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Recent Advance of Sustainable Polymers for Packaging Applications

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Abstract:

The extensive application of non-renewable polymers has brought about deep environmental concerns, demonstrating the immediate requirement for new biodegradable and biobased packaging choices. The work offers an in-depth look at a wide array of degradable and biobased polymers like Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), and Polyvinyl Alcohol (PVOH), as well as starch and cellulose materials, discussing their qualities, uses, and the issues faced in food packaging. These types of green polymers, either in new ways or from renewable sources, offer great advances not only from decomposition into harmless parts but also from the reduction of environmental damage. The essay covers the exploitation side of this material, be it the role of PLA in enzymatic, hydrolytic, or microbial degradations, or the main tactical function of PHA in terms of a water barrier aimed at preserving the quality of stored food. Additionally, the multifunctionality of these substances is represented anew in packaging dairy goods, such as fruits, and vegetables, and specialized applications like edible films or water-soluble bags. The participation of compostable polymers has become increasingly vital in the area of food packaging to meet consumers' demands and to upgrade the present science technologies aimed at guiding food producers who are looking for more sustainability in their business.

Keywords: Sustainable polymer; Bio-based polymer; Food packaging.

1. Introduction

Packaging plays a crucial role in ensuring product safety, quality, and longevity in the rapidly evolving food industry as they journey from production facilities to consumers' homes. Food packaging protects food from contamination and spoilage and offers convenience and information, significantly influencing consumer choices. However, the widespread use of conventional packaging materials, predominantly derived from non-renewable polymers like petroleum-based plastics, has sparked a growing environmental crisis. While effective and economical, these materials are notoriously difficult to degrade, contributing significantly to environmental pollution and the burgeoning global waste problem. The alarming accumulation of plastic waste in landfills and oceans has raised urgent concerns about the sustainability of traditional packaging methods, pressing the need for innovative solutions to mitigate their environmental impact.

As awareness of environmental issues rises, there is a growing movement towards adopting sustainable materials that can replace or complement traditional packaging. Central to this movement are renewable polymers, which present a promising alternative to conventional plastics. These polymers are derived from natural, renewable resources such as plants and microorganisms and are designed to be biodegradable, recyclable, or both. Unlike traditional polymers, renewable polymers break down more readily in the environment, thereby reducing pollution and conserving resources. The transition to these materials in food packaging is an ecological imperative and a strategic economic opportunity, as it opens new avenues for innovation and market growth in the packaging industry. By using renewable materials like bioplastics made from corn starch, sugarcane, or algae, the food industry can reduce its environmental footprint. These alternatives are often biodegradable or compostable, helping to cut down on waste and lower carbon emissions [1].

Sustainable polymers, characterized by their biodegradability, renewability, and recyclability, are increasingly seen as vital components of sustainable packaging solutions. Biodegradable polymers, for example, can decompose into natural substances such as water, carbon dioxide, and biomass under the right conditions, effectively closing the loop in the life cycle of packaging materials. Renewable polymers, sourced from agricultural feedstocks or waste, reduce dependence on finite fossil resources and lower carbon emissions during production. Recyclable polymers, meanwhile, offer the potential to be reprocessed and reused, extending their lifespan and reducing waste. By integrating these materials into food packaging, companies can address the dual challenges of reducing environmental impact and meeting consumer demand for sustainable products. Environmentally, shifting to sustainable polymers for packaging reduces pollution, waste, and carbon emissions. Economically, it lowers reliance on finite resources, stabilizes production costs, meets consumer demand for sustainability, and offers new business opportunities and competitive advantages.

Among the sustainable polymers that hold promise for food packaging, Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), Polyvinyl Alcohol (PVA), and other biobased polymers stand out as key candidates. PLA is a biodegradable polymer derived from renewable resources such as corn starch or sugarcane, offering an alternative to traditional plastics in a wide range of applications. PHA, produced by microbial fermentation, is another biodegradable polymer that has garnered attention for its potential in packaging due to its excellent environmental credentials and versatility. PVA, known for its water solubility and biodegradability, is increasingly being used in applications where traditional plastics would pose environmental hazards. Biobased polymers, which are derived from biological sources and may be biodegradable or non-biodegradable, represent a broad category of materials with significant potential for reducing the reliance on fossil fuels in the packaging industry.

The essay will delve into these materials, exploring their properties, applications, and the challenges associated with their widespread adoption. By highlighting the potential of sustainable polymers, this essay aims to contribute to the ongoing dialogue on sustainable development and the future of food packaging. The ultimate goal is to underscore the importance of innovation in materials science as a critical factor in achieving a more sustainable and environmentally responsible food industry.

2. Biodegradable materials in food packaging

Biodegradable materials are substances that can maintain plastic properties for a specific period but can fully degrade into environmentally friendly compounds (such as carbon dioxide and water) within one to two months under composting conditions. These materials are derived from a wide range of sources, including common food items from daily life and certain microorganisms, and these materials have the capability to biodegrade.

2.1 Synthetic polymers

Synthetic polymers, such as PLA, PHA, PBS, and PVA, exhibit similar physical and chemical properties comparable to traditional petroleum-based materials. However, these new materials generally fall short of traditional plastics in terms of overall performance. Compared to traditional plastics, the higher production costs, inferior mechanical properties and durability of biodegradable plastics present a significant challenge. To address these limitations, researchers have increasingly focused on developing composite films of biodegradable materials, aiming to enhance functionality for food packaging applications or to reduce production costs [2].

2.1.1 Polylactic acid (PLA) based packaging

Polylactic acid (PLA) is a bio-based material synthesized through biological fermentation and polymerization. The monomer of PLA, which is lactic acid, is sourced from renewable resources such as corn and potatoes. As a result, the raw material base for PLA is highly versatile. PLA exhibits many advantageous properties, including biocompatibility, degradability, transparency, and ease of processing. It is capable of efficient degradation and can be processed using techniques commonly employed in the modern packaging industry, such as blow molding, injection molding, and extrusion molding. However, the thermal stability and mechanical strength of PLA are lower than petroleum-based materials. To address these deficiencies and improve the performance of food packaging, PLA can be compounded and modified with fillers, plasticizers, and other additives, thereby enhancing its properties to meet the requirements of practical applications [3].

The degradation of PLA mainly consists of the following three forms of degradation, enzymatic degradation, hydrolytic degradation, and microbial degradation. For enzymatic degradation, PLA can be broken by various enzymes such as lipase, esterase, alcalase, cutinases, and proteases (including serine proteases). The efficacy of these enzymes in catalyzing PLA degradation is contingent upon specific environmental conditions and microbial activity.

Hydrolytic degradation refers to the hydrolysis of PLA in aqueous environments. During this process, the ester bonds within the PLA polymer backbone are cleaved, resulting in the formation of hydroxyl and carboxyl end groups. This cleavage leads to a reduction in molecular weight and mechanical strength, producing degradation products such as oligomers and lactic acid monomers. The presence of carboxyl groups can further catalyze hydrolysis, with the rate of this reaction being influenced by the pH of the surrounding environment. In practical applications such as food and beverage packaging, PLA may be exposed to moist conditions or liquids with varying pH levels (e.g., juices or dairy products), which can accelerate hydrolytic degradation [4].

Microbial degradation occurs when PLA is exposed to soil, where microorganisms decompose the plastic at a relatively slow rate. As shown in Figure 1, a variety of microorganisms capable of degrading PLA have been identified in both soil and aquatic environments, including specific bacteria, fungi, and actinomycetes [4,5]”DOI”:”10.1016/j.ijbiomac.2023.123703”,”ISSN”:”01418130”,”journalAbbreviation”:”International Journal of Biological Macromolecules”,”language”:”en”,”page”:”123703”,”source”:”DOI.org (Crossref.

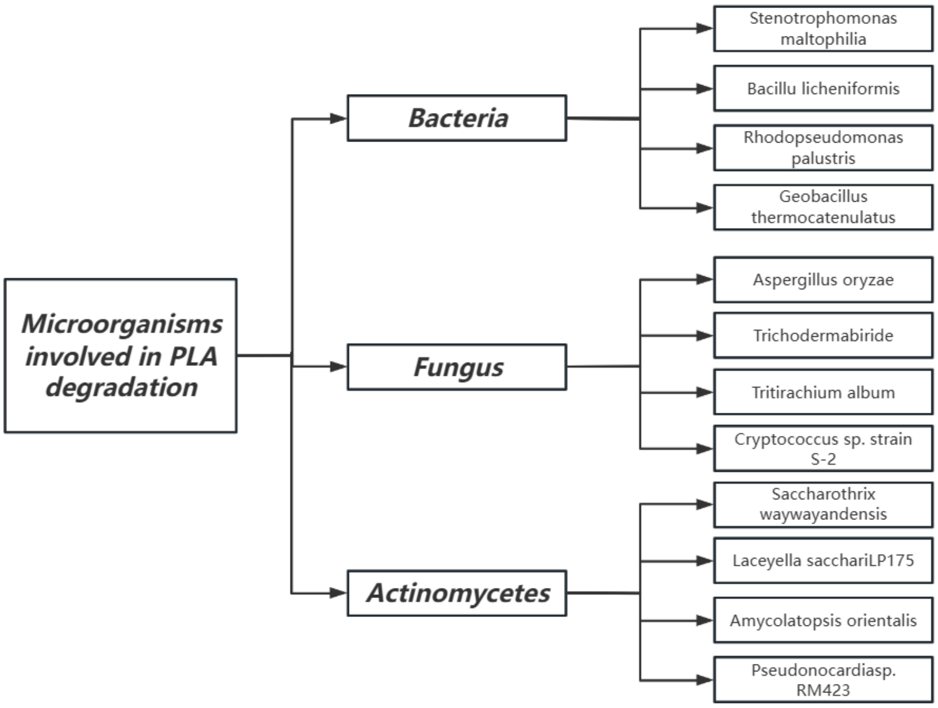

Fig.1 Microorganisms involved in PLA degradation [4]

2.1.2 (PHA) based packaging

Polyhydroxyalkanoates (PHA) are a kind of polyester that has been identified as a promising alternative to traditional petroleum-based plastics since the discovery of poly-3-hydroxybutyrate (PHB) in the 1920s. PHAs are synthesized intracellularly by a diverse array of bacterial species and include various polymers such as 3-hydroxybutyrate (PHB), 3-hydroxyvalerate (PHV), 4-hydroxybutyrate (P4HB), and polyhydroxybutyrate-co-valerate (PHBV). These polymers differ in their monomer chain lengths and compositions, resulting in distinct material properties [6]this special sector of the plastic market displays remarkably increasing quantities of its annual production. Caused by the ongoing limitation and strongly fluctuating prices of fossil feedstocks, classically used for plastic production, there is an evident trend to switch towards so-called “bio-plastics”. Especially for bulk applications such as food packaging, a broad implementation of “bio-plastics” constitutes a future-oriented strategy to restrict the dependence of global industry on fossil feedstocks, and to diminish current problematic environmental issues arising from plastic disposal. However, food packaging demands a great deal of the utilized packaging material. This encompasses tailored mechanical properties such as low brittleness and adequate tensile strength, a sufficient barrier for oxygen, CO2, and aromatic flavors, high UV-resistance, and high water retention-capacity to block the food´s moisture content, or to prevent humidity, respectively. Due to their hydrophobic character and the broad flexibility of their mechanical features, prokaryotic poly(hydroxyalkanoates. Within bacterial cells, PHAs function primarily as carbon storage compounds and energy reserves. The production of PHA typically involves the cultivation of mixed microbial cultures, with periodic adjustments to the external carbon source concentrations. This approach transitions cells from a state of minimal metabolic activity to one of enhanced growth rates, during which substrate absorption is redirected toward the accumulation of intracellular polymers. The extraction of PHA from bacterial cells is achieved through physical and chemical methods, such as solvent extraction and irradiation, which facilitate the disruption of cell walls and the recovery of the intracellular polymer [1].

Food packaging materials typically require superior gas and liquid barrier properties to effectively isolate the contents from external environmental factors, so they can maintain a sterile internal environment and prevent microbial respiration and oxidation. This is crucial for ensuring the safety and flavor retention of the packaged food.

Polyhydroxyalkanoates (PHAs) are recognized for their excellent biodegradability, biocompatibility, non-toxicity, thermal processability, and barrier properties, positioning them as promising alternatives to traditional biodegradable food packaging materials [7].

In terms of barrier performance, 3HV in PHA copolymers inversely affects the polymer's crystallinity. Specifically, a lower proportion of 3HV results in increased crystallinity, which reduces the permeability to small molecules such as water and oxygen. This enhanced crystallinity diminishes diffusion rates and thus improves the overall barrier properties of the polymer (see Table 1). PHAs demonstrate significant oxygen barrier capabilities, attributable to the conditions necessary for microbial respiration during the polymerization process. Specifically, certain bacterial strains require the restriction of aerobic respiration and the oxidation of unsaturated fatty acids to synthesize homopolymers, thereby contributing to the effective barrier properties of PHAs [6]this special sector of the plastic market displays remarkably increasing quantities of its annual production. Caused by the ongoing limitation and strongly fluctuating prices of fossil feedstocks, classically used for plastic production, there is an evident trend to switch towards so-called “bio-plastics”. Especially for bulk applications such as food packaging, a broad implementation of “bio-plastics” constitutes a future-oriented strategy to restrict the dependence of global industry on fossil feedstocks, and to diminish current problematic environmental issues arising from plastic disposal. However, food packaging demands a great deal of the utilized packaging material. This encompasses tailored mechanical properties such as low brittleness and adequate tensile strength, a sufficient barrier for oxygen, CO2, and aromatic flavors, high UV-resistance, and high water retention-capacity to block the food´s moisture content, or to prevent humidity, respectively. Due to their hydrophobic character and the broad flexibility of their mechanical features, prokaryotic poly(hydroxyalkanoates.

Table 1. Characteristics of PET and other sustainable materials [8,9]

Polymer films	WVTR (g/m2/day)
PET	12(38℃)
PHBV-6	13(25℃)
PHBV-12	21(25℃)
PHBV-18	26(25℃)
PLA	172(25℃)

PET-poly(ethylenetetraphthalate); PHBV-poly(β-hydroxybutyrate-co-hydroxyvalerate); 6, 12, and 18 percentage valerate;PLA- poly(L-lactic acid)

The water vapor transfer rate (WVTR) quantifies the amount of water vapor that permeates through a packaging material per unit area and time. As illustrated in Table 1, polyethylene terephthalate (PET) exhibits superior mechanical properties and effective water barrier performance, which accounts for its prevalent use as a material for carbonated beverages in the market. In comparison, polyhydroxyalkanoates (PHAs) demonstrate a WVTR that approximates that of PET under relatively low temperatures and exceeds that of polylactic acid (PLA). Furthermore, PHAs offer excellent thermoplasticity, facilitating their processing. Consequently, PHAs possess considerable potential for advancement in the food packaging industry as effective moisture barriers. Recent progress in biosynthesis and chemical modification technologies has significantly reduced the cost of PHA polymers, thereby broadening their applicability and potential for large-scale use in food packaging.

2.1.3 Polyvinyl alcohol (PVA)

Polyvinyl alcohol (PVA) is an important chemical raw material, its structure is $+CH2-CH^{+}$, is a polymer, polyvinyl alcohol molecular formula [C2H4O]n, its molecular structure is composed of many repeating vinyl ($-CH=CH_2$) and alcohol hydroxyl (-OH) units.

Polyvinyl alcohol (PVA) has unique atomic and molecular properties that give it an advantage in sustainable polymer food packaging. Although traditionally produced from petroleum-based vinyl acetate, advances in green chemistry have made it possible to produce biobased PVA using renewable resources such as biomass. The process usually involves the polymerization of biologically derived vinyl acetate, which is then hydrolyzed to produce

PVA. This shift to bio-based feedstock is consistent with sustainability principles by reducing reliance on fossil fuels and reducing the carbon footprint associated with PVA production. Although traditionally produced from petroleum-based vinyl acetate, biobased PVA can be extracted from renewable resources. It is known for its water solubility and biodegradability. The hydroxyl groups in the PVA structure make the polymer highly hydrophilic, which contributes to its water solubility. This property is essential for packaging applications that require water-soluble packaging, making it a good candidate for water-soluble packaging solutions. Hydroxyl groups can form hydrogen bonds or cross-linking with other molecules to enhance the strength and stability of PVA films. This crosslinking can be controlled to adjust the solubility and mechanical properties of the packaging material. PVA has a linear polymer main chain, which can strike a balance between flexibility and strength. This flexibility is essential for packaging materials that need to be adapted to all shapes without breaking or breaking.

PVA is used in food packaging applications such as water-soluble bags, coatings and biodegradable films. It is particularly valued for its strong film-forming capabilities and resistance to oil and grease.

2.2 Biobased polymers

Biobased polymers are materials derived from renewable biological sources, such as plants, animals, and microorganisms, rather than from non-renewable fossil fuels. These polymers are an integral part of the transition to sustainable packaging solutions, providing an environmentally friendly alternative to traditional petroleum-based plastics. By leveraging renewable resources, bio-based polymers help reduce their carbon footprint and dependence on limited resources, in line with the principles of circular economy.

Bio-based biodegradable materials present a viable alternative to conventional plastics derived from non-renewable fossil fuels, aiming to reduce the carbon footprint associated with petroleum-based plastics. These materials, which are partially or wholly derived from biological sources like starch and sugars, contribute to sustainable development. Biodegradability is defined as the ability of a material to decompose into non-toxic compounds through natural processes, such as microbial activity. It is important to note that not all bio-based plastics are biodegradable, and not all biodegradable plastics are bio-based. However, the unique combination of both bio-based and biodegradable properties in certain plastics offers a particularly eco-friendly solution [10].

Biobased polymers have many advantages. Bio-based polymers are derived from corn, sugar cane, cellulose and other renewable biomass, which contribute to the sustainable management and utilization of resources.Diversification of biobased polymers. Depending on its chemical composition, bio-based polymers can be designed to replicate the mechanical and thermal properties of conventional plastics, or introduce new features, such as enhanced biodegradability or improved barrier properties.Biobased polymers help reduce the carbon footprint. Biobased polymer production typically involves lower greenhouse gas emissions than conventional plastics, helping to reduce the overall carbon footprint. Biobased polymers have the potential for biodegradation. Some bio-based polymers are biodegradable, meaning they can be broken down into natural substances under specific environmental conditions, reducing plastic pollution.

2.2.1 Starch-based polymers

Starch-based polymers, derived from natural resources such as corn, potatoes, or cassava, are biodegradable materials commonly used in low-strength applications like biodegradable bags, loosely packed packaging, and disposable tableware. While they are inherently water-sensitive, their properties can be enhanced through blending with other biobased or conventional polymers and chemical modifications. Recent innovations include the use of rice husk fibers and antimicrobial agents in starch-based films, which significantly improved their mechanical strength, water resistance, and biodegradability. For instance, Srivastava et al. demonstrated that adding 20% rice husk fiber and 0.05% benzalkonium chloride to corn starch-based biocomposite films not only enhanced their tensile strength and moisture resistance but also provided effective antimicrobial properties and complete biodegradability within 30 days under composting conditions. These advancements underscore the potential of starch-based polymers in active food packaging [11].

2.2.2 Cellulose polymers

On the other hand, cellulose-based polymers, derived from the abundant cellulose in plant cell walls, are renewable, biodegradable, and offer good barrier properties against gases and aromas. These polymers can be modified to improve their mechanical properties and water resistance, making them suitable for various packaging applications, including films, coatings, and breathable packaging. Recent research has explored innovative uses of cellulose, such as creating highly porous, bioactive aerogels from Arundo donax lignocellulosic waste, which exhibit excellent water and oil absorption capabilities and antioxidant properties. This study highlighted the potential of these aerogels for reducing color loss and lipid oxidation in meat products during storage [12]. Additionally, cellulose films made from cocoa pod husks and sugarcane bagasse fibers have shown reduced water absorption and enhanced durability [13], while films produced from banana stem fibers have demonstrated improved gas transmission rates and biodegradability, making them effective in extending the shelf life of tropical fruits [14].

3. Sustainable polymers for Food Packaging applications

3.1 Common Food Packaging

3.1.1 Dairy packaging

A variety of renewable plastics are now utilized in food packaging applications, including polyhydroxybutyrate (PHB) for dairy products and high-fat foods such as mayonnaise. Compared to conventional food contact materials like polypropylene (PP), PHB demonstrates superior performance at elevated temperatures. However, it is important to note that PHB exhibits reduced flexibility at lower temperatures, which may impact its performance under such conditions [15].

3.1.2 Fruit and vegetable packaging

For fruit and vegetable packaging, it is essential to allow for controlled gas permeability, differing from other food packaging applications that require complete sealing to prevent oxidation. The appropriate gas exchange is crucial for maintaining the respiration of the fruits and vegetables within the package, thereby preserving their freshness and extending shelf life. Recent studies have explored the use of polylactic acid (PLA) in equilibrium-modified atmosphere packaging (EMAP). By employing mechanical or laser perforation techniques to create micro-holes in PLA films, it is possible to facilitate gas exchange across the packaging film. Experimental evaluations with cherries and peaches have indicated that PLA films offer enhanced water vapor permeability compared to conventionally oriented polypropylene (OPP) films, thereby demonstrating improved performance in maintaining the freshness of produce [16]”volume”:”111”,”author”:[{“family”:”Mistriotis”,”given”:”Antonis”},{“family”:”Briassoulis”,”given”:”Demetrios”},{“family”:”Giannoulis”,”given”:”Anastasios”},{“family”:”D’Aquino”,”given”:”Salvatore”}],”issued”:{“date-parts”:[[“2016”,1]]}}}],”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”} .

3.2 Specialty packaging

3.2.1 Edible film and coating

PVA is used to make edible films and is used as a disposable part of the packaging, such as seasoning packs or food supplements. These films dissolve in water and leave no waste behind, thus helping to reduce waste. PVA can be used as a coating for a variety of foods, extending shelf life by providing a barrier against moisture, oxygen and microbial contamination. For example, it can be used in fruits, vegetables and processed foods to prevent spoilage.

3.2.2 Water-soluble bags

PVA is commonly used to produce water-soluble bags for food ingredients such as spices, sauces, or dehydrated foods. These bags dissolve when mixed with water, providing convenience while minimizing packaging waste. PVA bags are also used in institutional food service environments where they can package pre-measured food portions, reducing preparation time and packaging waste.

3.2.3 Biodegradable packaging film:

PVA is able to form flexible, durable films that make it suitable for all types of food packaging, including packaging paper and bags. These films are particularly suitable for packaging dry foods, snacks and baked goods, where moisture resistance is not a major consideration. PVA can be combined with other biodegradable polymers, such as starch or cellulose derivatives, to create composite membranes with enhanced mechanical properties and biodegradability. These composites can be tailored to specific packaging needs, balancing performance and environmental considerations. PVA is biodegradable under appropriate conditions, especially in wastewater treatment plants, where it breaks down into non-toxic components. However, its water solubility limits its use in some packaging applications.

4. Conclusion

In conclusion, the shift towards renewable, biodegradable, and biobased polymers in food packaging is a critical response to the environmental challenges posed by conventional petroleum-based plastics. PLA is valued for its biodegradability, transparency, and ease of processing, making it versatile for various packaging applications. However, it requires enhancement in thermal stability and mechanical strength to compete with traditional plastics. PHA, with its excellent biodegradability, biocompatibility, and barrier properties, provides an effective alternative for applications needing robust protection against gases and liquids. Recent advancements in biosynthesis and chemical modification have significantly reduced the cost of PHA, enhancing its potential for widespread use in the packaging industry.Polyvinyl Alcohol (PVA) exemplifies the advancements in biobased polymers. Its unique molecular structure allows for water solubility, biodegradability, and the formation of strong, flexible films, making it ideal for applications that require dissolvable or biodegradable packaging. The development of PVA from renewable resources, rather than petroleum-based methods, aligns with sustainability principles, reducing fossil fuel dependence and carbon footprints. Innovations in biobased polymers, including starch-based and cellulose-based materials, further expand the applications of these materials in food packaging by improving mechanical properties, water resistance, and biodegradability.Biopolymers like PHB, PLA, and PVA demonstrate versatility in various packaging applications, from dairy products and high-fat foods to fruits, vegetables, and specialty packaging like edible films and water-soluble bags. While these materials offer substantial environmental benefits, challenges remain, particularly in optimizing their mechanical properties and cost-effectiveness. Ongoing research and development are crucial to overcoming these challenges, enhancing the performance and adoption of sustainable polymers in the packaging industry.

Overall, the integration of biodegradable and biobased polymers into food packaging is not only an environmental imperative but also a strategic economic opportunity. By embracing these materials, the packaging sector can significantly reduce its environmental impact, promote sustainability, and contribute to a circular economy, ensuring a more sustainable future for food packaging.

Authors Contribution

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

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