Enzymatic Degradation and Recycling of Polyethylene Terephthalate (PET): A Comprehensive Review

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Abstract: This research paper provides a comprehensive review of enzymatic degradation and recycling processes for Polyethylene Terephthalate (PET), a widely used synthetic polymer. The paper explores the types of plastic and specifically focuses on PET, highlighting its usage in various industries. The evaluation of current enzymatic degradation processes and the current situation of PET recycling are discussed in detail. Additionally, the paper presents a discussion on the emerging magnetic bead-based system for PET degradation. The findings contribute to the understanding of PET degradation and recycling techniques, with the aim of mitigating plastic pollution and promoting sustainable waste management practices.

I. INTRODUCTION

Plastic pollution is a pressing global environmental issue with detrimental consequences for ecosystems and human health. Among the vast array of plastics, Polyethylene Terephthalate (PET) has emerged as a major contributor to this crisis. PET, a durable thermoplastic, is extensively used in single-use beverage bottles, textiles, packaging materials, and consumer goods. However, its resistance to degradation has led to the accumulation of PET waste in landfills and oceans.

Enzymatic degradation utilises microbial enzymes to break down plastics and has gained significant attention as a promising approach to reduce the PET waste in landfills. The discovery of microbial enzymes that can naturally act on plastics in their environment offers potential for efficient and sustainable PET degradation. However, PET's complex molecular structure and non-hydrolysable covalent bonds make it resistant to degradation. Understanding PET's molecular composition and exploring novel enzymatic approaches are critical for effective degradation processes. Evaluating current recycling methods and exploring innovative systems, such as magnetic bead-based approaches, can enhance PET recycling efficiency.

It is vital to explore PET's molecular structure, applications, and evaluate current enzymatic degradation and recycling methods. By consolidating existing knowledge and analysing PET degradation and recycling practices, this research seeks to contribute to sustainable strategies for mitigating plastic pollution and promoting a circular economy.

II. TYPES OF PLASTIC

There are several types of plastic formed by polymer chains which are required for different applications. The structure and properties of these plastics help us to understand their use and enzyme degradation processes.

(1) High Density Polyethylene (HDPE): It is a heat-resistant plastic that is produced from petroleum with no phthalates or BPA present. Its structure ensures that it softens at 75°C and is resistant to chemicals and moisture. Moreover, its waxy surface and opaque nature make it easily identifiable.

(2) Polyvinyl Chloride (PVC): This material has the potential to cause severe environmental and public health risks such as

chronic bronchitis, birth defects and indigestion right from its initial production to its eventual usage. Softening at 80°C, it is considered to be tough and heat-resistant

(3) Low Density Polyethylene (LDPE): Commonly used as the packaging for milk and juices, this soft flexible polyethylene softens at 70°C. It is also heat resistant, fragile and rigid making it the perfect component for packaging purposes

(4) Polypropylene (PP): Used for food and beverage containers, it is a hard and translucent plastic softening at 140°C

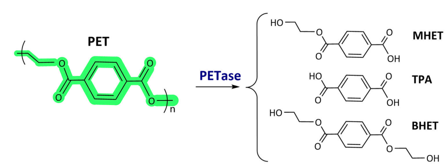
(5) Polystyrene (PS): Another petroleum based plastic containing benzene which has the potential to cause carcinogenic and cytogenetic effects on the body. It is a semi-tough, opaque plastic which softens at 95°C

(6) Polycarbonate (PC): A common application for this type of plastic is for packaging consumer goods such as reusable bottles. Containing BPA, it softens at around 150°C

These types of plastic have different structures from PET, the focus of this research paper which shows that the enzymatic degradation process will vary for different types and structures of plastic.

III. WHAT IS PET AND WHERE IS IT USED?

Polyethylene terephthalate (PET) is a highly durable and rigid synthetic polymer that finds extensive use in the production of single-use disposable beverage bottles. This thermoplastic material is created through the polymerisation of ethylene and terephthalic acid, resulting in the formation of ester linkages. PET has become a major contributor to the escalating plastic pollution crisis, primarily due to its widespread utilisation in products that are discarded after a single use, ultimately ending up in landfills and oceans.



In response to the urgent need for effective PET waste management, enzymatic degradation has emerged as a promising approach. Certain microbial enzymes have exhibited remarkable capabilities to act on plastic materials within their natural environment, offering a potential solution to the PET pollution dilemma. PET's molecular structure encompasses a subunit substrate known as diethylene glycol terephthalate, further contributing to its durability. A crucial criterion for assessing the effectiveness of microbial degradation is the decrease in molecular weight of PET monomers. This reduction in molecular weight indicates the breakdown of PET into smaller, more manageable compounds.

The enzymatic degradation of PET holds significant promise for combatting plastic pollution. It offers a pathway to transform PET waste into biodegradable compounds, reducing its environmental impact. Through continued exploration and innovation, enzymatic degradation of PET has the potential to revolutionise the field of plastic waste management, offering hope for a cleaner and greener future.

IV. EVALUATION OF CURRENT ENZYMATIC DEGRADATION PROCESSES

The number of enzymatic degradation processes has taken the world by surprise as scientists are developing new ways to degrade the drastic amounts of plastic that engulf our planet. The three most well-known types of degradation are mechanical degradation, chemical degradation, and biodegradation. Each of these methods has its own set of conditions, advantages, and disadvantages as continuous improvements are being made in these fields.

Mechanical degradation is simply the re-use of plastic products through the re-processing of thermoplastic polymers without altering their structure. It requires high temperatures but results in a fast rate of degradation. It is a cost-effective method, costing approximately 250 euros per ton, and is commonly used. However, it is considered to be environmentally hazardous, a possible source for infectious diseases, and possibly ineffective for multilayer-sensitive plastics.

Chemical degradation, on the other hand, involves plastic depolymerisation to monomers via hydrolysis and other similar methods. Once again, it requires high temperatures and produces a fast degradation rate. However, it is double the cost of the first method, at approximately 500 euros per ton. Chemical degradation has proven to be effective for PET degradation, but it is not a common method, is not environmentally friendly, and is limited to only condensed polymers.

Lastly, biodegradation is the conversion of plastic polymers into monomers through enzymes produced by microorganisms. While the degradation rate remains moderate, it is an environmentally friendly process, with only 63 euros required per ton of PET. Furthermore, the by-products of biodegradation can be used for various other applications. However, its drawback is that it is extremely time-consuming, and it is difficult to retain the enzymes that are vital for this degradation process.

In enzymatic degradation, mineralization of the monomers takes place, and the end products include CO2. One of the main gases produced as a byproduct is methane, which is a very important biogas that can be used as a fuel for producing light and heat, as well as an ingredient in the manufacturing of certain types of organic acids. Enzymes play a crucial role in biodegradation, as they act as biocatalysts that participate in the conversion of plastic polymers into valuable products.This highlights the potential of enzymatic degradation in breaking down plastic materials and facilitating their transformation into more environmentally friendly forms.

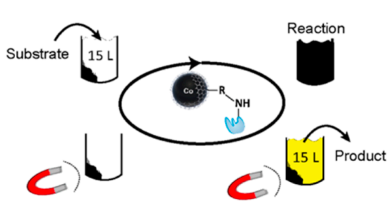
V. EVALUATION OF CURRENT SITUATION OF PET RECYCLING

The evaluation of the current situation of PET recycling reveals several key challenges that need to be addressed. The formation of lactic acid during the reaction process leads to a decrease in the pH of the reaction mixture. This acidic environment can cause the degradation of enzymes responsible for PET recycling. To overcome this obstacle, researchers have been exploring methods to manipulate the active site of these enzymes. By modifying the structure and functional groups of the active site through techniques like site-directed mutagenesis, the stability of plastic-degrading enzymes can be enhanced. Furthermore, the process of isolating microbial species that possess plastic-degrading enzymes needs to be standardised and made more efficient. By optimising the isolation process, researchers can accelerate the development and application of PET recycling technologies.

Additionally, it is important to acknowledge that plastic biodegradation is a slow process that is highly influenced by external factors such as temperature, pH, humidity, and ultraviolet rays. These factors can impact the efficiency of PET recycling methods. Therefore, it is crucial to consider environmental conditions when designing and implementing recycling processes. Developing strategies that can accommodate a wide range of temperature and pH conditions will be instrumental in improving the effectiveness of plastic degradation and promoting efficient PET recycling. Enhancing the stability of plastic-degrading enzymes, standardising the isolation process of microorganisms, and accounting for environmental factors are crucial steps towards improving PET recycling technologies.

VI. DISCUSSION OF MAGNETIC BEAD BASED SYSTEM

Magnetic bead systems have emerged as a promising approach for enhancing the efficacy of PET degradation through the immobilisation of PETases. These enzyme carriers exhibit crucial properties such as mechanical and chemical stability over a wide range of pH values. The immobilised enzyme-particle conjugates retain their activity and stability, enabling efficient recycling from millilitre to litre scales within short recycle times. The magnetic bead system is a proposal to recycle and reuse the PETase enzymes to make the crucial process of PET degradation more cost efficient.



The choice of carbon-coated metallic nanoparticles as a support for enzyme immobilisation proves to be practically advantageous. These nanoparticles possess a large surface area, high magnetic saturation, and manipulatable surface chemistry, making them ideal for PETase immobilisation. The magnetic-driven separation technique employed with these systems offers significant advantages over traditional methods such as cross-flow filtration and centrifugation. The magnetic nanoparticles, particularly those with stable core structures and high magnetic saturation, provide easy and fast separation, while also maintaining high dispersion and reactivity.

The immobilisation process involves covalently attaching the active PETase protein to the particle surface using diazonium and carbamate chemistry. This covalent binding minimises enzyme loss and ensures the retention of approximately 50% of the enzyme's original activity after washing away non-bound material. Moreover, the chemical functionalisation of carbon surfaces and protein coupling chemistry using activated carboxylic acids facilitate the immobilisation of enzymes on highly magnetic nano-supports.

Overall, the magnetic bead system for PETase immobilisation offers several advantages. It enables good storage stability, recyclability, and improved magnetic properties, allowing for the usage of magnetically immobilised enzymes in high volumes. The combination of magnetic separation technology with enzymatic degradation presents a promising approach for addressing the challenges associated with PET waste management. This advancement aligns with the rapidly growing field of chemical biocatalysis, benefiting from established magnetic separation techniques utilised in other applications, such as analytical immunoprecipitation and cell separation.

VII. CONCLUSION

The research highlighted the importance of understanding the different types of plastic, with PET being one of the most commonly used and versatile materials in various industries. PET is extensively utilised in the production of bottles, packaging materials, textiles, and more. However, the improper disposal of PET and the limited recycling infrastructure have led to significant environmental challenges. The evaluation of current enzymatic degradation processes demonstrated that enzymes hold great potential in breaking down PET and reducing its persistence in the environment. However, there are still challenges to overcome, such as optimising enzyme efficiency, scalability, and cost-effectiveness.

Furthermore, the assessment of the current situation of PET recycling highlighted the need for improved collection, sorting, and recycling infrastructure. While mechanical recycling processes have made significant progress, there are limitations in their ability to fully address the plastic waste crisis. The magnetic bead-based system discussed in the paper presents a novel and innovative approach to PET recycling. This system utilises magnetic nanoparticles to selectively capture and separate PET from mixed plastic waste, enabling more efficient sorting and recycling. Investment in research and development, policy initiatives, and public education campaigns are key components in achieving a more sustainable and circular plastic economy. In conclusion, addressing the plastic waste crisis requires a multifaceted approach that encompasses improved waste management practices, development of sustainable recycling technologies, and greater public awareness.

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