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Enzymatic Degradation of Plastic Waste: A Review of Microbial Strategies and Future Perspectives

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Enzymatic Degradation of Plastic Waste: A Review of Microbial Strategies and Future Perspectives

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Introduction

It is said that humans generate 2.01 billion tons of municipal waste every year and this number is projected to explode to a massive 3.40 billion tons annually by the year 2050 (Ellis, 2018). This increase in waste production perfectly underscores a growing reliance on materials that persist in ecosystems long-term. This contamination, generated from large-scale industrial practices to doing your laundry at home, is best exemplified by the proliferation of microplastics throughout the environment.

What are microplastics? The first documented use of the term microplastics can be traced to a 1990 publication in the South African Journal of Science article titled “Plastic and other artefacts on South African beaches: Temporal trends in abundance and composition” by Peter G. Ryan. This publication used the term microplastics as a vague all-encompassing term for small broken plastic particles. This definition was refined over time, and today microplastics are more precisely defined as small plastic particles between 5 mm and 100 nm in size. This category is then broken down into primary and secondary microplastics. Primary microplastics are manufactured in their microplastic form often for use as an exfoliating grit in consumer products like face wash and shampoos.[1] Secondary microplastics are formed from the recycling and waste processing of larger plastics through physical, chemical, and biological means.[2]

Today, the leading industries that have been identified as the greatest contributors to microplastic pollution are the textile, laundry, and agricultural industries as well as the wastewater treatment industry.[3–6] The environmental hazards associated with these industries, compounded by domestic activities such as littering, make up the bulk of microplastic generation.

Environmental and Bio-Accumulation of Microplastics and Toxicity

Microplastics generated from the activities mentioned above are stable in soil and water and are known to bioaccumulate. In a study of tomato plants, it was found that the concentration of microplastics in soil directly affected the number of species as well as the overall quantity of microorganisms in soil thus negatively impacting soil quality, nitrogen content, and the tomato plant’s ability to uptake nutrients due to microplastic deposition in roots.[7] A separate study of microplastic toxicity was carried out on a laboratory-scale with fish in contaminated water sources. Microplastics were found to be deposited in the fish’s intestines and were also found to have lowered immune response and rate of reproduction, and a high rate of organ failure across multiple systems.[8] Humans understandably are very much at risk of microplastic accumulation not only through their polluted environments but also through accumulation through tainted foods (e.g. fish and tomatoes). Microplastic accumulation in humans has been found to have a strong link to many cancers through the inhibition different cell functions and enzymatic activities.[9]

Mechanisms of Enzymatic Degradation

Due to the toxic effects of microplastic pollution mentioned above, there has been extensive research on pathways to degrade and reduce overall microplastic waste in systems before they are able to bioaccumulate. This is complicated by the different types of microplastic polymers and the specific enzymes needed to break each of them down. Some of the most common polymers are listed on the table below.[10]

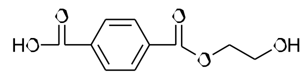
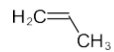
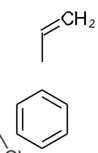
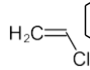
No	Polymer name	Monomer name	Monomer structure	Chemical formula	Density (g cm^3)
1	Low-density polyethylene (LDPE)	Ethene	$H_2C{=}CH_2$	C_2H_4	0.91–0.92
2	High-density polyethylene (HDPE)	Ethene	$H_2C{=}CH_2$	C_2H_4	0.93–0.97
3	Polyethylene terephthalate (PET)	Ethylene terephthalate		$C_{10}H_8O_4$	1.37–1.38
4	Polypropylene (PP)	Propylene		C_3H_6	0.89–0.92
5	Polystyrene (PS)	Styrene		C_8H_8	0.28–1.04
6	Polyvinyl chloride (PVC)	Vinyl chloride		C_2H_3Cl	1.10-1.47

Table 1: Polymeric microplastics and their monomers, monomer structure, chemical formula, and density

These microplastic reducing enzymes function to reduce a microplastic polymer to its respective monomer state, which can be a viable carbon source for certain microorganisms to use, such as *Ideonella sakaiensis* in PET degradation. For the example of numbers 1 and 2 of table 1, LDPE and HDPE would be degraded to ethylene.

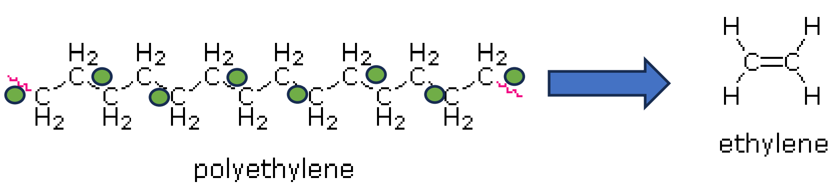


Figure 1: Polymeric de-linkage points (noted in green) and the reduction of a polymer being reduced to a monomer state.

HDPE and LDPE are two of the most commonly used plastics. In the case of LDPE, there has been an established methodology of enzymatic reduction for over fifty years using of Staphylococcus epidermis.[11] The enzymatic reduction works in a two-step process, firstly the enzyme converts the polymer into its monomer units. Secondly, the monomers undergo mineralization in which the monomers are broken down and taken up as CO_2, H_2O, and CH_4. The enzymes used in this case are laccase and alkane hydrolase.[12] Laccase has also been found to degrade HDPE, and while many other bacteria have been tested, many of those that produce this enzyme have had similar effects.[13]

PET is a plastic commonly found in bottles. There has been a lot of concern regarding its application due to PET having a noted link to endocrinal toxicity, and a study has shown that toxic levels of PET have a direct correlation to a highly increased rate of breast cancer.[14] Due to the negative health outcomes associated with PET exposure, there has been a major push to identify new degradation methods for these microplastics. Much like LDPE and HDPE, there have been advancements in PET degradation and mineralization through the bacteria *Ideonella sakaiensis*, which has been found to produce a specific set of PET-degrading enzymes, PETase and MHETase. As shown in the figure below, PET is broken down by PETase into MHET (mono(2-hydroxyethyl) terephthalic acid). A secondary enzyme, MHETase, then breaks MHET down into easily processed and less toxic molecules that can be mineralized by the initial bacteria.[15]

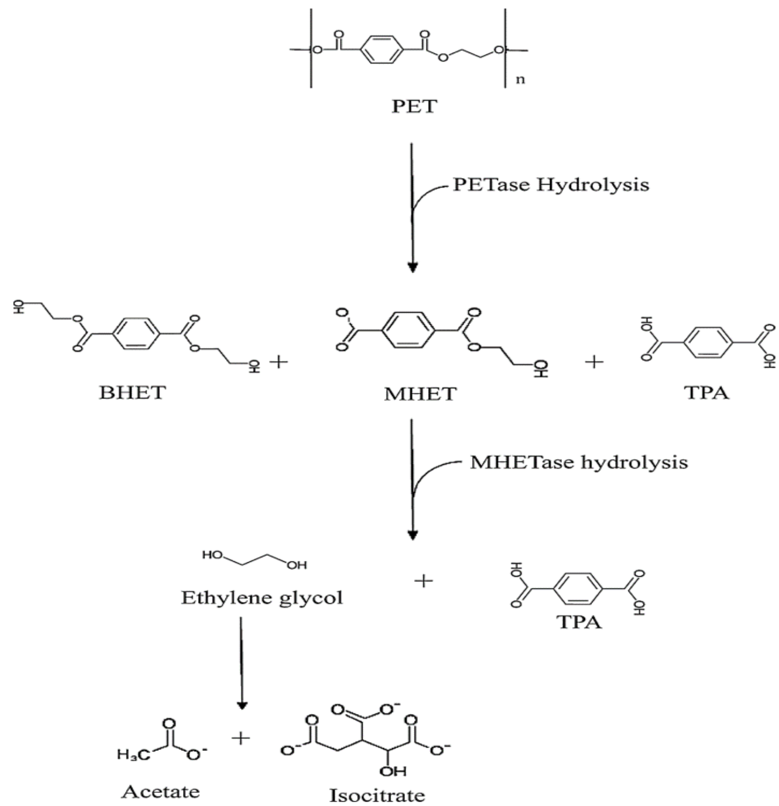


Figure 2: A diagram showing the enzymatic degradation of PET and MHET and the products of each process.

PP is a popular plastic widely used in the cosmetic industry due to its light weight and flexibility and durability which allows it to be used as a skin barrier in creams, lotions, and lip products. It is also a plastic that needs further research into degradation methods. While there have been some studies that have found species capable of degrading PP, particularly *Bacillus gottheilii*, there is a lack of further detailed studies identifying the specific enzymes involved in this process.[16,17]

PS is a potent aquatic toxin that, despite being less toxic to humans, has been found to have a negative impact on the reproduction of fish.[18] PS is an interesting case in that, there has been minimal research into new ways to be degraded. This is because there have been multiple species that have been found to already degrade and mineralize PS naturally. One example is *Achatina fulica*, a terrestrial snail, that can reduce and mineralize over 30% of ingested PS across a four-week study.[19]

Finally, PVC has been documented to have a potent toxicity with links to the liver, lung, and brain cancers.[20] Much like PP, PVC also lacks in-depth research into enzymatic degradation methods. However, a promising method in PVC degradation involves burying PVC films into soil inoculated with PVC degrading fungi, namely *Phanerochaete chrysosporium*. However, further method development needs to be explored for this process to be safe on a larger scale, as there are worries of PVC leachates with industrial-level implementation.[21]

Challenges and Future Directions

While microbial enzymatic degradation is a promising solution to microplastic pollution, there are multiple challenges that need to be addressed. First, based on the most recent findings, enzymatic degradation and microbial mineralization are effective methods for less robust plastics such as HDPE, LDPE, and PET. However, more resistant plastics such as PP and PVC need further research. This is likely due such physical properties as PP's hydrophobicity and lack of enzyme susceptible functional groups, and PVC's high chlorine content and related toxic byproducts. Much like the available research on PVC-degrading fungi, it is reasonable to believe that PP research would benefit from pivoting to a new degradation type.

For the future of microplastic degradation, there needs to be a greater system for stopping microplastic generation at the source. For example, in Essex County NJ, the only plastics that are picked up by municipal recycling are PETE, HDPE, and PP. Further public education is needed on the topic of plastics pollution, as well as proper recycling habits (e.g. the use of plastic resin identification codes), infrastructure development, and policy reform. In order to avoid these issues altogether, however, an overall pivot to more easily degraded bio-based plastics and non-plastic alternative materials is a must.

Conclusions

Overall, the issue of microplastic pollution is an ongoing challenge to manage for the purpose of maintaining our environmental and individual health. This review focused on many of the most common microplastics in our environment. Despite their different structures, the enzymatic reduction of these listed plastics should ideally follow similar processes of degradation and whole mineralization. Those which need further procedure development and research have been highlighted and noted as such. In conclusion, microbial degradation of plastics holds significant promise, and to fully hamper the toxic effects of microplastic pollution it is necessary that our society pursue not just technological research advancement, but also educational and policy advancement as well to ensure long-lasting environmental safety.

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