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Research on the Modification and Application of Biodegradable Polylactic Acid Materials

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Abstract. Polylactic acid (PLA), a biodegradable polymer derived from renewable plant resources like corn and sugarcane, exhibits significant environmental benefits compared to petroleum-based plastics, as it degrades into carbon dioxide and water in natural environments, aiding in addressing "white pollution" and supporting "carbon neutrality" and "sustainable development" goals. Currently, PLA is applied in disposable tableware, packaging films, and medical supplies such as absorbable sutures and drug sustained-release carriers. However, its poor mechanical properties, and inadequate barrier properties restrict wider use. To enhance its performance, modification technologies are employed, such as blending with polymers to improve toughness, filling with inorganic fillers or natural fibers to boost mechanical strength and heat resistance; and chemical modification to enhance flexibility and heat resistance. Modified PLA has expanded applications, including composite materials for automotive parts and insulation boards, functional paper coatings for food/express packaging, agricultural mulch films with adjustable degradation rates, and medical materials matching bone mechanical properties. Future research should focus on economical modification methods, industrial-scale production technologies, and functional systems to improve competitiveness and expand application scenarios.

Keywords: Polylactic acid, modified technique, degradable material

1. Introduction

Polylactic acid (PLA) is a new type of biodegradable polymer material produced from renewable plant resources such as corn and sugar cane. It is manufactured through processes such as fermentation and polymerization. Compared to petroleum-based plastics, PLA has remarkable environmental benefits, decomposing into carbon dioxide and water in natural environments (such as soil and compost) to eliminate "white pollution". The PLA raw material is based on plants rather than petroleum, which to some extent reduces the consumption of fossil energy. As a new type of biodegradable material, it is also more conducive to achieving strategic goals such as "carbon neutrality" and "sustainable development".

Nowadays, PLA has been applied in many industries: for example, disposable tableware (such as lunch boxes and water bottles), PLA can effectively alleviate the environmental pollution caused by non-degradable disposable tableware; in addition, PLA films can be used for packaging of food and cosmetics, compared to traditional plastic materials, PLA itself can degrade, thus not generating

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excessive packaging waste and increasing the burden of environmental pollution; moreover, in the medical field, it is a major application area, such as making absorbable sutures, which not only helps with the recovery of human body wounds but also solves the problem of removing sutures during secondary surgeries, and PLA can also be used as medical supplies such as drug sustained-release carriers.

However, the shortcomings of PLA often limit its wider application. On the one hand, due to the relatively rigid PLA molecular chains, the material is brittle, with an impact strength of about 2-3 kJ/m^2, only about 1/10 of that of traditional polyethylene (PE) materials at 20-30 kJ/m^2 [1]. When subjected to external forces or bent, it is prone to cracking and cannot meet the requirements for materials with toughness (such as load-bearing packaging). And because it is an unbiodegradable material, it is difficult to handle in natural environments. On the other hand, its heat resistance is also poor, with a glass transition temperature of approximately 60-65 ℃, and its melting temperature is even higher, around 170-180 ℃. This results in PLA being unable to withstand items with high heat (such as not being suitable for holding hot dishes or beverages); moreover, PLA has poor barrier properties, with a high water and oxygen permeability rate. As a food packaging material, it can cause the contents to get damp and oxidized, shortening the shelf life.

Therefore, improving the comprehensive performance of PLA through modification technology and expanding its application fields to replace traditional non-degradable plastics, thereby benefiting the environment, is one of the very important research directions in current development.

2. Deficiencies in PLA

The limitations of PLA's properties mainly lie in the following three aspects.

2.1. Mechanical properties

There are a large number of ester bonds in the molecular structure of PLA, and the intermolecular forces are small, so the material is very brittle, with an impact strength of about 2-3 kJ/m^2, only about 1/10 of that of traditional polyethylene (PE) materials at 20-30 kJ/m^2. When subjected to external forces or bent, it is prone to cracking and cannot meet the requirements for materials with toughness (such as load-bearing packaging). The plastic bags made of PLA are prone to being crushed when a heavy object is placed on them; or in a cold environment (especially when frozen), PLA will lose its toughness and cannot be used as traditional PE plastic bags.

2.2. Heat resistance

Compared with PA, the heat deformation temperature of PLA is slightly lower, approximately 50-60 ℃. When the temperature is higher than 60 ℃, it will soften or deform. Therefore, it cannot be used in situations requiring high-temperature tolerance, such as PLA lunch boxes being used to hold hot soup, which can cause the lunch box to deform and leak; nor can it be applied to car interiors, especially in hot summer days, when the temperature inside the car can reach above 70 ℃.

2.3. Barrier properties

The molecular chains of PLA have relatively low polarity, low crystallinity, and poor permeability to water vapor and oxygen. Data shows that the water vapor permeability of PLA films is approximately 10-20 g/(m2·24h), and the oxygen permeability is around 1000-2000 cm3/(m2·24h·0.1MPa), which is many times higher than that of PVA and other barrier materials.

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This will cause the food inside the packaging, such as bread and fruits, to get damp and oxidized, leading to food spoilage or quality problems. The shelf life of PLA food packaging is reduced by 30%-50% compared to traditional barrier packaging.

3. Modification of PLA

3.1. Blending modification

Blending modification involves mixing PLA with other high-molecular materials in a certain ratio to improve PLA's performance through interfacial action. This method mainly relies on the complementary advantages of different materials, which is the key point of blending modification. For example, blending PLA with polybutylene succinate - terephthalate (PBAT) results in a material with strong flexibility (breakdown elongation rate reaching 500% - 600%), significantly improving the impact resistance of the blend. When PBAT accounts for 30% of the mixture, the impact strength of the blended material can reach 15 - 20 kJ/m^2 [2]. Another example is blending PLA with starch. Starch is abundant, inexpensive, and easily degradable, with relatively lower prices. However, it requires the addition of a compatibilizer (such as maleic anhydride grafting), to enhance the compatibility between the two materials. Without good interfacial bonding, it will cause a decrease in strength due to uneven intermolecular tension between the materials.

3.2. Blending modification

Reinforcement modification involves adding inorganic fillers (nanoparticles, fibers, etc.) to the PLA matrix to improve the performance of the modification. Commonly used nano-fillers include nano calcium carbonate and nano montmorillonite. Due to their large specific surface area, nanoparticles can strongly interact with the PLA molecular chains, and when the addition amount is 5% - 10%, the tensile strength can be increased by 10% - 20%. The layered structure of nano montmorillonite can prevent heat transfer and hinder molecular chain movement, increasing the material's heat distortion temperature by 5 - 10 °C, significantly improving the material's heat resistance [3]. In addition, natural fibers (such as bamboo fibers, hemp fibers) can also be used as fillers, increasing mechanical properties on one hand and improving the material's biodegradability on the other.

3.3. Chemical modification

Chemical modification of PLA can further enhance its performance, mainly achieved through copolymerization and crosslinking methods. That is, PLA monomers react with flexible monomers (such as isobutylene lactone, ethylene glycol, etc.) to introduce flexible chain segments, thereby reducing the rigidity of the molecular chains; or using radiation or chemical crosslinking agents (peroxides) to cause crosslinking reactions between PLA molecular chains to form a three-dimensional network structure, enhancing intermolecular forces. For example: when PLA is copolymerized with PCL, the material's fracture elongation rate can increase from the original 3% - 5% to 50% - 100%, significantly improving its toughness; while crosslinking PLA molecular chains through radiation or chemical crosslinking agents can result in PLA polymers with a 10 - 15 °C increase in high-temperature resistance and significantly enhanced solvent resistance [4].

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4. Applications of modified polylactic acid

The improved performance of modified PLA has significantly expanded its application fields, mainly reflected in the following aspects:

4.1. Composite materials field modified

PLA can replace part of petroleum-based materials in composite materials as structural materials for manufacturing various components. After blending PLA with glass fibers and undergoing modification, it can achieve an tensile strength of 80-100 MPa and a heat deformation temperature of over 100°C. As a material for making door lining sheets and instrument panels, it can reduce the weight of vehicles by 10-15% compared to traditional polypropylene (PP) composite materials, and can be degraded after disposal, without causing environmental pollution [5]. When PLA is combined with basalt fibers and processed by blending to make insulation boards, it can have high mechanical strength and good insulation performance. Moreover, it does not release toxic gases during combustion and has a better safety factor compared to traditional polyurethane insulation materials.

4.2. Functional paper field

Because modified PLA can significantly improve the barrier properties of films, it becomes an ideal coating material for functional papers. By blending PLA with EVOH and coating it on paper substrates, the water vapor permeability of the paper can be reduced to 1-2 g/(m²·24h), and the oxygen permeability is less than 100 cm³/(m²·24h·0.1MPa), which is suitable for packaging of oily foods such as hamburgers and fried chicken, preventing oil leakage and food spoilage [6]. The modified PLA-coated paper used in the field of express delivery packaging not only has good tear resistance and water resistance, but also can replace the non-degradable plastic packaging paper commonly used in the express delivery industry, helping to reduce "white pollution".

4.3. Other applications

In the agricultural field, modified PLA-made plastic films can adjust the degradation rate of the film according to the growth cycle of different crops (6-12 months), and can degrade by themselves after the crops are harvested, without causing soil compaction and fertility decline due to the residue of the film [7]. In the medical field, PLA mixed with hydroxyapatite (HA) through modification can be prepared to have mechanical properties similar to human bones (with an compressive strength of 80-100 MPa), and can gradually degrade into harmless substances in the human body, without the need for a second surgery to remove it, thus bringing more convenience to patients [8].

5. Conclusion

Polylactic acid can effectively improve its mechanical properties, heat resistance, and barrier properties through methods such as blending, filling, and chemical modification, thus breaking through its own limitations. These improvements are crucial: better mechanical properties enhance durability, heat resistance expands its use in high-temperature environments, and superior barrier properties make it more suitable for packaging applications.

The modified polylactic acid can be applied in composite materials, functional paper, agriculture, and medicine, etc. For example, in agriculture, it can be made into biodegradable mulch films that reduce soil pollution; in medicine, it serves as absorbable sutures that eliminate the need for

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removal. As such, it can be used as an alternative to petroleum-based plastics in various fields, ultimately reducing environmental pollution problems caused by non-degradable plastics.

In the future, the modification of polylactic acid should focus on the following aspects: First, explore economically feasible modification methods. For instance, developing continuous production processes for melt blending can lower energy consumption and improve efficiency, while applying industrial waste residues as cheap fillers—abundant in supply and low in processing cost—not only reduces the material cost of polylactic acid but also alleviates waste disposal pressure, thereby improving the market competitiveness of polylactic acid products. Second, develop simple and rapid industrial production technology routes. This involves optimizing production processes to solve issues like low efficiency and unstable quality, enabling polylactic acid materials to move smoothly from the laboratory to industrial-scale mass production. Third, develop modified polylactic acid material systems with various functions, such as combining antibacterial and flame-retardant functions. Antibacterial properties suit food packaging to extend shelf life, while flame retardancy fits electronic casings for safety, expanding application scenarios and ensuring polylactic acid achieves its environmental benefits throughout its entire life cycle.

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