to a worldwide environmental disaster capable of destroying planetwide ecosystems. Since the 1950s, an estimated 80% of the plastics produced have landed in landfills or the environment (Cai et al., 2023). At present production of 415 million tons a year, plastic waste generation is projected to hit 460 million tons in 2025, thereby calling for efficient degradation and disposal methods (Asher, 2023).

Degradation of plastic refers to the breakdown of polymer chains into small pieces and eventually into simple monomers through physical, chemical, and biological means. It is influenced by the environment, polymer composition, and availability of a catalyst in the form of UV light, heat, oxygen, and microorganisms (Yousif & Haddad, 2013; Lee & Li, 2021; Oh & Stache, 2024). On the basis of the mechanism of degradation, rate of breakdown, intermediate formed, and final environmental fate of plastic waste are decided (Peterson et al., 2001; Kale et al., 2015).

The ocean environment is a significant repository for plastics, where 8–12 million metric tons are deposited in ocean systems annually (Yang et al., 2021). Eventually in marine ecosystems, the plastics are subjected to complex degradation processes such as photooxidation, mechanical breakage, and microbial settlement. Such processes give rise to the formation of microplastics (less than 5 mm in diameter) and nanoplastics (less than 1 μm in diameter), which are ingested in marine animals and transferred through the food web (Bajt, 2021; Paul et al., 2024; Zhang et al., 2024).

Plastic degradation mechanisms play a fundamental role in designing optimum waste disposal technologies, biodegradable substitutes, and bioremediation technologies (Niaounakis, 2017; Schneier et al., 2024). Recent reports on enzymes and microorganisms for degrading plastics have brought biotechnology technologies for treating plastic waste into focus (Sevilla et al., 2023; Suresh et al., 2025). We present an account of available data on plastic degradation mechanisms, degradation kinetics under various environmental conditions, and emerging technologies for disposing of plastic waste (Urbanek et al., 2018; Xu et al., 2023).

Mechanism of Degrading Plastics

Degradation of plastics occurs through a series of interlinked mechanisms, each on differing timescales and under different environmental circumstances. Photodegradation, thermal degradation, oxidative degradation, biodegradation, hydrolytic degradation, and mechanical degradation are the primary degradation mechanisms (Jansen, 2015; Oh & Stache, 2024).

Photodegradation is a primary degradation mode for outdoor-exposed plastics under the influence of sunlight. Ultraviolet radiation in the 280-420 nm region carries sufficient energy to break through C-C and C-H bonds in polymer backbones, introducing free radical formation. Photodegradation encompasses three primary stages: initiation through chromophore absorption, propagation through radical chain reactions, and termination through either radical coupling or involvement of stabilizers. Polystyrene, through phenyl chromophores, is particularly susceptible to photodegradation, readily yellowing and embrittling on exposure to UV light. Photodegradation produces carbonyl compounds, oligomers, and consequently ends up through complete mineralization after

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prolonged exposure (Yousif & Haddad, 2013; Lee & Li, 2021).

Thermal degradation is the effect of exposing polymers to high temperatures, normally in excess of 200°C. It is a molecular breakdown resulting from the chain scission and cross-linking reactions, and it modifies the molecular weight distribution and mechanical integrity. Polymers have different thermal stability properties, with fluoropolymers such as PTFE having high resistance resulting from high C-F bond strengths, whereas PVC is very prone to thermal degradation even at the service of processing it. Degradation products include monomers, volatile fragments, and char residues depending on polymer type and degradation environment (Peterson et al., 2001; Madorsky & Straus, 1959).

Biodegradation is a promising route towards the environment-safe disposal of plastics in a non-polluting way where polymers are decomposed through enzymatic activity of microorganisms. Marine and terrestrial microorganisms possess some enzymes including PETases, cutinases, lipases, and laccases, which are in a position to break polymer bonds. It encompasses initial microbial colonization on the surfaces of the plastics, accumulation of a biofilm, release of enzymes, and depolymerization of polymer into oligomers and ultimately into monomers. These low-molecular-weight fractions are transformed through a series of metabolic reactions to CO_2, H_2O, and biomass in aerobic reactions or CH_4 in anaerobic reactions (Cai et al., 2023; Yang et al., 2023; Zhai et al., 2023; Urbanek et al., 2018; Schneier et al., 2024; Sevilla et al., 2023).

These are chemical degradation processes consisting of oxidative degradation and hydrolytic degradation, respectively, and play a crucial role in the biodegradation of plastics upon environmental exposure. These are reactions, respectively, where contact with oxygen occurs via free radical mechanism inserting carbonyl functionality into polymer chains. Hydrolytic degradation, on the other hand, acts on condensation polymers such as polyesters, polycarbonates, and nylons via water molecule reaction resulting in chain scission and loss in molecular weight (Oh & Stache, 2024; Zhang et al., 2024; Xu et al., 2023).

Table 1. Plastic Degradation Mechanism

Degradation Type	Primary Cause	Temperature Range (°C)	Time Scale	End Products
Photodegradation	UV radiation exposure	20-50	Months to years	Carbonyl compounds, oligomers
Thermal Degradation	Elevated temperatures	200-850	Minutes to hours	Monomers, volatile compounds
Oxidative Degradation	Oxygen and free radicals	25-70	Months to years	Ketones, alcohols, acids

Biodegradation	Microbial enzymes	15-70	Weeks to months	CO2, H2O, biomass
Hydrolytic Degradation	Water contact	25-80	Months to years	Monomers, oligomers
Mechanical Degradation	Physical stress/abrasion	Ambient	Days to months	Microplastics, fragments

Microbial Degradation of Plastics

Plastic-degrading microorganisms were discovered to change the course of knowing the mechanism of biological degradation of plastics. *Ideonella sakaiensis* was first described in 2016 and is known as a breakthrough microorganism for utilizing PET as a carbon and a source of energy via the synthesis of PETase and MHETase enzymes. It is capable of degrading low-crystallinity PET films up to 30-70% under the best conditions (Sevilla et al., 2023; Zhu et al., 2022; Maurya et al., 2020; Suresh et al., 2025).

Marine ecosystems harbor diverse microbial communities for the breakdown of plastics, such as algae, fungi, and bacteria. Genera such as *Alcanivorax*, *Bacillus*, *Pseudomonas*, and *Rhodococcus* also have high potentials for plastic breakdown through different polymer classes. Microorganisms develop plastisphere on plastics, where they develop localized microenvironments for enzymatic breakdown. The plastisphere, comprising a distinctive microbial community for plastic litter, remarkably varies from communities in surrounding areas and functions as a main agent for breakdown of plastics in marine ecosystems (Zhai et al., 2023; Jamali, 2024).

Mechanisms of enzymatic degradation entail particular enzymes attacking various polymer linkages. PETases hydrolyze PET in such a way as to produce mono(2-hydroxyethyl) terephthalic acid (MHET), the subsequent breakdown of which is carried out by MHETases to terephthalic acid and ethylene glycol. Cutinases and lipases are enzymes with wide substrate specificity where they break numerous polyesters via hydrolysis of the ester bond. Laccases, mainly from fungi, bring about oxidative breakdown of recalcitrant polymers via radical mechanisms (Cai et al., 2023; Yang et al., 2023; Schneier et al., 2024).

Ecological factors play a determining role in the tempo and efficiency of microbial breakdown of plastics. Temperature is an important factor, and most microorganisms for degrading plastics have an optimum for breakdown in the 30–70 °C range. pH does affect the activity of enzymes and microbial growth, and near neutral to slightly alkaline pH values are usual optimum values for breakdown of plastics. Availability of oxygen determines the aerobic/anoxic nature of breakdown, and both channels produce different end products (Urbanek et al., 2018; Cai et al., 2023; Xu et al., 2023).

Table 2. Plastic Degrading Microorganisms

Microorganism	**Polymer Target**	**Enzyme Type**	**Degradation Rate (%)**	**Environment**

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Ideonella sakaiensis	PET	PETase, MHETase	30-70	Terrestrial
Pseudomonas aeruginosa	PE, LDPE, HDPE	Lipase, Esterase	15-40	Marine/Terrestrial
Bacillus cereus	PE, PET, PP, PS	Hydrolase, Oxidase	20-50	Terrestrial
Rhodococcus ruber	PE, PET	Cutinase, Laccase	10-35	Terrestrial
Aspergillus niger	PU, PE	Laccase, Peroxidase	25-60	Terrestrial
Penicillium chrysogenum	PU, PS	Urethane hydrolase	15-45	Terrestrial
Alcanivorax sp.	PS	Styrene monooxygenase	20-40	Marine
Marinobacter sp.	PE, PP	Alkane hydroxylase	10-30	Marine
Shewanella sp.	PE, PVC	Depolymerase	15-35	Marine
Bacillusmegaterium	PE, PET	Cutinase	20-45	Terrestrial

Environmental Factors Affecting Degradation

Rate and magnitude of degradation are significantly determined by environmental variables, establishing the main degradation mechanisms and contribution ratio of each to each other (Yang et al., 2023; Cai et al., 2023). Temperature is a determining factor, with rates of degradation normally also fulfilling Arrhenius kinetics, in which the rates of reactions are doubled for every 10°C of higher temperatures (Kale et al., 2015; Yousif & Haddad, 2013). Higher temperatures enhance molecular motion, functionality of enzymes, and rates of chemical reactions, accelerating every degradation process (Xu et al., 2023; Paul et al., 2024).

Humidity and water content have a marked influence on hydrolytic and biological degradation reactions (Lee & Li, 2021; Schneier et al., 2024). Humid high-temperature conditions favor water uptake through polymer matrices, allowing hydrolytic bond breakdown. For biodegradation, water offers favorable conditions for the growth of microorganisms and the functioning of enzymes. Tropical areas with high humidity and temperature values demonstrate rapid plastic degradation in contrast to desertic regions (Urbanek et al., 2018; Zhai et al., 2023).

Exposure duration and strength of UV radiation are directly related to rates of photodegradation (Peterson et al., 2001; Bajt, 2021). UV-B radiation (280-315 nm) is more efficient in initiating photooxidative degradation through chromophore activation. Latitude, seasonal change, and weathered atmospheric conditions influence exposure to UV, resulting in extreme local variation in rates of photodegradation (Maddison et al., 2023; Zhang et al., 2024). Dual exposure to mechanical stress and UV acts synergistically in accelerating fragmentation, where experimental microplastic yields are increased tremendously under such profiles of exposure (Niaounakis, 2017; Oh & Stache, 2024).

Degree of the oxidative degradation process is regulated via the supply of oxygen (Yousif & Haddad, 2013; Sevilla et al., 2023). Aerobic conditions promote oxidative chain reactions, whereas anaerobic conditions inhibit oxidative degradation but enhance certain biodegradation reactions (Zhu et al., 2022; Yang et al., 2021). Salinity also affects the composition of microbial communities and the stability of enzymes in seawater, influencing biodegradation rates (Cai et al., 2023; Suresh et al., 2025). Mechanical stress imposed via wave action, wind, and sediment friction increases the acceleration of the fragmentation, particularly in weathered plastics with lesser mechanical strength (Asher, 2023; Xu et al., 2023).

Table 3. Environmental Factors Degradation

Factor	Optimal Range	Effect on Degradation	Impact Level
Temperature	30-70°C	Accelerates at higher temps	High
pH	6.5-8.5	Neutral pH optimal	Medium
Humidity	60-90%	Higher humidity enhances	High
UV Radiation	280-400 nm	Initiates photo-oxidation	Very High
Oxygen Availability	15-21% O2	Essential for oxidation	High
Salinity	0-35 ppt	Affects microbial activity	Medium
Mechanical Stress	Variable	Increases fragmentation	High
Microbial Activity	10^6-10^8 cells/ml	Enables biodegradation	Very High

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Formation of Microplastics and Nano plastics

Degradation of plastics necessarily culminates in the generation of microplastics (1 μm to 5 mm) and nanoplastics (<1 μm), perhaps the most problematic feature of plastic pollution (Bajt, 2021; Maddison et al., 2023). They are a result of the durable breakdown of larger pieces of flotsam through the synergistic operation of physical, chemical, and biological processes (Peterson et al., 2001; Cai et al., 2023). The break-up procedure initially commences with embrittlement and surface oxidation, then a mechanical disintegration into steadily diminutive fragments (Yousif& Haddad, 2013).

Plastic degradation in marine settings exhibits staggering growth in particle concentrations with exposure time (Pfohl et al., 2022). Microplastic concentrations for polystyrene reach up to 92,465 particles/mL in four months of marine exposure, while nanoplastic concentrations can reach over 640 million particles/mL (Maddison et al., 2023). This exponential growth in particle count through degradation underscores the scale of microplastic generation from discarded plastics (Zhang et al., 2024).

Size distribution of degradation product follows familiar patterns, such that particle abundance increases with decreasing particle size (Asher, 2023). Fragmenting expanded polystyrene loses as much as 76.5% of initial volume in the form of submicron particles in a simulated accelerated weathering test (Xu et al., 2023). These data indicate that existing monitoring methods are likely to underestimate substantially actual microplastic burdens through lack of sensitivity in detecting nanoparticles (Zhai et al., 2023).

Microplastics are carriers of chemical pollutants such as persistent organic chemicals, heavy metals, and plasticizers (Niaounakis, 2017; Urbanek et al., 2018). They have high surface area-to-volume ratio and therefore high contaminant adsorption and carriage capability. Microplastics also have the capacity to cross through biological membranes and become sequestered in tissues, with traces of occurrences in human liver, kidney, and placentas (Schneier et al., 2024; Paul et al., 2024).

Biotechnologies methods for plastic degradation

Recent biotechnology advances have brought promise for cleanup through engineered biological technologies against plastic pollution (Sevilla et al., 2023; Zhu et al., 2022). Such technologies are applied in a more efficient way through genetic engineering, bioprocessing, and enzyme optimization based on inherent natural biodegradation of microorganisms (Maurya et al., 2020).

Enzyme engineering works towards the optimization of PETase and related enzymes through directed evolution and rational design approaches (Suresh et al., 2025). Engineered PETases have 3.3-fold increased activity compared to wild-type enzymes and have increased ability to break supercrystalline PET from commercial bottles (Zhu et al., 2022). Surface display technologies such as use of the biofilm-integrated nanofiber display (BIND) strategy are applied to promote the longevity and life span of enzymes as well as reduce production costs (Xu et al., 2023).

Whole-cell biocatalysts offer various advantages over purified enzymes, including increased stability, reduced production costs, and opportunities for steady-state operation (Sevilla et al., 2023). Engineered *E. coli* cells displaying PETases on their surface were seen to break down 4.8% PET within seven days remaining in activity, in contrast to rapid inactivation of purified enzymes (Maurya et al., 2020). Such biocatalysts can be engineered for biocontainment with features including genetic kill switches to not escape into the environment (Zhu et al., 2022).

Microbial consortia methods accept the reality that biodegradation of plastics in nature is a multi-organism synergistic process (Yang et al., 2021). Such processes are more efficient in biodegrading complex polymer mixtures than single-organism methods and are potentially more stable for a wide range of different environmental conditions (Lee & Li, 2021). Marine consortia have shown capability to biodegrade PVC under anaerobic conditions and widen the spectrum of polymer treatability (Urbanek et al., 2018).

Future biotechnology breakthroughs focus on building low-cost pretreatment technologies, defining biocatalyst longevity in functional systems, and scaling processes for industrially relevant applications (Suresh et al., 2025). Coupling with the upcycling paths of plastics can produce value-added chemicals from waste plastics for higher process economies and sustainability (Zhang et al., 2024).

Global impact and future perspectives

Plastic pollution globally must be managed through comprehensive methods including prevention, management, and remediation strategies (Cai et al., 2023). Existing waste infrastructure is poor such that 3 billion individuals have no controlled disposal facilities whatsoever and 2 billion have no frequent collection of wastes (Asher, 2023). Such a gap in infrastructure is the major cause of environmental leakages of plastics, especially in the rapidly industrializing world (Schneier et al., 2024).

Export of foreign waste plastics makes matters worse, as high-income economies export over 4.4 million metric tons annually of plastic waste to low-disposal-capacity economies (Maddison et al., 2023). Export of wastes places environmental and health burdens on already vulnerable societies while failing to resolve deeper patterns of overconsumption and overproduction (Niaounakis, 2017).

Immediate intervention is needed owing to the climate change contribution of plastic breakdown (Zhai et al., 2023). Plastic production is a cause of 3.4% of global greenhouse emissions, and this is set to double in 2060 if nothing is done (Paul et al., 2024). Plastic might use 20% of oil and produce 15% of carbon emissions by 2050 (Yang et al., 2023). It is further anticipated that the plastics industry might pose a notable contribution to environmental problems. It constitutes a pressing necessity for industry sustainability (Sevilla et al., 2023).

Future research focuses are the development of standardized procedures for measuring biodegradation efficiency, the implementation of high-throughput screening technologies for the identification of enzymes, and the determination of industry standards for biotechnology-based plastics disposal (Maurya et al., 2020; Zhu et al., 2022).

Computerized learning and artificial intelligence can expedite enzyme engineering and optimization of processes (Xu et al., 2023). Circular economy principles must inform technology development for new technologies such that solutions are applicable to eliminating generation of wastes at the origin in addition to generating value from current plastic wastes (Yang et al., 2021; Suresh et al., 2025).

CONCLUSION

Degradation of plastics is a multifaceted environmental process made up of various interacting mechanisms occurring on various spatial and temporal scales (Cai et al., 2023). Although natural degradation processes offer little respite from production of plastic waste, available rates are not in a position to cater for the sheer volume of generation of plastics globally (Zhai et al., 2023). Occurrence of plastic material in the environment, including disintegration of the material into micro- and nanoplastics, generates notable ecological and human health threats lasting for centuries unless some measure is implemented (Schneier et al., 2024; Urbanek et al., 2018). Identification and characterization of microorganisms and enzymes capable of degrading plastics present promising biotechnology strategies for managing plastics waste (Sevilla et al., 2023; Zhu et al., 2022). Implementation of such technologies, however, faces stiff challenges regarding inefficiencies in processes, lack of economic feasibility, and environmental unsafety (Suresh et al., 2025). Combining various strategies such as source minimization, enhanced waste infrastructure, and advanced technology for treating wastes will be needed to manage the plastics pollution problem effectively (Yang et al., 2023). Local environmental factors play a significant role in determining the rates and channels of degradation, hence the necessity to incorporate such elements in methods of waste disposal (Lee & Li, 2021). Shifts in degradation processes in plastics from impacts of climate change such as changed temperatures and patterns of ultraviolet rays require close monitoring and revision in disposal methods (Paul et al., 2024). Creation of nanoplastics and microplastics in degradation processes requires sophisticated technologies for detection and elimination in an attempt to reduce ecological and human health impacts (Maddison et al., 2023). More research is needed to generate economically viable and environmentally friendly technologies on a scale sufficient to solve the challenge of plastic pollution globally (Zhai et al., 2023). Developing better enzyme engineering, building stable microbial systems for different plastics, and conceiving comprehensive schemes for waste disposal linking prevention, treatment, and valorisation methods are some of them (Suresh et al., 2025). It is only through a collaborative endeavour on a global scale involving technological development, generation of informative policies, and behaviour change that the challenge of degradation of plastics can ultimately be overcome for the preservation of environmental and human health for future generations (Cai et al., 2023; Sevilla et al., 2023).

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