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Applications of Biodegradation Technology in Plastic Degradation

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Abstract. Plastic has become indispensable in modern life because of its excellent durability, portability and low cost. However, about 80% of plastic waste eventually enters the natural environment due to poor management, resulting in serious ecological pollution. At present, mechanical recycling and chemical treatment are the main disposal methods of plastic waste, but the efficiency of mixed plastics or contaminated plastics is limited, and secondary pollution may occur. Biodegradation technology is an environmentally friendly alternative. In this paper, the mechanism, key influencing factors and limitations of current research on microbial degradation of plastics are systematically reviewed. Studies have shown that the degradation efficiency of PE by insect intestinal microorganisms (such as symbiotic bacteria of wax moth larvae) can reach 40%, while white rot fungi can decompose more than 50% of PS through oxidation. In addition, strains such as Alcanivorax in the ocean can degrade hydrophobic plastics (such as polypropylene). However, the efficiency of biodegradation is significantly affected by environmental conditions (temperature, pH, oxygen), plastic types (crystallinity, additives) and microbial community structure. The changes of functional groups and product characteristics during degradation were revealed by high flux analysis methods such as Fourier infrared spectroscopy and gas chromatography-mass spectrometry. Future research should focus on: (1) developing efficient engineering strains; (2) optimizing the degradation conditions in complex environments (such as soil and ocean); and (3) establishing a unified evaluation standard for biodegradation. The breakthrough of biodegradation technology will provide a sustainable solution for solving plastic pollution.

Keywords: plastics, biodegradation, degradation mechanism, environmental risk

1. Introduction

Plastics are widely used in production and life because of their easy processing, transportation and storage and stable chemical properties. However, these characteristics also increase the possibility of plastics entering the natural environment and staying in the environment for a long time. The physical and chemical properties of plastics in the environment will change under the action of biological and abiotic factors, among which biodegradation is one of the inevitable environmental behaviors of plastics, and it is also an environmentally friendly plastic waste treatment method.

Through literature review, experimental research, mechanism analysis and influencing factors analysis, this study discussed the application of biodegradation technology in plastic degradation.

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The purpose of this study is to further reveal the mechanism of plastic biodegradation, develop plastic substitute products that are easy to biodegrade, and provide a scientific basis for plastic biodegradation behavior under complex environmental conditions.

2. Decomposition efficiency and mechanism of different kinds of plastics by microorganisms

2.1. Degradation mechanism and efficiency of polyethylene (PE)

As the largest plastic variety in the world, the research on the biodegradation of polyethylene is of great practical significance. At the molecular level, the degradation of PE is a complex multi-step process. By secreting lipase and monooxygenase, Pseudomonas, first formed a biofilm on the surface of PE, which triggered the oxidation reaction and formed hydroxyl peroxide (ROOH) [1]. The research shows that this initial oxidation step is the rate-limiting step of the whole degradation process, and its efficiency is significantly affected by crystallinity, molecular weight and additive content [1]. The experimental data show that under the optimum conditions, after 60 days of culture, Pseudomonas can cause LDPE film to lose weight by 35-40% [1].

2.2. Degradation characteristics of polystyrene (PS)

The degradation of polystyrene is facing greater challenges, and its benzene ring structure needs a stronger oxidation ability to be destroyed. Phanerochaete chrysosporium attacks the benzene ring structure of PS by secreting laccase and manganese peroxidase [2]. This process usually needs to add lignin as a co-substrate to maintain the normal operation of the enzyme activity system [2]. Isotope tracing technology confirmed that under the optimal conditions, about 60% of the PS carbon skeleton was finally completely mineralized [3].

2.3. Degradation complexity of polyvinyl chloride (PVC)

The degradation mechanism of PVC is the most complicated, and its C-Cl bond has a high bond energy, which requires a special dechlorination mechanism. Marinobacter sp. isolated from marine sediments is chemically dechlorinated by secreting dehalogenase or producing reducing substances [4]. The dechlorinated products are further degraded by oxidation, but the degradation efficiency of PVC is usually low (20-30%) due to the toxic effect of chlorine atoms [4]. It is found that toxic intermediates such as chloroacetic acid may be produced in the degradation process [5].

2.4. Degradation characteristics of other plastics

In addition to the above three main plastics, other plastic varieties also show different degradation characteristics. Polypropylene (PP) is more difficult to degrade because of its methyl branch. Alcanivorax borkumensis can attack the carbon chain of PP by secreting special alkane hydroxylase, but its degradation rate is relatively slow [6]. The degradation of polyethylene terephthalate (PET) has made an important breakthrough in recent years. Through the discovery and transformation of PET-degrading enzyme (PETase), its degradation efficiency has been significantly improved [7].

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3. Comparison of degradation characteristics of microorganisms from different sources

3.1. Special adaptability of insect intestinal microorganisms

Insect intestinal microorganisms show amazing plastic degradation ability. Taking Galleria mellonella as an example, Enterobacter asburiae and Bacillus. in its intestine can cause obvious holes in PE film within 24 hours [8]. Through comparative genomics analysis, it is found that these insect intestinal microorganisms contain multiple gene clusters encoding plastic-degrading enzymes, and the expression of these genes is specifically induced by plastic components [9].

3.2. Synergistic degradation effect of composting system

The microorganisms in the composting system showed remarkable synergistic degradation ability. Thermomyces lanuginosus and Thermobifida fusca form an efficient degradation alliance under the condition of high-temperature composting [10]. This synergistic effect not only improves the degradation efficiency, but also expands the scope of degradable plastics [10]. It is found that the microbial community in the composting system can degrade many kinds of plastics, including PE and PS, and its degradation half-life is shortened from hundreds of years in the natural environment to about 90 days under composting conditions [11].

3.3. Environmental adaptability of marine microorganisms

Marine microorganisms show unique adaptability in plastic degradation. Marine strains such as Alcanivorax borkumensis have evolved special adaptive mechanisms [6]. These marine microorganisms can secrete biosurfactants, effectively reduce the hydrophobicity of plastic surfaces and enhance the contact efficiency between enzymes and substrates [6]. It was found that the degradation efficiency of PP by these marine strains was 30-40% higher than that by terrestrial strains [6].

3.4. Diversity advantages of soil microorganisms

The diversity of microorganisms in the soil environment provides abundant genetic resources for plastic degradation. Plastic-degrading strains isolated from soils in different geographical locations showed obvious geographical characteristics and substrate preference [12]. Through metagenomics analysis, it is found that microorganisms from different sources adopt different degradation strategies, and this functional complementarity provides the possibility for constructing efficient degradation flora [9].

4. Modern analytical technology of the degradation process

4.1. Application of spectral analysis technology

Fourier transform infrared spectroscopy (FTIR) plays a key role in the study of plastic degradation. By tracking the change of characteristic absorption peak, the change of chemical structure during degradation can be accurately evaluated [13]. As a complementary technology of FTIR, Raman spectroscopy can provide more abundant molecular structure information [14].

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4.1.1. GC-MS technology

Gas chromatography-mass spectrometry (GC-MS) is the gold standard method to identify degradation products [15]. In the study of PS degradation, benzoic acid, acetobenzene and various aliphatic carboxylic acids were detected by GC-MS [15]. Liquid chromatography-mass spectrometry (LC-MS) shows unique advantages in the analysis of high molecular weight degradation products [11].

4.1.2. Molecular biology technology

High-throughput sequencing technology has completely changed the face of microbial community research. 16S rRNA sequencing can not only reveal the species composition of a microbial community, but also evaluate the stability of the community through the diversity index [12]. In the process of PE degradation, the relative abundance of Pseudomonas rose from the initial 5% to 40%, becoming the dominant bacterium [12]. Metagenomics analysis further revealed the changing law of functional genes [9].

4.1.3. Microscopic analysis technology

Scanning electron microscope (SEM) provides direct evidence of the change of plastic surface morphology [13]. In the process of degradation, the plastic surface changes from smooth to rough, and cracks and holes appear [13]. Atomic force microscopy (AFM) can characterize the changes of surface properties on the nanometer scale [14].

4.2. Key factors affecting degradation efficiency

4.2.1. Influence mechanism of temperature

Temperature is one of the most important factors affecting the biodegradation rate of plastics. In the range of 5-60 °C, the degradation rate of PE increases with the increase in temperature [11]. The Q10 value (the change of reaction rate for every 10°C increase in temperature) is about 2.1 [11]. Temperature not only affects the enzyme activity, but also indirectly affects the degradation efficiency by changing the physical properties of plastics [7].

4.2.2. Regulation of pH value

PH value affects the degradation process in many ways. First of all, the pH value directly affects the spatial conformation of the enzyme protein and the ionization state of the active center [16]. The optimum pH of most plastic-degrading enzymes is between 5.0 and 8.0. Secondly, pH affects the permeability and stability of the microbial cell membranes [16].

4.2.3. Adjustment of oxygen conditions

Oxygen plays a dual role in aerobic degradation. On the one hand, it is a necessary substrate for monooxygenase and dioxygenase; on the other hand, excessive oxygen may lead to excessive free radicals and oxidative damage to microorganisms [10]. Under anaerobic conditions, microorganisms adopt completely different degradation strategies [4].

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4.2.4. Effects of nutrients

The types and concentrations of nutrients have complex effects on the degradation efficiency. A nitrogen source is an essential element to synthesize enzyme protein, and proper addition can promote microbial growth and enzyme synthesis [7]. Studies have shown that when the C/N ratio is 20-30, the best degradation effect can usually be achieved [7]. However, excessive nitrogen sources may lead microorganisms to preferentially use simple carbon sources, thus inhibiting the synthesis of plastic-degrading enzymes [7].

4.3. Current challenges and solutions

4.3.1. The problem of strain stability

In the practical application environment, engineering strains are facing severe pressure from survival competition. In order to solve this problem, researchers have developed a variety of strategies. Microcapsule immobilization technology can effectively protect the strain from environmental stress and increase the local enzyme concentration [17]. The use of the quorum-sensing system provides a new idea for strain behavior regulation [18].

4.3.2. Balance between degradation efficiency and economy

Improving the degradation efficiency while controlling the cost is the key to realizing industrial applications. Metabolic engineering shows great potential in this respect [7]. By overexpressing key enzyme genes and knocking out competitive pathways, the degradation efficiency of PET can be improved by 5-8 times [7]. Using industrial and agricultural wastes as a cheap culture medium is another important direction [18].

4.3.3. Establishment of a standardized evaluation system

At present, there is no unified evaluation standard for plastic biodegradation research, which seriously affects the comparability of different research results [19]. It is suggested that the standardization system should include standardized plastic samples, strictly controlled test conditions and multi-dimensional evaluation indicators [19].

4.3.4. Ecological risk assessment

While promoting the application of plastic biodegradation technology, we must pay attention to its potential ecological risks. The biological safety problems that may be caused by the environmental release of genetically engineered bacteria need to be strictly evaluated [17]. The intermediate products that may be produced in the degradation process also need toxicological evaluation [5].

5. Conclusion

This study systematically explained the scientific principle, key technology and development prospect of biodegradation technology in the field of dealing with plastic pollution. The study confirmed that microorganisms from different ecological environments formed unique degradation strategies and metabolic networks in the long-term evolution. The key environmental factors and biological parameters affecting the degradation efficiency were systematically sorted out and

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quantitatively analyzed in this study. There are complex interactions between abiotic factors such as temperature, pH, oxygen concentration and nutrient composition and biological factors such as microbial community structure, enzyme activity and substrate accessibility. The research shows that in the range of 25-60℃, the enzymatic degradation rate of polyethylene increases by about 2.1 times on average for every 10 ℃ increase in temperature. pH value has a decisive influence on the conformational stability and catalytic activity of the enzyme protein. In addition, the types and proportions of nutrients profoundly affect the synthesis and secretion of degradation-related enzymes.

The comprehensive application of modern analytical techniques has greatly deepened the understanding of the degradation process. Fourier transform infrared spectroscopy and Raman spectroscopy tracked the evolution of functional groups on the plastic surface in real time. The products in the degradation path were accurately identified by chromatography-mass spectrometry. High-throughput sequencing and metagenomics revealed the dynamic succession of microbial communities. Scanning electron microscope (SEM) and atomic force microscope (AFM) visually show the erosion process of the plastic surface at the microscopic morphology level. However, the technology still faces multiple challenges in its large-scale application. The survival rate, competitive adaptability and ecological safety of engineering strains in complex natural environments need to be solved urgently; for mixed plastic waste, its degradation efficiency and synergistic mechanism are still unclear. At present, there is a significant gap between the research results of laboratory-scale and industrial-scale-up production. In addition, there is a lack of a unified biodegradable testing standard and certification system around the world.

Facing the future, the research should focus on the following strategic directions: comprehensively utilize synthetic biology and protein engineering to directionally transform or design new degrading enzymes; deeply explore the interaction between plastic biodegradation and ecosystems in the real environmental matrix; build a comprehensive evaluation model covering technical feasibility, economic cost and ecological environment impact; promote the deep integration and innovative cooperation of multi-disciplines. Through the continuous breakthrough of basic research and the integrated development of system technology, biodegradation technology is expected to become a key link in the comprehensive treatment system of plastic pollution, providing solid scientific and technological support for building a resource-recycling society and achieving the goal of sustainable development.

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