WEP Warwick Evans Publishing

International Journal of Materials Science and Technology Studies
ISSN: 3006-7693 (Print), ISSN: 3006-3744 (Online) | Volume 2, Number 3, Year 2024
DOI: https://doi.org/10.62051/ijmsts.v2n3.05
Journal homepage: https://wepub.org/index.php/IJMSTS/index

Application and Performance Analysis of PLA in Food Packaging Materials: A Mini-Review

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ABSTRACT

Compared with traditional petroleum plastics (such as polyethylene, polypropylene and polystyrene) extracted from corn starch (PLA), it has significant advantages, especially in terms of strength, moisture -proof and biodegradability. Essence Due to its excellent performance, polymapilic acid has been commercialized in the field of textiles and packaging. This review aims to explain the difference between the performance of biodegradable packaging and traditional petroleum base materials in the application of biochemical packaging packaging and traditional petroleum base materials, and conduct critical analysis. The performance of breathability and antibacterial ability focused on the modification of polymapilic acid for food preservation packaging. Overall, polystrackic acid as a promising sustainable food packaging substitute has a biochemical and degradable environmental friendship, but it is necessary to further study to solve its production cost and performance restrictions. This article will take polystrackic acid (PLA) as an example to explain the performance advantages of biodegradable packaging and application and future development.

KEYWORDS

Polylactic Acid (PLA); Food Preservation Packaging; Biodegradability; Antibacterial Ability; Modification; Sustainability

1. INTRODUCTION

Plastics are widely used in food packaging, because the production cost of plastic itself is low and used for food packaging for a long time. However, the impact of plastic packaging itself has a great impact on the environment. The number of disposable plastic packaging wastes in the world is large, and there is a significant upward trend [1-2]. In order to build an environmentally friendly society, after the popularization of plastic, biodegradable materials are widely used worldwide to solve the problem of white pollution, that is, packaging materials can be under the conditions of appropriate natural environment. It is completely transformed into a low molecular compound to effectively reduce the pressure of plastic on the environment, which is of great significance in the context of calling for sustainable development. Data from plastic pollution show that among the 400 million tons of plastic products produced in the world, 2/3 is a one -time plastic with a short life. The abandoned plastics flowing into lakes, rivers and oceans up to 19 million-23 million tons/year. The impact of plastic pollution in the ocean on the ecosystem is huge. 88%of the research marine species are negatively affected by plastic. By 2040, the amount of plastic pollution flowing into the ocean will increase by nearly three times, an increase of 237 million tons per year. On May 31, 2021, the European Commission announced a guiding document -the final version of the "One -time Plastic Product Guide" to execute the EU instructions No. 2019/904 (SUP instruction) on the EU, and the instructions. It took effect on July 3, 2021. As mentioned in the instructions, the design and intention of the product must be used multiple times to strengthen the use of plastic. In the context of calling for sustainable development, it is crucial to choose and improve the degradable materials used to make packaging bags. This article will take polylactic acid (PLA) as an example to explain the application and development of biodegradable packaging.

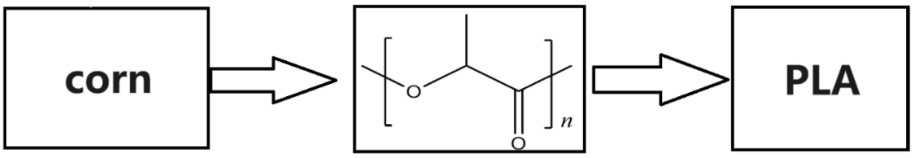

Figure 1. Simplified schematic of the production of Polylactic Acid (PLA) from corn.

The main raw material of PLA is corn starch (Figure 1). It is better than existing plastic polyethylene, polypropylene and polystyrene in terms of strength, compression, buffer, chemical resistance, moisture resistance, oil resistance, and sealability. PLA, as an important raw material, is suitable for a variety of processing methods such as blow molding and heat molding, and has a wide range of applications. For example, PLA can be processed into various downstream products, such as thermoplastic plastic, including film, bags, boxes, food containers, disposable fast food containers, beverage bottles, etc. Because lactic acid is the basic raw material of polymal acid, it is one of the physiological substances inherent in the human body, which is harmless to the human body.

Compared with traditional oil -based materials, polymer materials have stronger degradation, lower toxicity and stronger renewable. Polycal acid ester (PLA) used in large areas is a biodegradable polymer material synthesized by lactic acid as a single reaction. It is a non -toxic, non -irritating, and good biocompatibility new type of polymer material Essence It is decomposed by enzymes in the organism, and finally forms carbon dioxide and water, which is considered an environmentally friendly material. In 2001, the world's total lactic acid output was 130,000 tons; in 2002, it exceeded 200,000 tons. And showing a trend year by year. It is estimated that the total global lactic acid demand is about 15-20,000 tons. It means that the PLA dosage demand is large, and the output of plastic packaging is large. How to better degrade plastic packaging has become a very practical problem. Specifically, the degradation mechanism of packaging materials such as polystumin (PLA) such as polystumin (PLA) in this article is based on comparing the bacteriostatic performance, breathability and degradability of new and old packaging materials in actual application and evaluate it as a sustainable packaging solution to solve the solution of sustainable packaging. The potential of the plan. Through the summary of existing research, this summary analysis of PLA as the advantage of packaging is analyzed, and the possible ways of PLA packaging material performance improvement and suggestions for future research directions are proposed.

2. ADVANCES AND CHALLENGES IN POLYLACTIC ACID (PLA) RESEARCH AND APPLICATIONS

Compared to traditional petroleum-based materials, polymer materials such as polylactic acid (PLA) have been enhanced in several aspects, including significantly improved biodegradability. In industrial composting facilities, PLA can be fully decomposed into water and carbon dioxide within a few months, reducing the long-term burden on the environment. This is mainly because the raw materials used to produce PLA come from renewable plant resources such as corn starch, sugarcane, or beets. On the other hand, biodegradable plastics also reduce dependence on fossil fuels. The full life cycle carbon emissions of PLA are far lower than those of traditional petroleum-based plastics, alleviating pressure on the atmosphere and environment in the context of global warming. For users, biodegradable plastics have low toxicity and are safe to use, with no harm to human health and meeting food-grade safety standards.

However, the application of PLA also faces some challenges. The production cost of PLA is higher, which to some extent limits its competitiveness in the market. Due to the abundance of raw materials such as corn in China, the development prospects of lactic acid and PLA industries are broad. However, the high production cost of lactic acid and the difficulty of PLA polymerization have become the bottleneck restricting the development of the lactic acid industry. Reducing costs through technological innovation and scale effects will be an important direction for the future development of PLA. The inherent brittleness of the initial PLA material [4-5], poor impact strength, low tensile elongation (~10%), etc. greatly limit its application. In recent years, scholars have summarized the research on PLA toughening systems [6-8], mainly using composite, copolymerization, plasticization, and blending modification methods. However, after modification, problems such as difficulty in controlling the agglomeration of fillers and poor dispersion often arise. The heat resistance and mechanical strength of PLA still need to be continuously developed to meet the needs of more application scenarios [9]. The latest research on PLA is focused on solving its slow degradation problem. For this, Liang et al. prepared PLA-based food packaging films by using the solution casting method with salicylic acid phenyl ester as an antibacterial agent and cellulose acetate as a plasticizer [10]. The research results show that the addition of the antibacterial agent makes the composite film of PLA show antibacterial activity against Escherichia coli while accelerating the degradation rate of the composite film. In addition, researchers have also added various additives to PLA to improve its antibacterial and tensile properties, which broadens the thinking for the application of PLA-based food preservation active packaging materials [11]. In contrast, although PVA is also a vinyl polymer that can be decomposed by bacteria and has good biocompatibility, it is not conducive to processability due to the high hydrophilicity and poor thermal stability of PVA materials. Butylene terephthalate (PBAT), which is also a new degradable material, also has disadvantages such as low elastic modulus, low flexural strength, poor stiffness, and high cost. PLA plastic bags, as an environmentally friendly material, have many advantages, but they still need to be improved and strengthened in terms of cost, performance, recycling system, market supervision, etc., in order to achieve its wider application and positive impact on the environment.

3. MODIFICATION AND PROPERTIES OF PLA IN FOOD PRESERVATION PACKAGING

Polylactic acid is a thermoplastic aliphatic polyester.The monomer of polylactic acid is lactic acid, and its structure contains both carboxyl and hydroxyl groups. Many lactic acid molecules are esterified to form long polylactic acid chains. Polylactic acid can be rapidly degraded by hydrolysis reaction, coupled with its own good mechanical and processing properties, suitable for blow molding, thermoplastic and other processing methods, convenient processing, widely used [12].

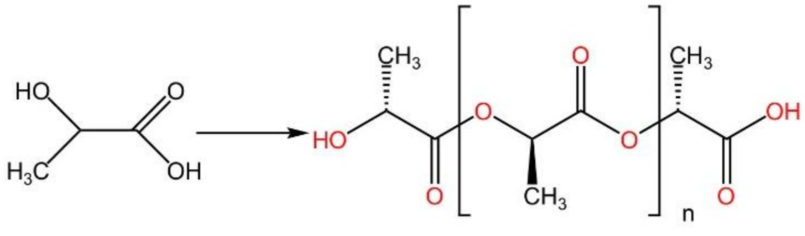

Figure 2. The structure of lactic acid and PLA

3.1. Mechanical Properties and Thermal Stability

Polylactic acid material has good mechanical and physical properties, with good mechanical strength and modulus, but it has poor toughness, brittle texture, heat resistance and other shortcomings, so it is usually necessary to toughen and modify it in the application field. At present, the mechanical properties of PLA are usually enhanced by blending modification. Zou Jun et al. prepared ultrafine talc modified PLA film by blow molding using twinscrew extrusion rod method, which improved its tensile strength and elongation at break. He Jiao et al. modified PLA with PEG blending, and found that with the increase of PEG content, the breaking strength of the blend was significantly increased, the modulus and strength were decreased, and the flexibility of PLA was improved [11-13]. Wei et al. improved the heat resistance of PLA by controlling the content and length of cotton stalk bast fiber. The results show that when the mass fraction of cotton stalk bast fiber is about 30%, the composite can obtain relatively good heat resistance. At the same time, the HDT of the composite increases with the increase of the length of the phloem fiber, but the HDT tends to stabilize when the length of the fiber is more than 10 mm, and the increase rate slows down. When the length of the phloem fiber is about 12 mm, the PLA-matrix composite can obtain the best heat resistance.

3.2. Air Permeability

Food preservation packaging materials need to have air permeability and water vapor permeability. Therefore, in order to meet the needs of self-regulating air packaging of fresh fruits and vegetables, PLA materials need to have appropriate air permeability and water vapor transmission properties. Yun Xueyan and other researchers made a triblock copolymer composite film by copolymerizing polyethylene glycol and polycaprolactone with PLA by chemical modification means. The film not only has good toughness and processing properties, but also significantly improves the selectivity of CO2/O2 and water vapor transmission, which is suitable for air conditioning packaging, helping to maintain the freshness of fruits and vegetables and extend their shelf life [14]. Dazhina prepared PLA/PEG copolymer films with different topological structures by chemical synthesis and blending technology, and carried out experiments on the preservation of cherry tomatoes. The study found that during storage, the gas concentration in the packaging bag is very suitable for the air conditioning and freshness of cherry tomatoes, and effectively improves the storage period of cherry tomatoes. Cai Yao et al. blended the melt-blended material with maleic anhydride and PLA, and then grafted it with epoxy soybean oil, which significantly improved the mechanical properties and hydrophobicity of PLA composite [15-16].

Table 1 presents a comparison of water and gas permeability characteristics for three materials: Polystyrene (PS), Polyethylene Terephthalate (PET), and Polylactic Acid (PLA). The key parameters shown include the Water Vapor Transmission Rate (WCTR), Water Permeability Coefficients, Oxygen Transmission Rate (OTR), and Gas Permeability Coefficients. PLA demonstrates the highest WCTR at 15.30 g/(m²/d), indicating that it allows more water vapor to pass through compared to PS and PET, with WCTR values of 3.48 g/(m²/d) and 5.18 g/(m²/d), respectively. Similarly, the Water Permeability Coefficients, which measure resistance to water permeability, show that PLA is the least resistant, allowing more water to penetrate, as reflected in its higher coefficient of 13.40. In contrast, PS and PET have much lower coefficients of 2.82 and 4.18, respectively, meaning they provide better water resistance. When examining the Oxygen Transmission Rate (OTR), PET allows significantly higher oxygen permeability at 531.58 cc/(m²/d), while PLA, with an OTR of 56.33 cc/(m²/d), falls between PS (9.44 cc/(m²/d)) and PET in terms of oxygen permeability. This suggests that PLA may permit more oxygen penetration than PS but still provides a reasonable barrier compared to PET. Lastly, the Gas Permeability Coefficients show that PLA has higher permeability to gases compared to PS, with a value of 4.33 kg/m/(m²/s/Pa), but it is much lower than PET's permeability, which stands at 39.10 kg/m/(m²/s/Pa). Overall, PLA exhibits higher water and gas permeability compared to PS, indicating it may still require additional modifications for applications demanding strong barriers against moisture and gases, especially in packaging scenarios.

Table 1. Comparison of water and gas permeability coefficients

Material	WCTR [g/(m²/d)]	Water Permeability Coefficients [10^{-1}*kg/m/(m²/s/Pa)]	OTR [cc/(m²/d)]	Gas Permeability Coefficients [kg/m/(m²/s/Pa)]
PS	3.48	2.82	9.44	0.7
PET	5.18	4.18	531.58	39.1
PLA	15.3	13.4	56.33	4.33

3.3. Bacteriostatic Property

In the process of fruit and vegetable preservation, bacteriostatic ability is also a very important part. The active packaging prepared by combining safe and effective bacteriostatic agent with PLA material can improve the antibacterial and antioxidant properties of the film, reduce the damage caused by microorganisms to fruits and vegetables, and thus improve the preservation effect. Song Jie and other researchers used two waste plant sources, pomegranate peel and onion peel, to extract dyeing and antibacterial components, and then combined with PLA to prepare biodegradable functional composite materials [17]. According to the experimental results, the figure shows that the two composites have obvious antibacterial ability, and the antibacterial ability against Staphylococcus aureus is greater than that against Escherichia coli. When the content of PGE is 9%, the antibacterial rate of the composite can reach more than 95%. Therefore, these two composite materials can be used in agricultural mulch, food and fruit preservation materials, packaging materials, antibacterial materials and other occasions. Using PLA and quaternary ammonium salt antibacterial agents as the main raw materials, Guan et al. used electrospinning technology to prepare antibacterial degradable film materials. The film formation was uniform, the double-chain antibacterial agent had good dispersion, and the antibacterial properties of the film materials were improved to a certain extent. Li W H et al. combined zinc oxide nanoparticles with polylactide film to prepare a composite film for fresh-cut apple preservation research, and the results showed that the film had a good effect on improving the shelf life of fresh-cut products [17]. All kinds of studies have shown that when polylactic acid film is used in storage and fresh-keeping of fruit products, more research methods are to use various molecular technologies to prepare polylactic acid composite film, and at the same time add a certain amount of essential oil for preservative and fresh-keeping treatment of fruit.

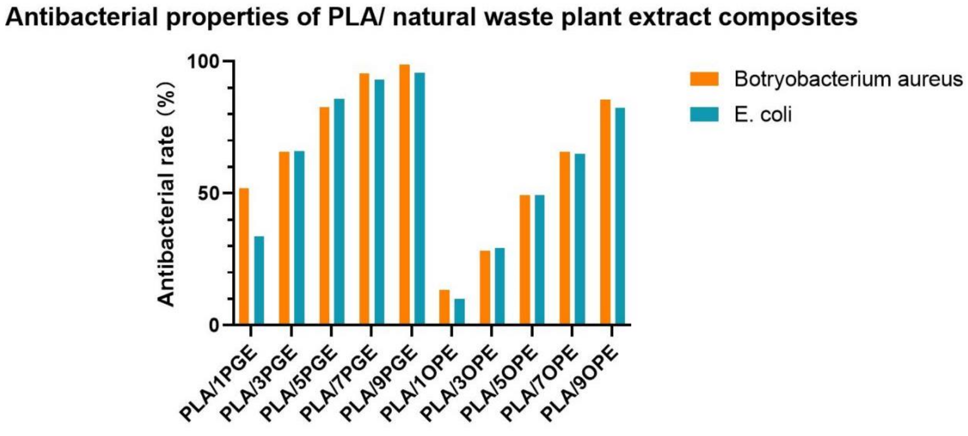

Figure 3. Antibacterial properties of PLA/natural waste plant extract composites.

3.4. Biodegradability and Resource Utilization

Regarding the degradation process of polylactic acid, due to the low solubility of PLA in water and its polymer structure, microorganisms cannot transport the polymer directly into the cell for degradation [18]. In this case, the microorganisms first release degrading enzymes outside the cell to degrade PLA to produce water-soluble compounds, which are then transported into the cell and metabolized, often using inducers such as gelatin, elastin, filamentin, and some amino acids and peptides to stimulate the process, further breaking down the oligomers into water and carbon dioxide. Currently, the reported PLA plastic degrading microorganisms include bacteria, actinomyces and fungi, which exist in a variety of natural environments such as compost, fresh water, ocean, anaerobic and soil, and the secreted enzymes have different optimal conditions for action. When the temperature and humidity are more suitable, the hydrolysis reaction can be completed more easily, and the decomposition rate is relatively fast.

Although there are a wide variety of microorganisms in nature, studies have shown that currently known microorganisms capable of degrading PLA are very limited. PLA is connected by ester bond between lactic acid monomers, and its degradation should be based on the break of ester bond. However, it was found that most lipases did not degrade PLA. The results of the study on 18 commercial lipases showed that although most lipases showed good activity to PCL, PBS, etc., only one lipase was derived from Alcaligenes sp. Under the condition of 55℃ pH8.5, the lipase can completely degrade PLA after 20 days [19]. In order to accelerate the biodegradation and realize effective recycling of PLA products after use, it is very important to develop a recycling system for PLA products. Some methods of recycling PLA have been reported, such as inducing its decomposition and hydrolysis at temperatures above 200℃ [20-21]. With the discovery of more PLA-degrading strains and enzymes, attempts have been made to develop biological treatment systems for PLA waste. Efficient degrading bacteria or degrading enzymes can not only accelerate the degradation of PLA, but also its hydrolytic products at all levels can be used as raw materials for polymer synthesis to realize the recycling of PLA. The enzyme treatment system also has many other advantages, its reaction conditions are mild, the treatment process is clean and pollution-free, and if the stereospecific enzyme is used, it can also meet the needs of people for different chiral products. Therefore, the biological treatment system is considered to be the most ideal PLA cyclic treatment system.

3.5. Biodegradability and Resource Utilization

At present, there are four main ways of resource utilization of PLA-based materials at home and abroad [22], and PLA-based degradable packaging materials can be carried out in the way of hierarchical resource utilization as shown in Figure 4.

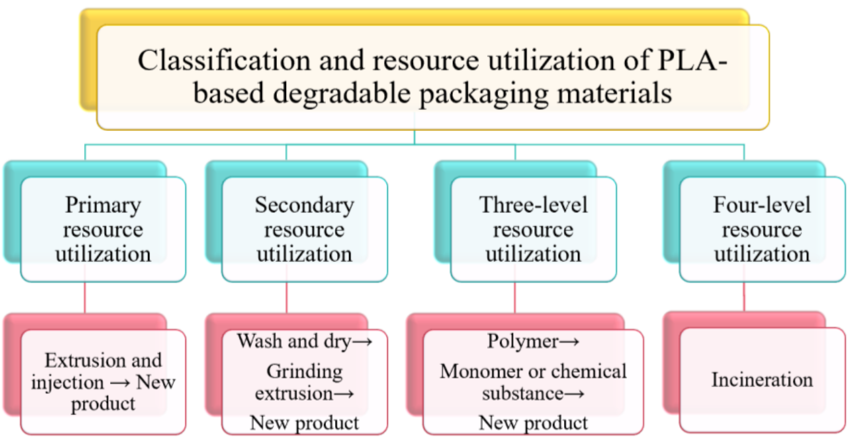

Figure 4. Graded resource reusing ways for PLA-based degradable packaging materials.

Firstly, primary resource utilization: the waste generated in the processing and production of PLA-based degradable packaging materials is collected and processed into other products through physical treatment technology to reduce waste and achieve value-added reuse of raw materials.

Second, secondary resource utilization: the process of processing post-consumption PLA-based degradable packaging materials into new products through physical treatment technology, including separation, washing, drying, grinding and extrusion. It may be necessary to add chain extenders or stabilizers during the recycling process to avoid material degradation affecting product performance.

Third, tertiary resource utilization: through hydrolysis, alcoholysis, pyrolysis or ammonolysis, the recovered PLA-based degradable packaging materials are fully or partially depolymerized into monomers or other chemical substances, and then the PLA-based degradable packaging materials are regenerated into polymers or products. Chemical treatment technology is the main way to achieve tertiary resource utilization. The recovered PLA-based degradable packaging materials are depolymerized into small molecule products, which are separated and purified as resource utilization for the production of PLA-based film food packaging materials. Leibfarth et al. further depolymerized PLA packaging materials at room temperature by adding highly active transesterification catalyst in the presence of various alcohols, and finally produced lactate, realizing the resource utilization of discarded PLA packaging materials. Chemical treatment technologies, including alcoholysis, hydrolysis, pyrolysis and ammonolysis, are considered to be a high-value recycling method [23].

Fourth level resource utilization: direct incineration of recycled PLA-based degradable packaging materials to obtain energy. This method can only be used as one of the means of processing PLA-based degradable packaging materials.

4. FUTURE DEVELOPMENT AND POTENTIAL CHALLENGES OF THE PLA

4.1. Cost-Benefit Problem

The high cost of these materials is a major factor hindering their widespread market acceptance. Public information shows that the current price of PE plastic per ton is about 8800 to 12000 yuan/ton, and the cost of polypropylene (PP) plastic per ton is 6700 to 8500 yuan/ton. The price of PLA plastic is 160-30,000 yuan/ton, and the price of PBAT plastic is 210-250 million yuan/ton. In order to become an acceptable option in the market, further improvements are urgently needed to close the gap between biodegradable plastics and conventional plastics. The cost is mainly attributable to raw material selection and energy consumption during fermentation and processing. Future research should focus on developing more cost-effective extrusion methods to enhance the competitiveness of PLA [24].

4.2. Recycling System Compatibility Problem

Today's society still has the problem of bio-based plastics and biodegradable plastics being incompatible with current recycling systems. The current recycling system does not have strict separation and sorting, and bio-based plastics will pollute the existing plastic recycling system. For example, PLA can contaminate the mechanical recovery chain of polyethylene terephthalate (PET), while bioPET or biopolyamide (PA) bioplastics polymerized with bio-based monomers and petroleum-based materials can be recycled alongside conventional plastics without changing technology or machinery [25]. These imperfections bring difficulties to the plastic recycling system, and at the same time bring two difficulties to the application and promotion of PLA. In the future, it is necessary to improve the recycling system, rationally classify different plastics, rationally design the degradation process, and upgrade the supporting infrastructure, so as to better promote the application of degradable bio-based materials.

4.3. Relevant Policy Issues

At present, the relevant national standards and industry standards of PLA materials in China are not perfect, resulting in uneven product quality and chaotic market order. This makes enterprises face certain risks when producing and applying PLA materials. In the production, sale and use of PLA materials, supervision needs to be strengthened. In pursuit of profit, some enterprises produce fake and shoddy products, which damages the image of the industry and affects consumer confidence. These problems make the application and promotion of PLA difficult, and some measures need to be taken in the future to improve the status quo and better promote its development. First, we need to increase policy support. The government should further increase its support for the PLA material industry, and promote the common development of upstream and downstream enterprises in the industrial chain through tax incentives, industrial support, scientific research investment and other measures. Then, improve the standard system. Establish and improve national and industry standards for PLA materials, improve product quality, standardize market order, and provide a strong guarantee for enterprises and consumers. Second, strengthen supervision. Strengthen the supervision of the production, sale and use of PLA materials, crack down on fake and shoddy products, maintain market order, and enhance consumer confidence. At the same time, it is also important to promote technological innovation and expand application fields. Encourage enterprises to increase investment in research and development, break through key core technologies, reduce production costs, improve the market competitiveness of PLA materials, actively promote the application of PLA materials in packaging, textile, medical and other fields, and gradually replace traditional plastic products to help China's green and low-carbon development.

5. CONCLUSION

In conclusion, polylactic acid (PLA) demonstrates considerable potential as a sustainable material for food preservation packaging due to its favorable mechanical properties, biodegradability, and non-toxic nature. The improvement of air permeability and gas transmission properties through copolymer films is crucial for extending the shelf life of perishable goods. Furthermore, the integration of natural antibacterial agents into PLA films significantly boosts their effectiveness in preventing microbial damage during storage. Despite these advancements, challenges such as the high production costs and inherent brittleness of PLA remain barriers to its widespread adoption. To realize the full potential of PLA in food packaging, ongoing research is essential to optimize its properties, develop efficient recycling methods, and establish comprehensive waste management systems. By addressing these challenges, PLA can contribute to reducing plastic waste and promoting a more sustainable packaging industry.

ACKNOWLEDGEMENTS

This research was funded by Enerstay Sustainability Pte Ltd (Singapore) Grant Call (Call 1/2023) _GHG (Project ID BS-001), Singapore.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: All authors declare no Competing Financial or Non-Financial Interests.

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