Dean&Francis

ISSN 2959-6157

Comparison of decomposition of different types of biodegradable plastics in the natural environment

Xinyi Dai[1, *],

Xinni Tan[2]

[1]Shanghai Qibao Dwight High School, Shanghai, China
[2]Songjiang No.1 High School, Shanghai, China
*Corresponding author: xydai_daisy@qibaodwight.org

Abstract:

In the current era, international environmental issues such as global warming are becoming increasingly severe, the carbon footprint needs to be decreased immediately, and humanity is constantly seeking sustainable development solutions. Biodegradable plastics have become a popular research topic in sustainable development. Biodegradable plastics are a type of environmentally friendly plastic that can be decomposed by natural microorganisms under specific environmental conditions and eventually transformed into harmless substances such as water and carbon dioxide. Is biodegradable plastic a perfect solution? What are their flaws? How can we optimize each of the material's flaws? What will its future development be like? This literature review focuses on different types of biodegradable plastics. We will analyzes and integrates the characteristics of various biodegradable plastic materials such as PLA, PBS, PBAT, and PHA, compares and evaluates them, as well as provide the optimization of each kind of degradable plastic with specific example. And ultimately form a comprehensive literature review on biodegradable plastics.

Keywords: Degradable plastics; degradable plastic; deposition rate.

1. Introduction

In the current era, the global plastic pollution crisis is intensifying: traditional plastics are difficult to degrade and have caused serious pollution to soil, fresh water and the ocean, drawing widespread attention from the public, policies and industries. On a global scale, the Sustainable Development Goals (SDGS 12, 14, 15, etc.) are driven by the United Nations Sustainable Development Goals, which call for reducing plastic waste and developing alternative materials. The rise of biodegradable plastics: PLA, PBS, PBAT, PHA and other biodegradable plastics are highly anticipated as new hopes to replace traditional plastics, and their market demand and output continue to grow.

However, the degradation rate depends on environmental conditions. Biodegradable plastics decompose rapidly in ideal environments (such as industrial composting), but their performance varies greatly in natural environments (such as seawater, soil, and freshwater), and may even show no significant difference from traditional plastics. In addition, there are various types of materials with significant performance differences. Different chemical structures such as PLA, PBAT, and PHA have essential distinctions in their degradation mechanisms and rates, making it difficult to generalize them in practical applications. The experimental data also lack comparability. Most studies only focus on a single material or a single environment, lacking systematic and standardized comparative experiments, which leads to a lack of scientific basis for policy and industrial choices.

2. Polylactic Acid (PLA)

PLA is a bio-based polymer material made from renewable resources such as corn starch and sugarcane, which is produced by fermenting lactic acid and then polymerizing it. Due to its biodegradability, renewability and good processing performance, it is widely used in packaging, fibers, 3D printing, medical and other fields.

2.1 Properties of PLA

First of all, PLA can be decomposed by microorganisms under industrial composting conditions (high temperature, high humidity, and aerobic environment) into carbon dioxide and water, and will not remain in the environment for a long time. Secondly, Using plants as raw materials can reduce dependence on petroleum resources and contribute to the carbon cycle [1].

PLA degrades slowly in natural environments (such as soil and seawater), and requires specific conditions of high temperature (about 58℃), high humidity and oxygen for efficient degradation. The degradation period in ordinary environments can last for several years [2]. What's more, the degradation products are safe but not beneficial to certain ecosystems

Although the main products of degradation are CO_2 and water, when the degradation is highly intensive, CO_2 is released instantaneously, which may have an impact on the local environment. For using PLA properly, the waste sorting and composting system needs to be improved.

If it fails to enter the professional composting system, PLA waste may still be mixed with ordinary garbage, making it difficult to achieve effective degradation [3].

2.2 Optimization of PLA

2.2.1 Blending modification

Blending modification involves mixing PLA with other high-molecular materials (such as PBAT, PCL, TPU, etc.) through physical methods to produce composite materials with superior properties. PLA itself has a relatively high brittleness and poor impact strength and ductility, which limits its application in packaging films, 3D printing, and other fields. By blending PLA with the more flexible PBAT (polybutylene adipate-co-terephthalate), the toughness of PLA can be significantly improved and its elongation at break can be enhanced. For example, after blending PLA with PBAT, not only does the softness and impact resistance of the material improve, but its degradation rate in a compost environment can also be accelerated. Additionally, the addition of elastomers like TPU (thermoplastic polyurethane) can also enhance the flexibility and wear resistance of PLA. During the blending process, the addition of compatibilizers (such as maleic anhydride grafting substances) can enhance the interfacial bonding force between the two phases, further optimizing the performance. This type of blending modification is simple and easy to implement and is suitable for industrialization [4].

2.2.2 Copolymerization modification

Copolymerization modification mainly involves introducing other monomers to copolymerize with lactic acid monomers, altering the molecular chain structure of PLA to regulate its properties. For instance, copolymerizing ε-caprolactone (CL) with lactic acid can yield PLLA-PCL copolymers, which possess both the biodegradability of PLA and the excellent flexibility of PCL. By adjusting the copolymerization ratio, the toughness, flexibility, and crystallinity of the material can be significantly enhanced, improving the brittleness and heat resistance of PLA. Moreover, copolymerization can lower the glass transition temperature (Tg) of PLA, making it more stable in low-temperature environments. Compared with physical blending, copolymerization can achieve a synergistic improvement in performance at the molecular level and has better compatibility, reducing the likelihood of phase separation. Copolymerization modification is suitable for high-end application fields with higher requirements for material performance, such as medical degradable devices and high-performance packaging materials [5].

3. Polybutylene Succinate (PBS)

Polybutylene succinate (PBS) is a biodegradable aliphatic polyester widely studied for its potential to replace conventional plastics in packaging, agriculture, and additive manufacturing. However, its degradation behavior varies significantly depending on environmental conditions, blend composition, and processing methods. This review synthesizes findings from recent research on PBS degradation, focusing on its performance in marine environ-

ISSN 2959-6157

ments, mechanical properties, and limitations.

3.1 Features of PBS

PBS exhibits high ductility with an elongation at break ranging from 460% to 1235%, along with a tensile strength of 5–40 MPa and a Young's modulus of 24–43 MPa [6]. Its thermal stability is another notable strength, with a melting point of ~115–130°C and a heat deflection temperature approaching 100°C, which can be further enhanced through modification to exceed 100°C, enabling its use in hot food packaging and beverage containers [7]. Additionally, PBS demonstrates superior processability, as it can be easily extruded, injection molded, or blow-molded using conventional plastic processing equipment, making it one of the most versatile biodegradable polymers for industrial applications. Its compatibility with fillers like starch and calcium carbonate allows for cost-effective production of composite materials.

A major drawback is its slow degradation rate in natural environments, particularly in marine and soil conditions, where it degrades less than 10% over 100 days due to low microbial activity and the persistence of crystalline aromatic segments [8]. While PBS achieves over 90% degradation in industrial composting (58°C) within 90 days, its performance in ambient environments is less impressive, often requiring 180 days for significant breakdown. The hydrophobicity and crystallinity of PBS further impede degradation, as water and enzymes primarily target amorphous regions, leaving crystalline segments intact and contributing to microplastic formation when molecular weight drops below 11,000 g/mol [9].

3.2 Corrective Actions

Efforts to mitigate these drawbacks include copolymerization with hydrophilic monomers (e.g., glycolic acid in PBSGA) to accelerate hydrolysis, blending with natural fibers (e.g., starch or PLA) to reduce costs and enhance biodegradability, and optimizing processing techniques like reactive extrusion to lower energy consumption. Despite these challenges, PBS remains a promising material due to its balance of strength, flexibility, and compostability, positioning it as a viable candidate for reducing reliance on non-biodegradable plastics in applications where mechanical durability and environmental sustainability are prioritized. Future advancements in copolymer design and industrial composting infrastructure could further enhance its viability as a mainstream biodegradable plastic.

4. Poly (butylene adipate-co-terephthalate) (PBAT)

PBAT is a copolyester synthesized via polycondensation of 1,4-butanediol (BDO), adipic acid (AA), and terephthalic acid (PTA). Its molecular structure combines aliphatic (BA) and aromatic (BT) segments, which govern its mechanical and degradation properties,providing high toughness, flexibility, and compostability [10]. PBAT is commonly used in packaging films, agricultural mulch films, and disposable products due to its mechanical properties comparable to traditional plastics like polyethylene (PE).

PBAT (polybutylene adipate terephthalate) is a biodegradable polyester that exhibits both significant advantages and notable limitations in its performance and environmental impact. The material's primary advantage lies in its excellent biodegradability, being 100% compostable under industrial composting conditions where specific microbial enzymes (lipases and cutinases from Thermobifida fusca and Aspergillus spp.) effectively break down its ester bonds, achieving 90% mineralization within 90 days at 58 °C and 60% humidity (ASTM D6400 compliant) [11]. However, this degradation efficiency significantly decreases in home composting (20-60 °C) due to reduced microbial diversity. PBAT demonstrates outstanding mechanical properties, combining high elongation (> 460%) from its flexible BA segments with considerable tensile strength (5-40 MPa) derived from rigid BT segments, while maintaining thermal stability with a decomposition temperature exceeding 375 °C. Its superior flexibility, evidenced by a low glass transition temperature ($T_g \approx -30$ °C), makes it more pliable than other biodegradable polymers like PLA or PBS, though blending with PLA can enhance rigidity at the expense of some flexibility.

The degradation of PBAT occurs extremely slowly in natural environments like soil and water bodies, severely limiting its effectiveness in combating marine plastic pollution. This slow degradation stems from the scarcity of specialized microbes capable of secreting the necessary esterases in temperate regions, with only geographically restricted species like the marine fungus Alternaria alternata FB1 producing effective PBAT-degrading enzymes [12]. Furthermore, the degradation process carries the risk of microplastic formation when PBAT's molecular weight drops below approximately 11,000 g/mol, creating persistent environmental hazards. These limitations highlight the need for further research and development to enhance PBAT's degradation efficiency in natural environments while maintaining its valuable mechanical and biodegradable properties [13].

5. Polyhydroxyalkanoates(PHA)

Polyhydroxyalkanoates (PHA) is a type of biodegradable polymer synthesized by microorganisms. It can be used as an environmentally friendly alternative to plastic and has excellent biocompatibility and degradability. It is widely applied in packaging, agriculture, and medical fields.

5.1 Properties of PHA

PHA can be decomposed by ubiquitous microorganisms in various natural environments (such as soil, fresh water, seawater and compost conditions), eventually turning into carbon dioxide and water. Compared with traditional petroleum-based plastics, PHA does not cause "microplastic" pollution and is more environmentally friendly. This characteristic makes it an ideal alternative to disposable plastics [14]. PHA itself is non-toxic, can be absorbed and metabolized by the body, and does not produce harmful metabolites. It has excellent biocompatibility. Therefore, PHA is widely used in the field of biomedical materials, such as tissue engineering scaffolds, sutures, and drug-controlled release carriers. In practical applications, PHA materials have been proven to be friendly to cells and without inflammatory reactions.

5.2 Optimization of PHA

The high production cost of PHA is a major obstacle for its commercialization. Researchers have overcome this by screening high-yield strains, using cheap or waste organic substances (such as agricultural waste, food processing wastewater, etc.) as carbon sources, optimizing nutrient and fermentation conditions, and increasing PHA production while reducing costs. Additionally, new processes such as continuous fermentation and combined fermentation have been developed. Using low-cost raw materials and efficient processes can reduce the costs of raw materials and energy consumption, thereby enhancing the economic and sustainable nature of PHA [15].

6. Research prospects

Even if the degradation rate of biodegradable plastics can be maximized, there are still some risks after their degradation. Firstly, the degraded plastic still poses health risks to the human body. The small molecules formed by the degradation of PLA are difficult to be directly excreted from the human body after entering it. They will be absorbed by intestinal microorganisms and participate in the metabolic process, which will have an impact on the body. In addition, the team led by Academician Wu Fengchang from the Chinese Research Academy of Environmental Sciences and Academician Wang Qi from Sichuan University jointly published their views in the journal Science, arguing that the weathering of degradable plastics releases a large amount of micro/nano plastics, toxic and harmful chemicals, etc. Environmental risks should be taken seriously, and corresponding policies need to be formulated urgently to address them. Biodegradable plastics are more prone to weathering in the environment, releasing a large number of diverse oligomers and complex chemical mixtures. These oligomers share common characteristics with persistent organic pollutants, raising concerns about potential hazards to ecosystems. Compared with larger solid plastic particles, oligomers have a higher bioavailability and pose a greater exposure risk to wild animals and humans.

To mitigate the potential risks brought about by the weathering of biodegradable plastics, it is necessary for the research community, industry and policymakers to act in concert to promote the development of a circular biodegradable plastic economy. Key strategies include: identifying the sources and degradation pathways of toxic biodegradable plastic-derived oligomers.

7. Conclusion

This comprehensive review examined the degradation behaviors and material properties of four major biodegradable plastics, PLA, PBS, PBAT,and PHA, highlighting their respective advantages, limitations, and environmental impacts. While all four materials demonstrate significant potential as sustainable alternatives to conventional plastics, their performance varies markedly across different environmental conditions.

PLA exhibits excellent biodegradability under industrial composting but degrades minimally in natural environments, raising concerns about its practical efficacy without proper waste management infrastructure. PBS shows superior mechanical properties and processability, yet its slow degradation in marine and soil environments poses challenges for widespread adoption. PBAT stands out for its exceptional flexibility and compostability, though its persistence in natural ecosystems and tendency to form microplastics during incomplete degradation remain critical issues requiring further research. PHA is a biodegradable and biocompatible polymer with great potential to replace conventional plastics, though reducing production costs through optimized processes and low-cost feedstocks remains essential for its broader commercialization. The comparative analysis reveals that each material presents a unique set of trade-offs between mechanical performance, degradation rates, and environmental safety. Notably, all the materials share common challenges, including the risk of microplastic formation and potential ecosystem impacts from degradation byproducts. These findings underscore the importance of developing standardized testing protocols to better evaluate biodegradable plastics across diverse environments and the urgent need for

ISSN 2959-6157

improved waste management systems to maximize their environmental benefits. Looking forward, researchers will require comprehensive efforts to ensure biodegradable plastics fulfill their promise as truly sustainable alternatives in the global fight against plastic pollution.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Auras, R. A., Lim, L.-T., Selke, S. E. M., & Tsuji, H. Poly(lactic acid): Synthesis, Structures, Properties, Processing, and Applications. John Wiley & Sons, 2011,1: 1.

[2] Balasooriya, W., Schrittesser, B., Pinter, G., Schwarz, T., & Conzatti, L. The Effect of the Surface Area of Carbon Black Grades on HNBR in Harsh Environments. Polymers, 2019, 11(1): 61.

[3] Haider, T. P., Völker, C., Kramm, J., Landfester, K., & Wurm, F. R. Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. Angewandte Chemie International Edition, 2019, 58(1): 50–62.

[4] Martí, M., Tuñón-Molina, A., Aachmann, F., Muramoto, Y., Noda, T., Takayama, K., & Serrano-Aroca, Á. Protective Face Mask Filter Capable of Inactivating SARS-CoV-2, and Methicillin-Resistant Staphylococcus aureus and Staphylococcus epidermidis. Polymers,2021, 13(2): 207.

[5] Sardinia. Sixteenth International Waste Management and Landfill Symposium. Waste Management, 2017, 61(1): 7-8.

[6] Qi, B. Wang, C.Sun, M. Yang, X. Chen, D.Zheng, W.Yao, Y. Chen, R. Cheng and Y. Zhang, Int. J. Mol. Sci., 2022, 23:6746.

[7] Alisa Sabalina,Sergejs Gaidukovs,Oskars Platnieks,et al.Environmental degradation and durability of bulk 3D-printed parts from biodegradable polyester blends of PBS, PLA, and PHB in seawater.Royal Society of Chemistry,2025,Advance Article,1:1Sabalina, O. Platnieks, G. Gaidukova, A. Aunins, T. V. Eiduks and S. Gaidukovs, RSC Adv., 2025, 15(1): 501–512

[8] Liu X, Wei W, Liu G, Zhu B, Cui J, Yin T. Effects of Conventional Non-Biodegradable Film-Derived Microplastics and New Biodegradable Film-Derived Microplastics on Soil Properties and Microorganisms after Entering Sub-Surface Soil. Agronomy. 2024, 14(4): 753.

[9] Sera, J.; Kadlečková, M.; Fayyazbakhsh, A.; Kučabová, V.; Koutný, M. Occurrence and Analysis of Thermophilic Poly(butylene adipate-co-terephthalate)-Degrading Microorganisms in Temperate Zone Soils. Int. J. Mol. Sci. 2020, 21: 7857.

[10] Wang, Yanning, Boyou Hou, Liping Huang, Bingjian Li, Shi Liu, Mingyang He, Qun Chen, and Jinchun Li. Study on Properties and Degradation Behavior of Poly (Adipic Acid/Butylene Terephthalate-Co-Glycolic Acid) Copolyester Synthesized by Quaternary Copolymerization, International Journal of Molecular Sciences, 2023, 24(7): 6451.

[11] Lingxiao Wang,Ruixue Chang,Zhiping Ren,et al.Mature compost promotes biodegradable plastic degradation and reduces greenhouse gas emission during food waste composting,Science of Total Environment, 2024,1: 1.

[12] Chin-San Wu,Characterization and biodegradability of polyester bioplastic-based green renewable composites from agricultural residues,Polymer Degradation and Stability,2012, 97(1): 64-71.

[13] Balasooriya, W., Schrittesser, B., Pinter, G., Schwarz, T., & Conzatti, L. The Effect of the Surface Area of Carbon Black Grades on HNBR in Harsh Environments. Polymers, 2019, 11(1): 61.

[14] Zhao, Xiaoli et al. Ecological risks of biodegradable plastics. Science, 2025, 388(6571): 1034.

[15] M. Wang et al., Nanomaterial innovations for environmental remediation, Nat. Nanotechnol. 2023,18: 403.