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The Development and Application of Biodegradable Plastics in Food Packaging

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Abstract

Food packaging plays a crucial role in maintaining food quality and facilitating the circulation of goods. However, the environmental pollution caused by traditional packaging materials, including plastics, paper, and metals, has garnered global attention. In response to this challenge, governments worldwide have begun to implement a series of environmental policies to encourage the development and adoption of eco-friendly alternatives, particularly biodegradable plastics. These materials can be decomposed by microorganisms in nature, significantly reducing the environmental burden. This paper delves into the current applications, development dynamics, and specific case studies and performance advantages of biodegradable plastics in the food packaging industry. Additionally, it looks toward the future, providing a forward-looking analysis of technological advancements and market trends, aiming to offer a strong reference and impetus for the widespread application and sustainable development trend of biodegradable plastics in food packaging.

Keywords: biodegradable plastics, bio-based polymers, fossil-based polymers, food packaging, sustainable development

1. Introduction

In modern society, food packaging is not only essential for ensuring food quality and safety but also serves as an important tool for facilitating commodity circulation and marketing. Despite their convenience, traditional packaging materials—including plastics, paper, and metals—have raised serious environmental concerns. The difficulty in degrading plastic packaging, in particular, has become a focal point of public and academic attention due to its long-term damage to ecosystems.

With the global rise in environmental awareness and the widespread promotion of sustainable development concepts, governments have started to promote the development and application of environmentally friendly materials through policy initiatives. For instance, China issued the "Opinions on Further Strengthening the Management of Plastic Pollution" in January 2020, commonly known as the "Plastic Restriction Order," which underscores the importance of limiting the use of plastic products and promoting eco-friendly alternatives such as biodegradable plastics. Additionally, a series of policy documents, including the "Twelfth Five-Year Plan," have emphasized the necessity of transitioning to a green, low-carbon, and circular economy to achieve sustainable socio-economic development.

Biodegradable plastics, as an emerging eco-friendly packaging solution, have gained increasing attention due to their ability to be decomposed by microorganisms in nature, thereby reducing environmental impact. These materials are categorized into various types based on their origin and degradation mechanisms, each with its unique properties and potential applications.

The aim of this paper is to explore the current application status and future development trends of biodegradable plastics in the food packaging sector. By analyzing specific case studies of using biodegradable plastics in food packaging, evaluating their performance, and discussing their potential advantages in enhancing packaging performance and reducing environmental impact, this paper seeks to provide new perspectives and impetus for research and practice in this field.

2. Development Status of the Biodegradable Plastics Market

2.1 Development in China

In 2023, the Chinese market for biodegradable materials is expected to reach RMB 23.072 billion, significantly showcasing the growth potential of biodegradable materials as an eco-friendly alternative. These materials are not only greener in origin but also greatly reduce environmental pollution with their degradation products, making them particularly crucial in the field of food packaging materials. Their application helps alleviate the environmental and food safety issues caused by traditional non-degradable materials. With the implementation of the "Opinions on Further Strengthening the Management of Plastic Pollution," commonly referred to as the "Plastic Restriction Order," and the introduction of the national standard for biodegradable plastics, the development of biodegradable materials in food packaging has taken an important step forward. Driven by national policies, the market size of degradable plastics in China reached RMB 18.9 billion in 2021, and it is expected that the market size will exceed RMB 50 billion by 2025, with the market demand continuing to grow. In 2021, the production capacity of biodegradable plastics in China was 670,000 tons, while the demand was about 910,000 tons, indicating a supply gap of approximately 250,000 tons in the market.

2.2 Development in Europe and America

With the growing global concern over traditional plastic pollution and its potential threat to human safety, biodegradable food packaging has become a hot topic of global attention. Many countries around the world have invested substantial resources in developing biodegradable plastics in hopes of replacing traditional plastic products. This effort has led to the rapid development of the biodegradable plastics product market. According to data from 2020, the global market for biodegradable plastics reached 1.45 million tons, with the Asia-Pacific region accounting for 810,000 tons, North America for 150,000 tons, and Europe for 410,000 tons. The main product types include PBS, PLA, starch-based materials, PBAT, and the less common PHA materials. The packaging industry, especially the food packaging sector, is the primary application area for biodegradable plastics, showing tremendous market potential. Particularly in Western Europe, thanks to strict legal regulations limiting or banning the use of traditional non-degradable plastics, biodegradable plastics have been rapidly promoted and developed. Although the development speed in North America and Asia-Pacific regions is not as fast as in Western Europe, the biodegradable plastics market in these regions is also growing rapidly. Supported by various governments' plastic ban and restriction policies, the demand for biodegradable plastics is experiencing explosive growth. By 2025, the global demand is expected to reach 3.9 million tons, with the Asia-Pacific region accounting for 2.74 million tons, North America for 250,000 tons, and Europe for 790,000 tons, with an expected annual compound growth rate of 21.9%. The product type structure is also expected to undergo significant changes, with the North American and European markets primarily focusing on PBS and PLA, while the Asia-Pacific market will be mainly dominated by PBAT, PBS, and PLA.

3. Applications of Biodegradable Plastics in Food Packaging

Biodegradable plastics, also hailed as "green ecological materials," are those that can be completely decomposed by microorganisms in the natural environment, ultimately transforming into substances harmless to the environment. Compared with traditional plastics, these materials demonstrate superior environmental performance and sustainability characteristics, marking an important step towards a green future.

The decomposition process of biodegradable plastics can be divided into three main stages, encompassing the diversity of materials, the complexity of structures, and various environmental conditions such as temperature. In the first stage, different types of microorganisms secrete hydrolases, attaching these enzymes to the surface of the material. Subsequently, in the second stage, these hydrolases facilitate the transformation of biodegradable plastics into low-molecular-weight compounds through hydrolysis and oxidation processes. Finally, in the third stage, microorganisms absorb these small molecular compounds and convert them into carbon dioxide and water through their metabolic process, completing the entire degradation process.

Biodegradable plastics are classified into two major categories based on their raw material sources: bio-based and fossil-based biodegradable plastics. Each type of biodegradable plastic has its unique application scenarios and environmental value, providing effective solutions to reduce the environmental burden of traditional plastics. A specific classification is shown in Figure 1.

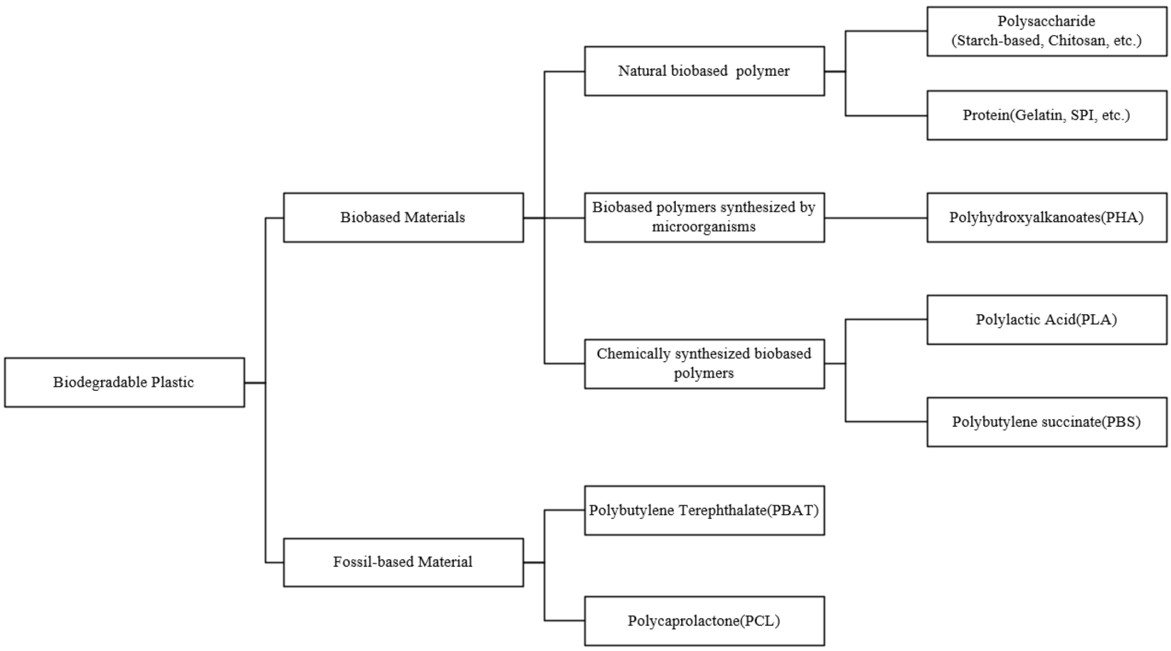

Figure 1. Classification of Biodegradable Plastics

3.1 Bio-based Biodegradable Plastics

Bio-based polymers can be categorized into naturally derived bio-based polymers, microbially synthesized bio-based polymers, and chemically synthesized bio-based polymers. This section will introduce the characteristics of bio-based polymers and their applications in food packaging.

3.1.1 Naturally Derived Bio-based Polymers

(1) Starch-based materials, derived from natural renewable high molecular polymers, are relatively easy to obtain. Films made from starch exhibit excellent transparency and gas barrier properties, effectively inhibiting food spoilage and extending shelf life. Starch films, known for their exceptional biodegradability, have become widely used and produced globally as biodegradable films, offering broad application prospects in the field of food packaging. However, starch films have some limitations in mechanical performance and are sensitive to water, which somewhat restricts their direct application in food packaging. To overcome these drawbacks, starch films are often modified to enhance their performance and meet diverse packaging needs. Baek and others successfully created a novel antioxidant film by combining cowpea starch with maqui berry extract (MBE) through solution casting. The cowpea starch film containing 20% MBE significantly slowed down lipid oxidation in salmon samples at 4℃, demonstrating the great potential of antioxidant packaging materials. Furthermore, with the advancement of intelligent packaging technology, starch-based smart food packaging capable of monitoring the freshness of aquatic products has been developed, offering consumers visual indicators. Zhang et al. developed a new pH-sensitive film based on cornstarch, PVA, and food-grade anthocyanins. This film can monitor a wide range of pH levels through the color change reaction of anthocyanins and shows a clear color change during the spoilage process of shrimp, providing an intuitive and convenient means for food safety monitoring.

(2) Chitosan, also known as deacetylated chitin or soluble chitosan, is the only naturally occurring alkaline amino polysaccharide discovered in nature. With its antibacterial, preservative, film-forming, and biodegradable advantages, chitosan has gained widespread attention in the food packaging sector. Chitosan, free from toxic substances and naturally degradable, is a new type of renewable and degradable eco-friendly material. Its role in food packaging mainly relies on its antibacterial and film-forming properties. Its antibacterial ability helps extend the shelf life of food, while its excellent film-forming property effectively blocks external factors, maintaining the freshness of food. However, chitosan also has some disadvantages, such as potentially less-than-ideal mechanical properties, which can be improved by compositing with other materials. Additionally, the relatively high cost of chitosan may limit its application in certain areas. Nonetheless, chitosan can be combined with monoglycerides, methylcellulose, etc., to prepare composite coating materials successfully

applied to cucumber preservation packaging. Furthermore, a composite film prepared by mixing chitosan with xanthan gum showed excellent performance in fresh pork preservation. Luo Aiguo and others prepared a composite film using phycocyanin and chitosan, studying the effects of phycocyanin addition on the physicochemical properties, mechanical performance, and antibacterial properties of the composite film, concluding that chitosan films with an appropriate addition of phycocyanin hold great potential as food preservation materials. Chen Lizhu and others extracted glucomannan from konjac tubers, developing various fully degradable films, such as single glucomannan films and konjac glucomannan oligosaccharide blend films.

(3) Protein-based polymers, formed by amino acids linked by peptide bonds, exhibit unique enzyme-degradable characteristics. Protein-based materials can hardly degrade spontaneously (non-enzymatically) in natural environments but can undergo enzymatic degradation through proteases or peptidases. Common protein-based materials are categorized into animal proteins and plant proteins based on their sources.

Gelatin, an animal protein, is a degradation product of collagen in animal connective tissues obtained through acid, alkali, sal-alkali methods, or under heating conditions. Due to its lack of a fixed structure and relative molecular weight, gelatin can transition from a gel to a solution as the temperature increases. Pereira and others incorporated nanoZnO and glycerol as reinforcement and plasticizer, respectively, into gelatin, maintaining the stability of the gelatin-based composite film under different relative humidity environments. When the mass fraction of nanoZnO reached 4%, it significantly enhanced the hydrophobicity of gelatin, establishing covalent and non-covalent interactions with gelatin, thereby significantly increasing the film's contact angle by 7.5%, making this composite film suitable as a humidity indicator.

Soybean Protein Isolate (SPI), a plant protein, contains rich amino acids with a protein content higher than 90%, providing excellent film-forming capability due to its high protein content, making it a renewable, easily degradable, and structurally stable protein. The presence of amino acids in SPI structure makes it prone to moisture absorption and bacterial growth, which can be mitigated by modifying SPI, adding antioxidants, and antimicrobial agents to prepare composite films to enhance performance. Guo Kuan and others used soybean protein isolate as the base material, adding beeswax and glycerin to prepare a new type of bio preservation film. When the addition amounts of beeswax and glycerin were 6% and 40%, respectively, the soy protein film exhibited the most ideal comprehensive performance, reducing the water vapor transmission rate by about 28.9% and increasing the tensile strength by 54.7%, effectively extending the preservation time of cut watermelon and maintaining the lycopene content of tomatoes.

3.1.2 Microbially Synthesized Bio-based Polymers

Polyhydroxyalkanoates (PHA) are a type of biodegradable polymer synthesized through microbial fermentation engineering technology. This material possesses excellent processability, with its molecular structure being diverse, enabling a variety of material properties based on different structural compositions to meet application needs across various fields. In the realm of food packaging, PHA can be degraded by extracellular depolymerase enzymes secreted by microorganisms under natural conditions, ultimately breaking down into carbon dioxide, water (under aerobic conditions), and methane (under anaerobic conditions), thus ensuring its environmental friendliness. Additionally, polyhydroxyalkanoates, whether existing alone or mixed with other substances, can be processed into films with good characteristics, especially in terms of antibacterial properties. Xu and others have developed a PHA nanocomposite film by blending PHA with long-chain alkyl quaternary ammonium salt-functionalized graphene oxide, which exhibited excellent antibacterial activity against both Gram-positive and Gram-negative bacteria. This PHA nanocomposite film also possesses good hydrophobicity and oxygen barrier properties, making it promising for widespread application in agriculture and food sectors.

3.1.3 Chemically Synthesized Bio-based Polymers

Polylactic Acid (PLA) is a biodegradable polyester synthesized from lactic acid polymerization. As a thermoplastic aliphatic polyester, PLA exhibits excellent biocompatibility and biodegradability. PLA films have high transparency and are easy to process, making them the second most used material for food packaging after starch-based films. However, due to the rigidity of PLA molecular chains, products obtained through conventional molding processes have low crystallinity, resulting in poor heat resistance. Nonetheless, PLA's heat resistance can be improved through chemical copolymerization, cross-linking modifications, blending with high heat-resistant polymers, and thermal treatment. Aldas and others used gum rosin (GR) as a plasticizer for blending PLA with poly(butylene adipate-co-terephthalate) (PBAT), finding that the addition of GR improved the processability of PLA. The resulting composite films showed significant enhancements in heat resistance, ductility, and barrier properties, indicating that PLA/PBAT/GR composite films could effectively replace traditional petroleum-based films in food packaging applications.

Polybutylene succinate (PBS) is an aliphatic polyester synthesized through polycondensation of succinic acid and 1,4-butanediol, known for its good heat resistance and flexibility but lower tensile strength and modulus, making it a crystalline thermoplastic polymer. PBS is white or off-white, odorless, and tasteless, and can be degraded and utilized by microorganisms in the environment, representing a new type of biodegradable polymer material. PBS is applied in packaging, drug delivery, disposable tableware, and biomaterials. MOE and others, using PBS as the base material and adding 1% lignin nanoparticle (LNPS), discovered it effectively inhibited the growth of Aspergillus niger and Penicillium, the main microorganisms causing bread mold. Additionally, the PBS/LNPS composite material, while not affecting the tensile properties of PBS, showed improved barrier performance and water contact angle, offering significant application potential in the food packaging sector.

3.2 Fossil-based Biodegradable Plastics

3.2.1 Polybutylene Terephthalate

Polybutylene Terephthalate (PBAT) is a type of biodegradable plastic that has been developed as an aromatic copolymer material. Its molecular chains have benzene rings on both sides, contributing to good mechanical properties and strong impact resistance. Additionally, PBAT offers good toughness, thermal stability, and breathability. PBAT is easy to process and suitable for various thermoplastic molding processes. Its primary application is in film products, mainly used for packaging fruits, vegetables, and frozen foods. Blending PBAT with Poly-L-lactic acid (PLLA) can modify PBAT to enhance its carbon dioxide permeability while maintaining oxygen permeability, serving to preserve fruits and vegetables. This improvement meets the needs for long-distance transportation of strawberries, avoiding the issues of high transportation costs and susceptibility to spoilage. Furthermore, a spontaneously modified atmosphere packaging bag made from a blend of PBAT and PLC in a certain ratio can adjust to a low oxygen and certain carbon dioxide concentration environment, which helps in storing mushrooms and extending their shelf life.

3.2.2 Adverse Events

Polycaprolactone (PCL) is a fully biodegradable semi-crystalline aliphatic polyester. Besides the easy processing characteristic of thermoplastic plastics, PCL also possesses good biocompatibility, rapid biodegradability, and excellent permeability. Moreover, PCL has excellent water resistance, oil resistance, and solvent resistance. Currently, PCL exhibits excellent antibacterial properties in the field of food packaging. Khalid and others prepared a composite film by blending PCL with pomegranate peel (PR) and starch, which showed good antibacterial properties, and the starch component in the composite film improved the rigidity of PCL. Ma Xiaofang and others used PCL as a matrix, modifying it by adding different ratios of PBAT. The composite films prepared in different ratios (PCL/PBAT(10%), PCL/PBAT(20%), and PCL/PBAT(35%)) were tested for mechanical properties, gas permeability, CO2/O2 selectivity ratio, and water vapor permeability. The PCL/PBAT(35%) blend film, which exhibited the best comprehensive packaging performance, was selected for post-harvest storage and preservation of Kyoho grapes.

4. Conclusion

In recent years, environmental pollution issues, particularly those caused by discarded packaging materials, have become a global challenge, which has spurred the rapid development of biodegradable plastics in the food packaging sector. Biodegradable plastics hold immense potential for application due to their ability to significantly reduce environmental burden and conserve resources. This article reviews the core characteristics and development trends of biodegradable plastics: for example, naturally derived bio-based polymers such as starch-based materials and polylactic acid (PLA) not only demonstrate excellent biodegradability but also possess outstanding performance characteristics; through modification processes, the performance of bio-based polymers has been significantly enhanced, meeting diverse packaging needs; furthermore, the exploration and application of composite materials have opened new possibilities for biodegradable plastics, such as the development of packaging materials with antioxidant functions, providing more options for food packaging.

Despite the progress made in the application of biodegradable plastics in food packaging, several challenges remain, such as the stability of material performance, improvements in modification, and synthesis techniques. Future research directions should include: first, in-depth investigation and optimization of the performance of biodegradable materials to ensure they meet the stringent standards of food packaging; second, the development of novel biodegradable materials and composite materials to enhance the functionality and application range of packaging materials; and third, the enhancement of research on the recycling and resource utilization technologies of biodegradable plastics, promoting their sustainable development in the food packaging sector. Through continuous technological innovation and research, biodegradable plastics are expected to find broader application in the field of food packaging, contributing to solving environmental issues and pushing the packaging industry towards a more green and sustainable direction.

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