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Opinion Article

Engineered Microbes for Biodegradation of Plastic Waste in Marine Environments

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DESCRIPTION

Plastic pollution in marine ecosystems has emerged as one of the most critical environmental issues of the 21st century. Millions of tons of plastic waste enter the oceans annually, posing significant threats to aquatic life, food chains, and global biodiversity. While mechanical and chemical approaches to plastic waste management exist, their limitations in cost, scalability, and environmental safety have directed attention toward biological alternatives. Among these, the use of engineered microbes presents a highly promising and sustainable strategy for the degradation of persistent plastics in marine environments. Microbial degradation refers to the ability of microorganisms to break down complex materials into simpler, non-toxic compounds. However, native marine microbes often lack the metabolic capability to degrade synthetic polymers such as Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), and Polyethylene Terephthalate (PET), which dominate marine plastic waste. Recent advances in genetic engineering and synthetic biology have enabled the development of engineered microbial strains with enhanced enzymatic capabilities tailored to target such polymers. These engineered microbes are designed to express plastic-degrading enzymes, including PETases, MHETases, and laccases, which can hydrolyze the ester and carbon-carbon bonds found in synthetic plastics.

One notable development in this field is the identification and subsequent engineering of *Ideonella sakaiensis*, a bacterium capable of degrading PET through the activity of PETase and MHETase enzymes. Genetic modification of this strain has led to improved thermostability and catalytic efficiency of these enzymes, significantly enhancing PET degradation rates. Researchers have also transferred these genes into more robust and fast-growing microbial hosts such as Escherichia coli and Bacillus subtilis to create engineered strains capable of operating under marine environmental conditions. Marine ecosystems, however, present unique challenges for microbial degradation. Salinity, temperature fluctuations, UV exposure, and nutrient limitations can hinder microbial survival and activity. To address this, current research focuses on engineering marine-derived microbes or extremophiles to possess both plastic-degrading capabilities and environmental resilience. Additionally, the use of synthetic gene circuits allows for controlled enzyme expression in response to specific environmental triggers, minimizing risks to native ecosystems and improving degradation efficiency.

Bioreactor-based pilot studies have demonstrated the feasibility of using engineered microbes in controlled environments to degrade plastic waste. However, translating these systems to open marine ecosystems requires careful consideration of ecological impacts and biosafety. Researchers are exploring encapsulation technologies to deploy microbes in biodegradable carriers that localize their activity and prevent uncontrolled proliferation. Moreover, microbial consortia groups of engineered microbes with complementary metabolic pathways are being developed to target mixed plastic wastes more effectively than single strains. Despite the promise of engineered microbes, several limitations must be addressed before large-scale application is feasible. These include optimizing enzyme expression and stability in saline water, enhancing microbial survivability without external nutrients, and ensuring the complete mineralization of plastic polymers into harmless by-products such as carbon dioxide and water. Furthermore, regulatory and ethical concerns surrounding the release of Genetically Modified Organisms (GMOs) into natural ecosystems remain significant barriers. Future research will need to focus on designing self-limiting or kill-switch mechanisms to prevent ecological disruption.

In parallel, omics-based approaches such as metagenomics, transcriptomics, and proteomics are being leveraged to understand the interactions between engineered microbes and native marine microbial communities. These tools provide insights into how introduced strains may influence microbial ecology, nutrient cycling, and trophic interactions. Additionally, integrating machine learning with synthetic biology can aid in predicting optimal gene combinations and environmental responses, streamlining the development of next-generation microbial systems. In conclusion, engineered microbes offer a

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novel and sustainable solution for tackling the growing crisis of plastic pollution in marine environments. Through the strategic use of synthetic biology, genetic engineering, and ecological design, these organisms can be tailored to degrade various plastic polymers effectively under challenging marine conditions. While significant scientific and regulatory hurdles remain, continued interdisciplinary research promises to transform this innovative concept into a practical biotechnological tool for environmental remediation.