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Environmental Factors Shaping Microbial Biodegradation of Marine Microplastics

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Abstract. Marine microplastics have become a major challenge to the global marine environment because of their persistence and widespread distribution. Polyethylene (PE) and polyethylene terephthalate (PET), as the two most widely used and frequently detected polymers, exhibit markedly different biodegradation potentials due to their distinct chemical properties. This review systematically summarizes the microbial degradation mechanisms of PE and PET, including surface biofilm formation, key enzymatic reactions, aerobic and anaerobic metabolic pathways, and the synergistic effects of abiotic weathering with biological processes. Building on this, the review further analyzes how marine environmental factors—temperature, pressure, light, oxygen, salinity, and nutrient supply—affect microbial degradation efficiency, with a particular focus on the contrasts between shallow and deep-sea systems. The findings indicate that temperature and oxygen availability are the primary limiting factors for plastic degradation in deep-sea environments, while high pressure, nutrient scarcity, and lack of light further constrain microbial metabolic activity. By integrating current research, this review highlights the central role of environmental drivers in shaping microplastic degradation, providing a theoretical foundation to better understand and enhance microbial degradation in marine ecosystems.

Keywords: microbial biodegradation, microplastics, marine, environmental factors

1. Introduction

Marine microplastics have emerged as a persistent and omnipresent threat to oceans worldwide, spanning from surface waters to the deepest marine trenches [1]. These tiny pollutants, measuring less than 5 mm in size, originate from both primary sources such as microbeads and industrial pellets, as well as secondary sources, which involve the breakdown of larger plastic materials [2]. In 2023, global plastic production reached approximately 414 million tonnes [3]. Unfortunately, poor waste management and inadequate recycling efforts have led to widespread contamination of marine ecosystems [4,5]. Large plastic items, once introduced into these environments, undergo mechanical wear, UV degradation, and chemical breakdown, progressively shattering into microplastics, further compounding this environmental crisis [6].

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Microplastics have pervaded seawater, sediments, and marine life, posing significant ecological and health concerns. Their minute size and hydrophobic nature make them prone to the adsorption of persistent organic pollutants and heavy metals, amplifying their risks [7,8]. Various marine species ingest these particles, which bioaccumulate in food chains. Ultimately, these contaminants enter the human food supply via seafood, further underscoring the urgency of addressing microplastic pollution.

PE and PET are prominently found in the environment due to their widespread use. PE is commonly utilized in packaging and films, whereas PET is predominantly used in bottles and synthetic textiles. Studies consistently reveal that PE comprises approximately 25% to 48% of microplastic samples, while PET accounts for about 14% to 16.5% [9-12]. Thus, their selection as key polymers for study are justified by their significant environmental presence. Both are consistently detected in water, sediments, and biota. PE is highly resistant to degradation, whereas PET degradation pathways (e.g., PETase and MHETase in Ideonella sakaiensis) are comparatively well understood. Contrasting PE and PET further illustrates how polymer chemistry influences biodegradation efficiency.

Table 1. Major microplastic polymers and their relative abundance in marine environments

Polymer	Common Uses	Marine Prevalence (%)	Notes
PE (Polyethylene)	Packaging films, bags, bottles	~25–48%	Most abundant; highly resistant; dominates surface waters [9,10]
PP (Polypropylene)	Food containers, fibers, nets	~16%	Frequently detected in water and sediment [9]
PET (Polyethylene terephthalate)	Bottles, textiles	~14–16.5%	Common in waters and biota; enzymatic degradation well studied [10,11]
PS (Polystyrene)	Foam, packaging	Variable (moderate)	Easily fragments into smaller particles [9]
PVC (Polyvinyl chloride)	Pipes, cables	Lower	Contains additives; potential toxicity [9]
PA (Polyamide/nylon)	Fishing gear, textiles	Variable	Often reported in fibers, especially in deep-sea [11]

This review therefore focuses on PE and PET, systematically examining how marine environmental factors—including temperature, pressure, salinity, light, and oxygen—affect microbial degradation, with emphasis on shallow versus deep-sea systems.

2. Microbial biodegradation mechanisms and pathways

As highlighted in the introduction, PE and PET are the most common microplastic polymers in marine environments. Their contrasting chemistries—stable C–C chains in PE versus hydrolysable ester bonds in PET—underlie both their persistence and differing biodegradation potential.

Microbial breakdown proceeds through a sequence: surface colonization and biofilm formation, extracellular depolymerization or oxidation, uptake of soluble products, and metabolic assimilation. This section reviews key plastic-degrading microbes, the role of biofilms, enzymatic pathways, aerobic versus anaerobic processes, and abiotic–biotic interactions, and concludes with emerging engineered strategies.

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2.1. Known plastic-degrading microbes

Several representative microbes have been identified that initiate plastic depolymerization.

2.1.1. PET degraders

The discovery of Ideonella sakaiensis marked a turning point in PET biodegradation. This bacterium adheres to PET surfaces, secretes PETase, and anchors MHETase to its outer membrane. PETase cleaves amorphous regions of PET to release mono(2-hydroxyethyl) terephthalate (MHET), bis(2-hydroxyethyl) terephthalate (BHET), and trace amounts of terephthalic acid (TPA) and ethylene glycol (EG); MHETase subsequently hydrolyzes MHET to TPA and EG [14, 22, 23]. Under anaerobic conditions, I. sakaiensis switches metabolism: it ferments PET to acetate and ethanol, and coculturing with the acetate-consuming bacterium Geobacter sulfurreducens generates electricity [13]. These findings demonstrate that PET can serve as feedstock for both aerobic respiration and anaerobic fermentation.

While I. sakaiensis remains the model organism, other microbes contribute to PET depolymerization. A thermophilic polyesterase dubbed DmPETase, cloned from Deinococcus maricopensis, shares about 60% sequence identity with hydrolases from Thermobifida species and cutinase LCC and exemplifies enzymes adapted to high-temperature PET hydrolysis [21]. The plant-pathogenic actinomycete Streptomyces scabies produces a lipase-like esterase Sub1; addition of the surfactant Triton X-100 enhances PET hydrolysis by roughly 2.6-fold and the enzyme remains stable at 37 °C for at least 20 days [20].

2.1.2. PE degraders

Because PE lacks hydrolyzable bonds, PE degraders rely on oxidative enzymes to introduce functional groups. Enrichment cultures using LDPE as the sole carbon source identified Actinobacteria and Proteobacteria as key players and showed that pretreatment with UV light significantly enhances degradation: UV-treated films lost 2.22–5.17% of their mass after 120 days, whereas untreated films lost only 1.32–2.80% [16]. An artificial consortium selected for laccase, lipase, esterase, and alkane hydroxylase activities revealed that Rhodococcus erythropolis predominated and that multilayer biofilms and surface pitting accompany PE degradation [17]. Over twenty bacterial genera—including Rhodococcus, Staphylococcus, Streptococcus, Bacillus, Pseudomonas, Ralstonia, Stenotrophomonas, Klebsiella, and Acinetobacter—and numerous fungi (e.g., Aspergillus, Acremonium, Fusarium, Penicillium) have been reported to oxidize PE and often collaborate within biofilms. A facultative anaerobe, Pluralibacter gergoviae TYB1, secretes surface-active compounds that reduce hydrophobicity and promote biofilm formation on LDPE, yielding up to 17.5% weight loss in 30 days without any pretreatment [19].

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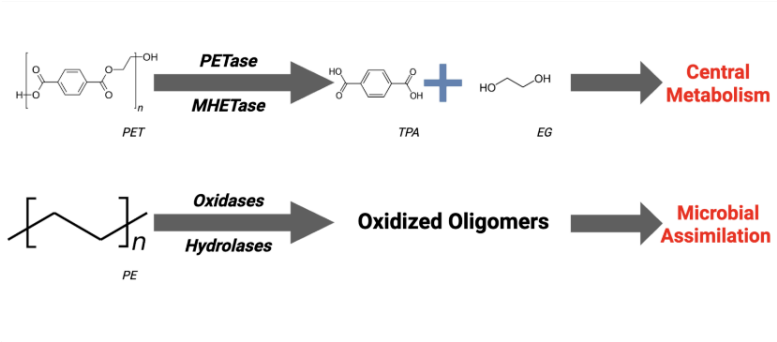

Figure 1. Microbial degradation of PET and PE

2.2. Biofilm formation on plastic surfaces

Beyond the activity of individual degraders, microbial colonization typically occurs within biofilms, which provide the structural and chemical context for efficient plastic breakdown.

The formation of microbial biofilms on microplastic surfaces—the plastisphere—is a key step in biodegradation. Biofilm development typically involves initial microbial attachment, secretion of extracellular polymeric substances (EPS), recruitment of additional species, and maturation into a structured community [24]. This process modifies the plastic surface, changing hydrophilicity and roughness, and creates microenvironments that favor enzyme activity and substrate access [25]. Biofilms often develop oxygen gradients, leading to the coexistence of aerobic and anaerobic zones [26]. Such spatial heterogeneity may enable different metabolic pathways to operate simultaneously, which could in turn facilitate polymer degradation. Plastisphere formation thus represents a key ecological niche for studying and promoting plastic biodegradation. High-throughput sequencing of marine PET biofilms showed that the phylum Proteobacteria dominated the communities (65.95%), containing a more diverse assemblage than samples from the surrounding seawater. The type of polymer rather than environmental variables dictated the bacterial community structure. Biofilm formation typically proceeds through initial attachment of pioneer species, secretion of extracellular polymeric substances, recruitment of secondary colonizers and maturation into a complex matrix [18]. For both PET and PE, biofilms concentrate extracellular enzymes at the polymer interface, facilitate interspecies interactions and create microoxic niches that allow coexistence of aerobic and anaerobic processes.

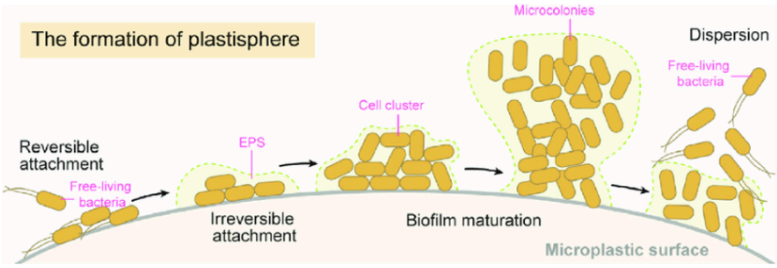

Figure 2. Stages of plastisphere formation on microplastic surfaces, including reversible and irreversible attachment, EPS secretion, biofilm maturation, and eventual dispersion of cells [27]

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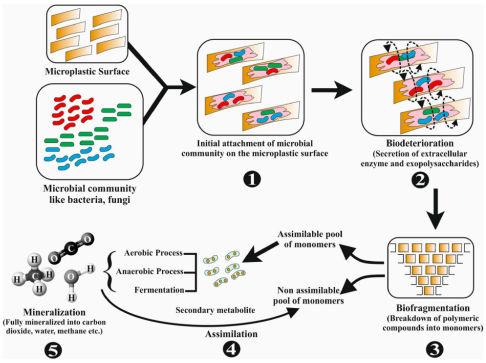

Figure 3. Schematic overview of microplastic biodegradation, showing microbial attachment, biodeterioration, biofragmentation, assimilation of monomers through aerobic or anaerobic processes, and final mineralization [28]

2.3. Enzymatic breakdown of polymers

Within these biofilms, extracellular enzymes are the primary agents that depolymerize plastics into smaller, assimilable molecules.

2.3.1. PET hydrolysis

Microbial PET degradation centers on hydrolytic cleavage of ester bonds. PETase attacks amorphous PET regions, generating BHET and MHET; MHETase then converts MHET into TPA and EG [22]. The monomers are assimilated via established metabolic pathways: TPA is metabolized by terephthalate dioxygenase into protocatechuate, which enters the β-ketoadipate pathway and subsequently central carbon metabolism, while EG is sequentially oxidized via glycolaldehyde and glycolate to glyoxylate. Thermophilic polyesterases such as DmPETase expand the temperature range for enzymatic PET depolymerization [21]. The Sub1 esterase from S. scabies further illustrates enzyme diversity; Triton X-100 increases its PET hydrolysis rate and the enzyme remains stable at 37 °C for at least 20 days [20]. Such enzymes complement PETase and MHETase and may be incorporated into engineered consortia or enzyme cocktails.

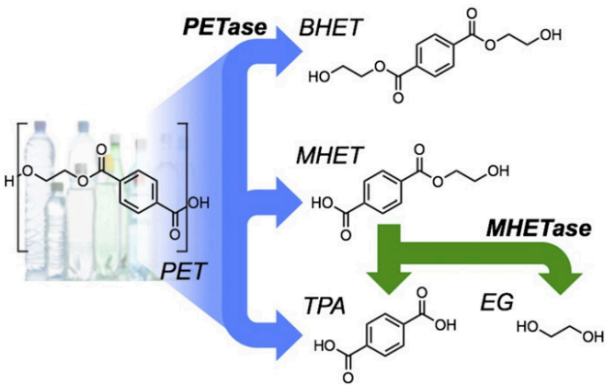

Figure 4. Enzymatic hydrolysis of PET. PETase converts PET into BHET and MHET, while MHETase further hydrolyzes MHET into terephthalic acid (TPA) and ethylene glycol (EG) [22]

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2.3.2. PE oxidation

PE degradation begins with oxidation to introduce polar groups. Lignin-degrading oxidoreductases —laccases, manganese peroxidases, and lignin peroxidases—transfer electrons to the PE chain, generating carbonyl and hydroperoxide groups. Alkane hydroxylases (AlkB family) catalyze terminal or subterminal oxidation of C–C chains, producing alcohols and acids that can enter β-oxidation pathways. Lipases and esterases hydrolyze oxidized side chains and additives, increasing surface hydrophilicity and promoting colonization [17]. Because pristine PE is highly hydrophobic, oxidative pretreatments (UV, thermal oxidation) are often needed to generate functional groups (Section 2.5). Effective PE degradation thus relies on consortia combining oxidases and hydrolases rather than single enzymes.

2.4. Aerobic vs anaerobic pathways

The preceding sections focused on the organisms, biofilm structures, and enzymatic reactions that enable plastic depolymerization. An equally important factor is the metabolic context: whether degradation occurs under aerobic or anaerobic conditions.

Oxygen availability determines metabolic fate. Under aerobic conditions, PET degraders such as I. sakaiensis oxidize TPA and EG to CO_2 and water after depolymerization. In the absence of oxygen, I. sakaiensis ferments PET: MHET generated by PETase is hydrolyzed by MHETase to TPA and EG, but EG is converted via acetaldehyde and ethanol to acetyl-CoA, yielding acetate and ethanol as products [13]. When co-cultured with the electrogenic bacterium G. sulfurreducens, I. sakaiensis enables electricity generation from PET-derived fermentation products such as acetate [13]. Strict anaerobic mineralization of PE has not been reported; even facultative anaerobes like P. gergoviae rely on oxygen to initiate radical formation for PE oxidation.

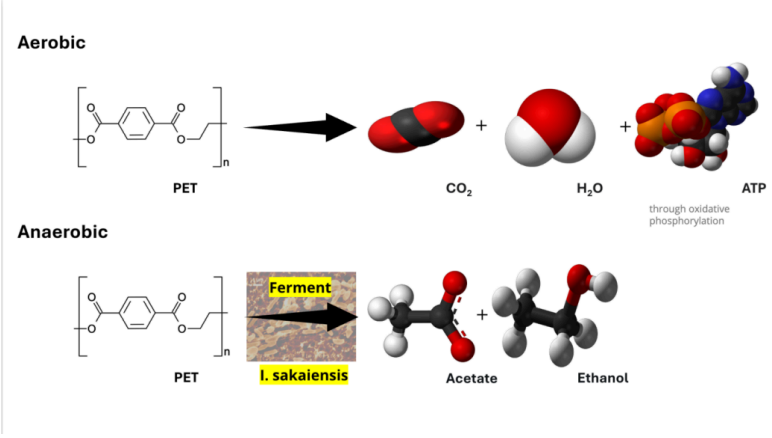

Figure 5. Aerobic versus anaerobic PET metabolism. Under aerobic conditions, PET is oxidized to CO_2 and H_2O with ATP generation, while under anaerobic conditions it is fermented by I. sakaiensis into acetate and ethanol

2.5. Abiotic–biotic interactions

In addition to oxygen availability, non-biological processes also shape the course of plastic degradation by altering polymer surfaces before microbial attack.

Abiotic weathering often primes plastics for microbial attack. For PET, ultraviolet radiation cleaves ester bonds, evidenced by attenuation of the 1713 cm^{-1} FTIR ester peak and emergence of a

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1685 cm^{-1} carbonyl peak; saturated humidity and elevated temperature (50 °C) accelerate these changes [15]. Oxidized PET has lower molecular weight, which may enhance accessibility to PETase and related enzymes. PE also shows a strong improvement upon pretreatment. For example, in the case of LDPE (a subtype of PE), UV-treated LDPE demonstrates significantly higher biodegradation efficiency than untreated plastic. In LDPE consortia, UV pretreatment increased weight loss to 2.22–5.17% after 120 days compared with 1.32–2.80% for untreated films [16], while sunlight and thermal pretreatments yielded moderate improvements. A separate study combining UV-treated PE with a fungal–bacterial consortium achieved ~7% weight loss versus 3% for untreated PE [16]. These results underscore a two-step model: abiotic oxidation introduces functional groups that enable biotic oxidation and depolymerization.

3. Environmental factors affecting microbial degradation in marine systems

Many environmental drivers influence microbial degradation in marine ecosystems, which varies according to environmental conditions. The main factors include temperature, hydrostatic pressure, sunlight, oxygen, salinity, and nutrient supply. The synergistic effect of these factors determines community composition, facilitates enzyme activities, and ultimately influences the microbial degradation of biodegradable microplastics.

3.1. Temperature gradients and microbial metabolism

Temperature is a key factor affecting enzyme kinetic behavior, and its relationship can usually be described by Arrhenius behavior, which states that for every 10 °C increase in temperature, the metabolic rate approximately doubles. In waters with surface water temperatures between 20–30 °C, hydrocarbon-degrading bacteria such as Alcanivorax borkumensis can achieve their optimal metabolic activity. However, in polar and deep-sea waters with temperatures below 5 °C, the degradation rate significantly decreases. Cold-adapted bacteria (such as Colwellia psychrerythea) can synthesize cold-adapted enzymes and antifreeze proteins with flexible structures to maintain their catalytic activity at low temperatures, but this adaptation comes at the cost of sacrificing catalytic efficiency: compared to enzymes derived from temperate environments, their turnover is reduced by 10 to 50 times [9]. The laboratory constant-temperature cultivation study further confirms that the degradation efficiency of PET film at 4 °C is much lower than that at 25 °C, indicating that temperature is the key limiting factor for plastic biodegradation in deep-sea and polar environments. This adaptation comes at a cost: turnover rates are 10–50 times slower compared to enzymes from temperate systems. Laboratory incubation studies have confirmed that PET films degraded far less efficiently at 4 °C compared with 25 °C, illustrating temperature as a primary bottleneck for deep-sea and polar plastic biodegradation.

3.2. Hydrostatic pressure and microbial adaptation

The hydrostatic pressure increases linearly with depth (about 0.1 MPa per meter), exceeding 40 MPa in deep-sea plains and 100 MPa in trenches. Elevated pressure reduces substrate diffusion into the biofilm and disrupts the stability of protein and lipid bilayers. Hydrophilic microorganisms, such as Colwellia piezophila and Shewanella violacea, adapt by synthesizing pressure-stable enzymes, polyunsaturated fatty acids that maintain membrane fluidity, and protein-folding partners [29]. Importantly, pressure can also alter the solubility and diffusion rate of hydrophobic substrates, further limiting plastic degradation. Experimental data show that applying a pressure of 50 MPa can

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inhibit enzyme activity and reduce the catalytic rate to below 20% of the catalytic rate observed at atmospheric pressure [30].

3.3. Sunlight availability: photic vs aphotic zones

IIn the transparent area (<200 meters), sunlight drives non-biological weathering. Ultraviolet radiation oxidizes polymer chains, producing carbonyl and hydroxyl groups, thereby increasing hydrophilicity and promoting microbial colonization [31]. However, ultraviolet radiation also produces reactive oxygen species (ROS), which can damage microbial DNA and membranes, partially offsetting its positive effects. Photoheterotrophic microorganisms, such as pelagic bacteria (containing protein-fixing bacteria) and Roseobacter (containing bacterial chlorophyll), utilize light energy to supplement organic matter degradation [32]. In contrast, aphotic zones without sunlight lack photochemical priming. There, biodegradation relies solely on chemoheterotrophy and enzymatic hydrolysis, which proceeds at orders of magnitude slower rates.

3.4. Oxygen availability and redox conditions

Surface water is usually aerobic, which facilitates aerobic pathways such as oxygenase-mediated cutting of PE and PET. Aerobic degradation typically leads to complete mineralization of CO_2 and H_2O. In contrast, low-oxygen sediments and oxygen-minimum zones limit degradation to anaerobic processes, which are less energetically favorable. Anaerobic communities use sulfates, nitrates, and even CO_2 as terminal electron acceptors [33]. However, these pathways are significantly slower: in sediment culture, the degradation rate of PET under anaerobic conditions is less than 30% of the aerobic control. Facultative anaerobic bacteria provide metabolic flexibility and can partially degrade during oxygen fluctuations.

3.5. Salinity and halophilic adaptations

The ocean salinity (~35 ‰) generates strong osmotic stress. Many degrading bacteria, including halophilic bacteria, tolerate this condition by accumulating compatible solutes or producing salt-tolerant enzymes [34]. In estuarine environments, salinity fluctuations can alter microbial composition and change degradation kinetics. High-salt lagoons (>100 ‰) can accommodate halophilic communities and degrade polyesters such as PHA and PBAT, but extreme conditions inhibit overall diversity and limit degradation efficiency [35]. Comparative studies have shown that when the salinity exceeds 80 ‰, the degradation rate of PE decreases by nearly 50%, indicating that there is an upper limit to microbial activity.

3.6. Nutrient availability and biofilm development

The enrichment of nitrogen and phosphorus promotes microbial colonization and biofilm growth on plastics [36]. Biofilms act as catalytic microenvironments: they concentrate extracellular enzymes, stabilize redox gradients, and enhance interspecies cooperation. For example, compared to the poor-nutrient control group, the enrichment of nitrogen and phosphorus in mesoscale ecosystems increased the weight loss of LDPE by about 30%. On the contrary, nutrient-poor high seas can limit microbial biomass, even in the presence of biodegradable polymers, which can limit biodegradation. This makes nutrient-driven biofilm dynamics a key determinant of degradation efficiency.

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4. Conclusions and future perspectives

This review systematically examines the mechanisms of microbial degradation of PE and PET in marine environments, along with the regulatory effects of various environmental factors—including temperature, pressure, light, oxygen, salinity, and nutrients—on the degradation process. Overall, extensive research confirms that microorganisms can partially degrade microplastics through processes such as surface colonization, biofilm formation, key enzymatic reactions, and aerobic/anaerobic metabolism, but the efficiency of degradation remains limited by the chemical stability of the polymers themselves and by complex environmental conditions. In deep-water environments in particular, the combined effects of low temperatures, high pressure, light deprivation, and nutrient deficiency significantly suppress microbial metabolic activity and enzymatic efficiency, making plastic persistence in these ecosystems even more pronounced.

However, recent studies have also revealed some positive signs. For example, certain psychrophilic, piezophilic, and halophilic strains show adaptability to extreme environments and possess measurable degradation potential; abiotic processes (e.g., UV radiation, thermal oxidation) can promote subsequent biological degradation by introducing functional groups; and advances in modified microbial communities and synthetic biology offer opportunities to overcome the efficiency bottlenecks of single-strain degradation. These developments provide new directions for enhancing microplastic degradation in complex and variable marine environments.

Future research and applications can be advanced at the following levels:

1. Analysis of adaptation mechanisms in extreme environments: Employ metagenomics, metatranscriptomics, and proteomics to uncover the degradation potential of microorganisms in deep-sea and polar environments, identifying new cold- and pressure-resistant enzymes and metabolic pathways.

2. Studies on multifactorial coupling effects: Emphasize the combined influences of temperature, pressure, salinity, oxygen, and nutrients, moving beyond single-variable studies to better approximate real-world ecosystem conditions.

3. Artificial microbial communities and synthetic biology applications: Construct complementary microbial consortia or engineered strains that enhance the degradation rate and stability of complex polymers through metabolic division of labor and enzymatic synergy.

4. Development and optimization of engineered enzymes: Improve the thermal stability, catalytic efficiency, and substrate adaptability of key degradation enzymes (e.g., PETase, MHETase, oxidases, peroxidases) via directed evolution and structural modification.

5. Assessment of environmental risks of degradation products: In addition to monitoring degradation rates, systematically investigate the ecotoxicity, mobility, and persistence of intermediates and end products to avoid secondary pollution.

6. Interdisciplinary integration and applied scenarios: Combine insights from materials science (design of biodegradable polymers), oceanography (modeling of environmental processes), and environmental engineering (bioremediation technologies) to accelerate the transition from laboratory research to practical applications.

In short, the microbial degradation of marine microplastics is a complex and slow process constrained by multiple environmental factors. Despite challenges such as low efficiency and incomplete mechanistic understanding, advances in molecular tools, the integration of synthetic biology with ecology, and strengthened interdisciplinary collaboration hold promise for the development of more efficient and sustainable solutions. Such advances could play a key role in mitigating marine plastic pollution and ensuring the long-term resilience and health of marine ecosystems.

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