Exploring Biodegradation of Marine Plastics

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Abstract

Bacteriophages are the most ubiquitous organisms found within the biosphere, composed of an estimated 1031 particles. The evolutionary "Plastic is the leading component of marine litter in the world today. It lines our roads and clogs our waterways. Nevertheless, plastic has revolutionized modern society. It emerged as a lightweight and durable material in the early 20th century (Napper et al.). Plastic is derived from the Greek word "plastikos," which means "able to be molded." Its high versatility enables it to be used in many industries, including healthcare, agriculture, packaging, transportation, and construction (Zeenat et al.) However, this high versatility comes at a cost, as plastics rarely degrade naturally, and thus they accumulate in large quantities. Large plastic waste deposits lead to severe environmental damage, particularly due to microplastics in marine ecosystems. The current plastic waste management practices such as landfilling, incineration, and recycling are inefficient and ineffective, thus we require alternative solutions. One proposed remediation for the accumulation of plastic is the biodegradation of plastics by bacterial and fungal species. Through enzymatic processes, these species offer great potential for advancements in plastic waste management that are currently under-researched. By exploring genetic advancements in microbial genomes, integration with waste management practices, and the global, ecological, and economic implications, we may be able to supplement existing plastic remediation strategies or create entirely new ones.

The single-use nature of the majority of plastic products people use today has contributed to their accumulation in marine ecosystems. Estimates put plastic as 75% of all marine litter, accumulating in the deep sea, washed up on beaches, and even in arctic sea ice. Scientists identified plastics as having a wide-scale impact on the marine ecosystem in the 1980s. However, it has only recently been perceived as a threat to our environment by the public on a global scale. Plastics are commonly characterized by size into three groups, macroplastics, >20 mm, mesoplastics, 5-20mm, and microplastics, <5mm (Zeenat et al.) This paper focuses on the prevailing existence of microplastics as a pervasive threat to our oceans, and mitigating responses. Microplastics that enter the environment as such are often produced by grinding or extrusion, however, the fragmentation of larger plastics will continue to produce microplastics in the future.

Background: Plastic and Waste Management

Plastic is composed of synthetic organic polymers, forming long chain-like molecules resulting in repeating structural units. These units are made of hydrocarbons, derived mainly from fossil fuels. There are also many harmful chemicals added to plastics for specific purposes. Carcinogens, neurotoxicants, endocrine disruptors such as phthalates, bisphenols, and per- and poly-fluoroalkyl substances (PFAS), are added to plastics to change their color, flexibility, stability water repellency, flame retardance, and UV-resistance. However, it wasn't until after World War II that plastic as we know it was mass-produced. Its production jumped up to 5 million tons in the 1950s, as consumerism gripped a new post-war society. Plastic's unique properties were soon realized and its annual production reached 30 million tons in 1988, then 359 million tons by 2018 (Kibria et al.) By 2025 we now see plastic creeping into all environments.

Current waste management solutions to the accumulation of plastic are inefficient and ineffective, as seen in the accumulation of plastic throughout the environment. The main strategies for current waste management of plastics include landfilling, incineration, thermal conversion, and export. These practices largely exclude the mitigation of microplastic damage to the environment. While these practices vary by country, landfilling accounted for the majority of plastic waste disposal in the year 2000, at 65%. Incineration accounted for 25% and recycling only 10% (Kibria et al.) Once these materials are in the landfill, they incur no further treatment. Due to this, the EPA has enhanced federal and state regulations to include landfilling beds, groundwater testing, and other practices, however, we are limited due to lack of space for landfilling operations. Waste management through incineration provides recaptured energy, as many plastic wastes are chemically similar to crude oil derivatives. Through the process of incineration, the result is energy, but also many toxic gases such as polycyclic aromatic hydrocarbons. Scientists and engineers are working toward developing safer and more efficient incineration practices to solve the plastic problem.

Role of Hydrocarbons

Petroleum-based hydrocarbons play a significant role in microplastic degradation. The majority of plastics have a hydrocarbon backbone, which is made up of hydrogen and carbon atoms. These plastics can be Alkanes, saturated hydrocarbons, found in polyethylene, and propylene, Alkenes, which are unsaturated hydrocarbons, and aromatic hydrocarbons, such as styrene, found in polystyrene. These compounds matter because some bacteria and fungi are hydrocarbonoclastic microorganisms, which are prokaryotes that can metabolize hydrocarbons. They have certain microbial enzymes that allow them to break the carbon-carbon bonds in these hydrocarbons.These enzymes such as laccases, peroxidases, hydrolases, and oxidases, can initiate plastic degradation (Cai et al.)

Mechanisms of MP Degradation

The mechanisms of microplastic degradation include physical degradation, chemical degradation, and biological degradation. Physical degradation is usually driven by waves, tidal movement, and interactions with sediments, which eventually fragment larger pieces of plastic into microplastics. Photodegradation of plastics is another driver of the breakdown of plastics, where the combination of ultraviolet light and infrared radiation can degrade plastics into smaller parts. Chemical degradation of plastics can also occur through oxidation, again only causing larger pieces of plastic to become smaller. This study focuses on biological degradation, which can be in the form of bacterial degradation or fungal degradation. This biodegradation occurs in four steps, biodeterioration, bio-fragmentation, assimilation, and mineralization. Bio-deterioration is the altering of the chemical and physical properties of the polymer. Bio-fragmentation is the breakdown of the polymer into a simpler form through enzymatic function.

Assimilation is the uptake of these molecules by the microorganisms, and mineralization is the production of oxidized metabolites such as carbon dioxide, methane, and water, following degradation. (Pathak et al.) Microbial organisms naturally colonize the surface of plastics, forming biofilms, and have enzymes that catalyze biodegradation. These biofilms are communities of microorganisms attached to a surface. The environmental cues that alert individual bacteria to form a biofilm vary from species to species. Many species will form a biofilm when it is suitable for growth, however, some species will only form a biofilm in low nutrient conditions. Temperature, osmolarity, pH, and oxygen and iron levels can all influence the formation of biofilms. (O'Toole et al.)

Bacterial Degradation of Microplastics

Bacterial species, *Bacillus*, *Pseudomonas,* and *Arthobacter,* have shown capability for degrading microplastics. The *Pseudomonas* species especially showed a great ability to biodegrade in the Bay of Bengal, achieving a percentage weight reduction of polyethylene of up to 20% within 120 days. (Zhai et al.) This species shows promise in the degradation of plastics, as seen in beaches contaminated by oil spills, *Pseudomonas aeruginosa,* metabolized 40.8% of the carbons of low-molecular-weight polyethylene into carbon dioxide after 80 days of composting. Along with Pseudomonas, Bacillus species strains could also degrade many petroleum-derived plastics. Rhodococcus and Bacillus strains, isolated from mangroves, could degrade microplastics. Weight loss of polyethylene, polyethylene terephthalate (PET), polypropylene, and polystyrene, was found due to Bacillus cereus, and Bacillus gottheilii, after 40 days of incubation. (Auta et al.)

Recent Studies and Findings in Bacterial and Fungal Degradation

The fragmentation of plastics by bacterial species has been studied increasingly in recent years. Researchers at the Netherlands Department of Environment and Health, along with the Flanders Marine Institute took to the laboratory to investigate the rates that proposed bacterial species had on floating plastic debris in the ocean. Researchers created a seawater microcosm to simulate a marine environment and encouraged the growth of bacterial biofilms. As an indicator of fragmentation, researchers took measurements of the weight loss of various plastic objects in a laboratory microcosm after 378-427 days. It was evident that plastics made of polymers with carbon-carbon backbones such as polyethylene, polystyrene, and polypropylene, were most resistant to biodegradation. These plastics had a maximum fragmentation rate of less than 1% per year. These results providing this low fragmentation rate may be due to the fact the laboratory microcosm is not completely representative of marine environments. There is a lack of physical degradation that occurs within natural marine environments, such as tidal movement, sediment abrasion, and most importantly, UV-radiation photodegradation, which is the natural initiating factor of degradation in the wild (Gerritse et al.)

The subject of biodegradation by microbes has been studied heavily in recent years, as the problems that the accumulation of microplastics poses begin to surmount. A recent study by the Royal Netherlands for Sea Research investigates marine fungal species and their ability to degrade microplastics. The list of degrading fungal species is short, however, biologists believe there to be many more. The fungus Parengyodontium album, along with other microbes, colonizes and forms biofilm on plastic in the ocean. Biologists isolated this marine fungus from plastic deposits in the Pacific Ocean, onto Carbon13 labeled plastics in the laboratory setting. Polyethylene was broken down by P. album at a rate of 0.05% per day with the condition of UV-light photodegradation (Vaksmaa et al.) While this number may not seem significant it shows implications for further study.

Advancements in Genetic Approaches to Biodegradation

One significant subject in the microbial approach to plastic decomposition is genetic modification. A recent study has discovered a bacterium that degrades and assimilates poly(ethylene terephthalate) (PET). Researchers in Japan recently discovered a novel species of the genus Ideonella, coined Ideonella sakaiensis, through soil, mineral, and wastewater samples from a PET recycling plant (Zhai et al.) This species is interesting for its unique ability to degrade polyesters containing a high ratio of aromatic compounds, which are highly resistant to microbial degradation. I. sakaiensis adheres to PET and secretes an enzyme called PETase by researchers, giving it the ability to assimilate previously believed resistant plastic structures to degradation. This enzyme has implications in the genetic modification scheme, potentially giving way to altering similar bacterial species.

While microbial organisms have been proven to decompose plastics in marine environments after initiation from photodegradation, it is unsure whether microbes can significantly degrade plastics without such light source initiation. As plastics are littered into marine environments and are transported by tidal movements, they are subject to sunlight, causing photodegradation. However, if some plastic collects no UV-radiation photodegradation, it may not be subject to biodegradation through colonization by microbes. Some deep-sea plastic deposits may have initially sank, forgoing photodegradation, and thus not being eligible for biodegradation by microbes. For further research, the possibility of a way for microbes to skip this photodegradation precursor should be investigated.

Discussion

While this research is important, there are currently many limitations and challenges faced in experimentation on the subject. Similar to the limitations in the Royal Netherlands experiment, it is difficult to simulate a test environment that subjects materials to the real-world marine environment. Simulation of marine environments should include photodegradation by sunlight, abrasion by sediments, and tidal movement. Without these naturally persisting forces, the biodegradation of plastics may be limited. Future studies should include large-scale systems where these factors can be accounted for. This research includes potential for future perspectives and application for bioremediation strategies. Biodegradation enhancement to microbial strains should be investigated for an increase in biodegradation ability. These enhancements would include nutrient supplementation, lack of nutrient availability, the addition of external stimuli, and other variables.

Integration with waste management practices may also prove to be worth investigating. Waste management facilities could be developed to combine current waste management practices such as landfilling, incineration, and thermal conversion, with microbial colonization, further enhancing the degradation properties. Along with such enclosed microbial colonization bioreactors or plants, the long-term wide-scale introduction of microbial biodegradation practices should be explored. The introduction of new or genetically engineered species may have varying long-term ecological effects on the environment. The possibility of a new genetic mutant of microbial species could cause drastic unseen effects on the biodiversity of marine environments. An introduction of any magnitude should be simulated to uncover possible side effects. Furthermore, the potential of new, undiscovered microbe species with the potential to degrade plastics should be investigated.

Conclusion

The global use of plastics over the past century has provided humans with a significant problem: how to clean up the materials that make our lives easier. One possible answer is the degradation of these materials. Plastic litter encroaching into marine environments poses a threat to the health of our oceans. Bacterial and fungal strains have demonstrated the unique ability to break down microplastics through natural enzymatic function. However further research indicates that supplementary physical and chemical degradation may be necessary. Despite advancements in research on the biodegradation of plastics, limitations are found in slow degradation rates, environmental representation, and inconsistency with the scale of experiments. For future research, there should be a focus on the genetic mutation of the enzymatic function of microbial species, the enhancement of biodegradation mechanisms, environmental stimuli, the discovery of new species with the ability to degrade plastics, and the integration of microbial colonization into current waste management practices. Applications for this research may be wide-ranging. Consideration should be given to ecological impacts and long-term sustainability.

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