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RECENT ADVANCEMENTS IN PLA FOR FOOD PACKAGING APPLICATIONS

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ABSTRACT

The growing menace of plastic pollution, fuelled mainly by the high usage of non-biodegradable, petroleum-based plastics in food packaging, has heightened the search of sustainable alternatives worldwide. An interesting alternative has been the development of biodegradable films, where Polylactic Acid (PLA) has become popular because of its bio-based nature, compost ability and good mechanical and barrier performance. Native PLA however has drawbacks including brittleness, poor moisture resistance, and low thermal stability which has driven the global search of PLA based blends and nanocomposites. Lately gained improvements, including copolymerization, plasticization with bio-based solvents, nano-reinforcement with cellulose nanofibers and nanoclays, and blending with other polymers, including PBAT and PHA, have made a big enhancement in the physicochemical performance of PLA. Its functionality and food safety possibilities are further increased by surface coatings, multilayer film structures, and the integration of intelligent packaging. Such advancements not only solve existing technical problems but also follow the principles of the circular economy and the objective of environmental sustainability. Future opportunities focus on green synthesis of nanofillers, new processing methods, and favourable policies that would make PLA a scalable and environmentally friendly alternative to food packaging in the next generation.

Keywords: Plastic pollution, Biodegradable films, Polylactic Acid (PLA), Sustainable packaging, Food packaging

1. INTRODUCTION

Plastic pollution has emerged as one of the most pressing environmental challenges of the modern era (**Figure 1**). Conventional petroleum-based plastics are widely used due to their low cost, versatility, and durability; however, these same properties make them extremely resistant to degradation, leading to long-term accumulation in the environment. Millions of tons of plastic waste end up in landfills, oceans, and soil each year, disrupting ecosystems, harming marine and terrestrial life, and entering the food chain as microplastics, thus posing potential risks to human health [1]. Microplastics have been detected in drinking water, food items, and even human blood and placenta, raising serious health concerns due to their potential to carry toxic chemicals and cause inflammatory responses [2]. Furthermore, the production of such plastics is heavily reliant on fossil fuels, contributing to greenhouse gas emissions and exacerbating climate change through the entire lifecycle from extraction, processing, use, and disposal.

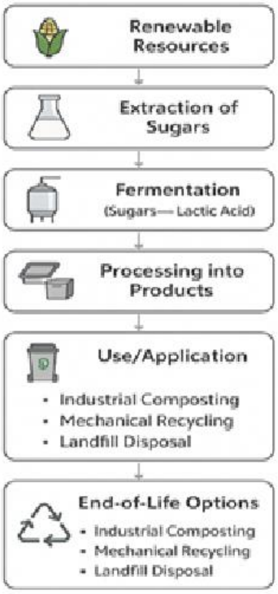

Figure 1: Lifecycle of PLA from renewable resources to degradation [3]

The seriousness of these issues has driven the urgent need for sustainable alternatives that can reduce environmental pollution while maintaining functionality in various applications, especially in food packaging. Food packaging accounts for a major share of plastic consumption worldwide due to its critical role in protecting food quality, ensuring safety, and extending shelf life. Therefore, identifying a suitable alternative that retains the beneficial properties of traditional plastics without the environmental burden is vital for achieving sustainability goals and circular economy targets [4].

Among the promising solutions, Polylactic Acid (PLA) has gained significant attention in recent years. PLA is a bio-based, biodegradable polymer derived from renewable resources such as corn starch, sugarcane, or cassava, offering a potential pathway towards reducing plastic pollution [5]. The monomers of PLA are produced via fermentation of sugars to lactic acid, followed by polymerization, making it a renewable and low-carbon material compared to petroleum-based plastics. It is compostable under industrial composting conditions, thereby reducing landfill accumulation and environmental toxicity [6].

Beyond its ecological advantages, including a lower carbon footprint, reduced greenhouse gas emissions, and industrial compostability, PLA exhibits favourable mechanical strength, thermal stability, and barrier properties suitable for diverse food packaging uses. However, its limitations, such as brittleness, lower heat resistance, and slower degradation in natural conditions, necessitate further modifications to improve performance for commercial applications [7]. Recent technological advances, such as blending with other biodegradable polymers (e.g., PHA, PBS), incorporation of nanomaterials (e.g., cellulose nanocrystals, graphene oxide), surface modifications, and copolymerization, have significantly enhanced PLA's mechanical, thermal, and barrier properties, expanding its application to packaging perishable foods, ready-to-eat meals, beverages, and microwaveable trays [8].

Moreover, increasing regulatory pressures and consumer demand for environmentally friendly and sustainable packaging solutions have accelerated research, policy initiatives, and industrial adoption of PLA-based materials worldwide (Figure 2). The European Union's directives on single-use plastics, extended producer responsibility schemes, and global sustainability commitments by multinational food companies have created a market pull for PLA adoption. This has resulted in innovative developments aiming to address PLA's challenges and commercialize advanced PLA-based materials with improved functionality, economic viability, and environmental performance. This paper provides a comprehensive overview of the latest advances in PLA-based food packaging materials, including technological innovations, functional enhancements, market trends, and environmental implications.

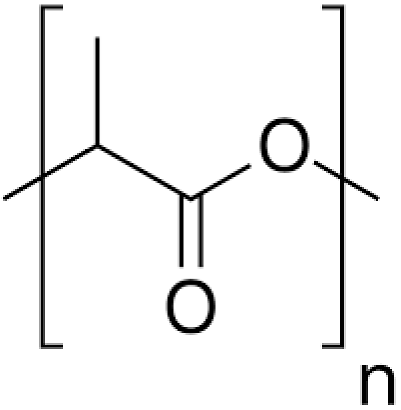

Figure 2: PLA (Polylactic Acid) [9]

Table 1: PLA for Food Packaging Applications

Authors (Year)	**Title / Source**	**Focus Area**	**Key Methodology / Scope**	**Key Findings / Contributions**
Marano et al. (2022) [10]	*Tailoring the barrier properties of PLA: a state-of-the-art review for food packaging*	PLA's barrier properties (O_2, CO_2, moisture)	Literature review of enhancement strategies	Identifies chemical modifications, nanocomposites, and coating techniques to improve PLA's gas

	applications, Polymers			and moisture barrier performance for food packaging.
Swetha et al. (2023) [11]	*A comprehensive review on polylactic acid (PLA) – Synthesis, processing and application in food packaging*, IJBM	Synthesis, processing, and food applications of PLA	Comprehensive review covering chemical synthesis to end-use	Discusses eco-friendly synthesis, various PLA processing methods (e.g., extrusion, casting), and its suitability in food-grade packaging materials.
Rodríguez-Núñez et al. (2018) [12]	*Composite materials based on PLA and its applications in food packaging*, Composites Materials for Food Packaging	PLA composites for packaging	Application-based review of PLA-based composite materials	Highlights blending PLA with materials like starch, nanoclays, and PHA to improve strength, barrier capacity, and biodegradability in packaging.
Wu et al. (2022) [13]	*Electrospinning of PLA nanofibers: Recent advances and its potential application for food packaging*, J. Agric. Food Chem.	PLA nanofibers& electrospinning	Review of recent progress in nanofiber production	Demonstrates the use of electrospun PLA nanofibers for antimicrobial, breathable, and high-surface-area food packaging materials.
Shao et al. (2022) [14]	*Recent advances in PLA-based antibacterial food packaging and its applications*, Molecules	Antibacterial PLA packaging	Review of bioactive and antimicrobial agents in PLA	Evaluates incorporation of natural and synthetic antimicrobials into PLA (e.g., essential oils, metal oxides) for enhancing shelf life and food safety.
Sorrentino et al. (2007) [15]	*Potential perspectives of bio-nanocomposites for*	Bio-nanocomposites for packaging	Conceptual and experimental insights	Early foundational work identifying nanofillers like

	food packaging applications, Trends in Food Sci. & Tech.			layered silicates as reinforcements in PLA and their potential for functional, eco-friendly food packaging.

1.1.Environmental Impact of Conventional Plastics

Traditional plastics are made mainly from non-renewable petroleum sources. They have been widely used in the packaging industry because they are durable, versatile, and affordable [16]. However, these same qualities make them harmful to the environment. Plastics like polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) do not break down easily and can remain in the environment for hundreds of years [17].

Every year, millions of tons of plastic waste end up in landfills, rivers, and oceans. In marine environments, plastic waste threatens aquatic life because animals can get entangled or mistakenly ingest it, causing injuries or death [18]. Even smaller pieces, called microplastics, form when larger plastics break down. These microplastics have been found in seafood, drinking water, and even human tissues, raising concerns about their effects on human health [19].

The production and disposal of plastics also release large amounts of greenhouse gases, contributing to climate change [20]. From extracting fossil fuels to manufacturing, transporting, and burning plastics, the entire life cycle creates a high carbon footprint. Improper disposal and open burning of plastic waste release toxic chemicals such as dioxins and furans, which are harmful to human health and the environment [21].

Because of these serious impacts, countries worldwide are introducing policies to reduce plastic use, promote recycling, and develop greener packaging solutions. Biodegradable and bio-based polymers like polylactic acid (PLA) are increasingly seen as promising alternatives to reduce environmental pollution from conventional plastics [22].

1.2.Definition and Significance of Biodegradable Films

Biodegradable films are packaging materials made from renewable sources like starch, cellulose, and PLA that can break down naturally into harmless substances through microbial action. They help reduce plastic pollution by degrading faster than conventional plastics and are important in food packaging as they lower dependence on fossil fuels, reduce landfill waste, and can incorporate antimicrobial agents to keep food fresh and safe.

- ***Definition of Biodegradable Films***

Biodegradable films are thin, flexible materials that can naturally break down into non-toxic substances such as carbon dioxide, water, and biomass. This happens through the action of microorganisms like bacteria and fungi under suitable conditions. Unlike conventional plastic films, which persist in the environment for centuries, biodegradable films are made from renewable sources like starch, cellulose, chitosan, polylactic acid (PLA), and polyhydroxyalkanoates (PHA). They degrade much faster when composted or exposed to natural environments, thus reducing pollution [23].

These films can be designed to have enough strength, flexibility, and barrier properties for use in packaging. Their properties can also be improved by blending with other polymers or adding plasticizers and fillers to meet specific requirements [24].

- ***Significance of Biodegradable Films in Food Packaging***

Biodegradable films are important because they help solve the problem of plastic pollution, especially in the food packaging sector, where large amounts of single-use plastics are used daily [25]. By replacing petroleum-based plastics with biodegradable films, industries can reduce their reliance on fossil fuels and lessen the burden on landfills [26].

Additionally, biodegradable films can be combined with antimicrobial or antioxidant agents to keep food fresh for longer and maintain safety standards. This adds extra functional value to packaging [27].

With growing global regulations and consumer demand for sustainable packaging, the use of biodegradable films is increasing rapidly. They represent an important step towards eco-friendly packaging, providing solutions that meet both performance needs and environmental goals. Using biodegradable films in food packaging can help conserve natural resources, reduce pollution, and support long-term environmental sustainability for future generation.

1.3.Need for sustainable and high-performance alternatives

The growing environmental challenges posed by traditional petroleum-based plastics have created an urgent need to develop new materials that are environmentally friendly and deliver high performance, particularly in food packaging where plastic consumption is significant and often limited to single-use applications [28]. While conventional plastics exhibit excellent mechanical strength and barrier properties, their resistance to degradation leads to long-term accumulation in landfills and oceans, resulting in severe ecological damage, greenhouse gas emissions, and microplastic contamination.

These adverse impacts have accelerated the global shift towards eco-friendly packaging materials that minimise environmental harm while meeting regulatory requirements and consumer preferences for greener products. Initially, many biodegradable materials failed to match the performance standards of conventional plastics in terms of strength, thermal stability, and moisture resistance, limiting their commercial viability. However, advancements in material science have led to the development of high-performance biopolymers such as Polylactic Acid (PLA), polyhydroxyalkanoates (PHA), and cellulose-based films, which provide the necessary functional properties for packaging applications [29].

These innovative materials offer a balance between environmental responsibility and functional efficiency, being derived from renewable resources and capable of degrading naturally without leaving persistent pollutants. The adoption of such alternatives is no longer optional; it has become essential in response to stricter environmental regulations and heightened awareness about plastic pollution. This transition not only contributes to the protection of natural ecosystems but also ensures long-term economic viability for the packaging industry by aligning production and product design with global market demands and environmental policies.

1.4.Background of PLA (Polylactic Acid) as a biopolymer

Polylactic Acid (PLA) is a bio-based and biodegradable thermoplastic polyester that has emerged as a leading alternative to traditional petroleum-based plastics, particularly in the food packaging industry [30]. PLA is produced from renewable agricultural resources such as corn starch, sugarcane, or cassava, whose sugars are first fermented into lactic acid and then polymerized into high-molecular-weight PLA [31]. Although the concept of PLA dates back to the 1930s, it was not until the early 2000s that commercial production became viable, owing to significant advancements in fermentation and polymerization technologies, which reduced production costs and improved scalability.

Commercialization of PLA has been spearheaded by companies such as NatureWorks LLC, which produce PLA at an industrial scale for applications ranging from food packaging to textiles and biomedical devices. PLA possesses several desirable characteristics, including high clarity, good mechanical strength, and excellent printability, making it especially suitable for food contact materials such as trays, containers, and films [32].

However, despite these advantages, PLA has certain limitations. Its low thermal resistance and moderate barrier properties against moisture and gases restrict its use in some high-temperature and long-shelf-life applications [33]. To overcome these challenges, recent innovations in material science have focused on enhancing its performance through blending with other biodegradable polymers, copolymerization, and the development of PLA-based nanocomposites. These modifications improve PLA’s thermal stability, mechanical flexibility, and barrier properties, thereby expanding its applicability in more demanding packaging scenarios [34].

With the increasing global emphasis on reducing environmental impacts and the regulatory push towards minimizing single-use plastics, PLA stands out as a pioneering sustainable biopolymer [35]. Its renewable origin, industrial compostability, and improving material properties position it as a critical material in the transition towards a circular economy, where packaging materials are designed to be resource-efficient, environmentally benign, and aligned with global sustainability goals.

1.5.Importance of sustainable food packaging

Sustainable food packaging is crucial for reducing environmental pollution, lowering carbon footprints, and enhancing food safety (Figure 3). Materials like polylactic acid (PLA), starch-based films, and cellulose derivatives are biodegradable or compostable, preventing long-term waste accumulation and microplastic contamination [36]. They also emit significantly fewer greenhouse gases compared to petroleum-based plastics, thus mitigating climate change impacts. Moreover, sustainable packaging with antimicrobial properties can extend the shelf life of perishable foods, reduce spoilage, and improve food safety standards. Additionally, growing consumer demand for eco-friendly products and strict global regulations have made sustainable packaging essential for ensuring regulatory compliance, enhancing brand image, and achieving future market readiness [37].

1. Environmental Conservation

Sustainable food packaging plays a critical role in reducing environmental impacts by minimising the use of non-renewable, petroleum-based resources and decreasing plastic waste [38]. Materials such as Polylactic Acid (PLA), starch-based films, and cellulose derivatives are biodegradable or compostable under industrial conditions, preventing long-term pollution and microplastic contamination. For instance, Tetra Pak’s paper-based cartons, which use biopolymer coatings instead of conventional polyethylene layers, have shown a significant reduction in ocean-bound plastic waste, safeguarding ecosystems and biodiversity.

2. Reduction in Carbon Footprint

Using renewable and biodegradable materials like PLA significantly reduces the carbon footprint of packaging. A life cycle assessment (LCA) study found that PLA production emits 60–70% fewer greenhouse gases compared to petroleum-based plastics such as PET or PS [39]. This reduction is attributed to the lower energy requirements of fermenting plant-derived sugars into lactic acid and the carbon sequestration effect of the crops used, thereby contributing to climate change mitigation.

3. Food Safety and Shelf-Life Enhancement

Many sustainable packaging materials possess inherent or enhanced barrier properties that preserve food quality. PLA-based films, when combined with antimicrobial agents like essential oils or nanoparticles such as silver and zinc oxide, can inhibit microbial growth, reduce spoilage, and extend the shelf life of perishable foods [40]. For example, a study by Ramos et al. (2020) demonstrated that PLA films incorporated with oregano essential oil reduced bacterial counts in packaged chicken meat by over 3 log CFU/g during refrigerated storage, minimising the need for synthetic preservatives.

4. Consumer Demand and Brand Image

Modern consumers are increasingly eco-conscious, preferring products with minimal environmental impact. Brands using sustainable packaging gain a competitive advantage by aligning with these preferences. For example, Nestlé’s ‘YES!’ snack bars, launched in Europe with paper-based recyclable wrappers, attracted significant positive consumer response and improved brand reputation [41]. Sustainable packaging not only appeals to ethical consumerism but also fosters brand loyalty and market differentiation.

5. Regulatory Compliance and Future Readiness:

Governments worldwide are implementing stringent regulations to curb single-use plastic pollution. The European Union’s Single-Use Plastics Directive (2019/904) bans or restricts several plastic packaging types, compelling industries to adopt biodegradable or recyclable alternatives [42]. Companies transitioning early to sustainable packaging are better prepared for evolving policies, avoiding fines, supply chain disruptions, and reputational risks, while also positioning themselves as leaders in environmental responsibility.

6. Case Study: Coca-Cola PlantBottle™ Technology

Coca-Cola’s PlantBottle™, launched in 2009, is an example of partially bio-based PET packaging incorporating up to 30% plant-derived monoethylene glycol (MEG). Although not fully biodegradable like PLA, it demonstrates how bio-based alternatives reduce reliance on fossil fuels while maintaining existing recycling streams. As technology advances, fully bio-based and compostable bottles are being researched, reflecting the industry's shift towards a circular economy.

Figure 3: Importance of Sustainable Food Packaging [43]

1.6.Objectives and scope of the review

This review focuses on the recent scientific and technological advancements in the use of Polylactic Acid (PLA) as a food packaging material. It critically analyses the **inherent** properties of PLA and explores how its performance can be enhanced through blending with other polymers and nano-reinforcements to meet packaging requirements effectively. The review further outlines and evaluates modern processing techniques such as extrusion, thermoforming, and electrospinning, highlighting their applicability in the commercial production of PLA-based packaging formats, including trays, films, and containers. Additionally, it discusses the emergence of active and intelligent packaging innovations using PLA systems, along with regulatory considerations and industrial developments supporting their market expansion.

The objectives of this review are:

1. To examine the environmental concerns associated with conventional plastic packaging and define the necessity of adopting biodegradable alternatives.

2. To assess the characteristics and benefits of PLA as a biopolymer for sustainable food packaging applications.
3. To survey recent developments in PLA-based blends, copolymers, and nanocomposites that improve its mechanical, thermal, and barrier properties.
4. To explore new processing techniques and packaging designs that expand PLA's usability across various sectors of the food industry.
5. To identify the major challenges, limitations, and opportunities associated with the large-scale adoption of PLA-based packaging solutions.

In summary, this review aims to provide a holistic understanding of PLA's role in transforming the food packaging industry towards environmental responsibility. The following section delves into the fundamental properties of PLA, discussing its structural, physical, thermal, and mechanical characteristics that underpin its performance as a viable packaging material.

2. PROPERTIES

Polylactic Acid (PLA) is widely used in the food packaging sector because it combines environmental benefits with desirable material properties, making it an effective and sustainable alternative to conventional plastics [44]. Table 2 summarises its key physical, thermal, mechanical, and barrier properties, which determine its performance and suitability for various food packaging applications.

Table 2: Physical, Thermal, and Mechanical Properties of Polylactic Acid (PLA) [45]

Property	Value / Range	Description / Source
Density	1.24 – 1.26 g/cm³	High density compared to other biopolymers
Glass Transition Temperature (Tg)	55 – 65°C	Determines heat resistance and rigidity
Melting Temperature (Tm)	150 – 180°C	Suitable for cold and ambient food packaging
Crystallinity (%)	20 – 40%	Semi-crystalline; affects mechanical strength and clarity
Tensile Strength	50 – 70 MPa	Comparable to PET; indicates mechanical strength
Elongation at Break	2 – 10%	Indicates brittleness; low flexibility
Young's Modulus	3.0 – 3.5 GPa	High stiffness; good rigidity
Oxygen Transmission Rate (OTR)	400 – 500 cc/m²·day·atm	Moderate oxygen barrier
Water Vapour Transmission Rate (WVTR)	1000 – 3000 g/m²·day	High moisture permeability; limits some packaging applications

2.1.Mechanical and Thermal Properties

- **Mechanical Properties of PLA:** Polylactic Acid (PLA) exhibits good mechanical behaviours as it possesses great tensile strength and stiffness; thus, it is structurally similar to other commercial plastics like terephthalate (PET) and polystyrene (PS). These properties are more significant in use in food packages such as trays, containers, cups and films used in the food packaging industry which needs to have properties of durability and shape retention. Nevertheless, brittleness is one of the main drawbacks of PLA because it may influence brittleness and flexion of PLA. The challenge of this is normally overcome by mixing PLA with plasticizers or other polymers so as to make it strong enough or even melt able yet making it tough and flexible at the same time .
- **Thermal Properties of PLA:** Thermally, PLA possesses a glass transition temperature of about 55-65 °C, and melting point of between 150-180 °C. Such heat properties qualify PLA to be used in food packaging that requires cold or ambient temperatures. Nevertheless, its heat resistance is relatively weak so it is a challenge for microwaveable packages or oven-safe packaging. As a way of eliminating this shortcoming, scientists and manufacturers have resorted to methods such as the polymer crystallization or creation of heat resistance PLA blends that enhance its dimensional stability and ensure that it retains its shape even after contact with warmer temperatures without undergoing deformation.

2.2.Barrier Properties (Oxygen, Moisture, CO_2)

Barrier properties are also important in food packaging as they safeguard these foods against foreign forces that may potentially tamper their quality, clearness as well as tastiness. Polylactic Acid (PLA) has moderate gas barrier against both oxygen and carbon dioxide. Effective protection of gases such as oxygen, carbon dioxide as well as moisture is needed to extend shelf life and reduce spoilage or contamination [46]. The fresh produce, baked goods and dry snack packaging benefits by having this characteristic where it is important to control the rate of oxidation and the rate of respiration. PLA allows less oxygen to enter the food products and keeps carbon dioxide trapped, hence extending the sensory and nutritional value of the food product. Nevertheless, the moisture barrier of PLA is relatively low as compared to other conventional plastics such as polyethylene (PE). This is not optimum when it comes to packaging products which are hypersensitive to humidity or moisture-control. As a way to overcome this deficiency, a number of strategies are being used, including the use of surface coatings, the creation of multifaceted film structures or mixing PLA with other biodegradable substances that have better water vapour resistances. This is an important area where improvements must be particularly made so as to enhance the application of PLA in packaging more sensitive food packets that require greater level of protection by the environment.

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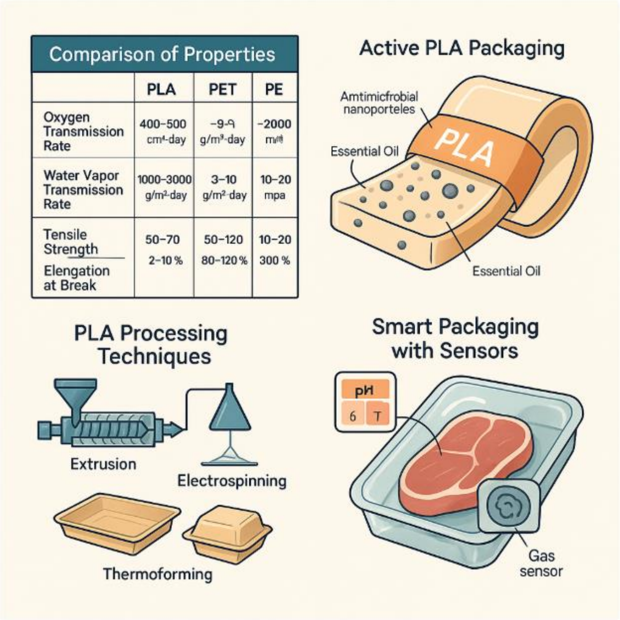

Comparison of Properties

	PLA	PET	PE
Oxygen Transmission Rate	400–500 cm^4-day	−9-9 g/m^3-day	−2000 m/#
Water Vapor Transmission Rate	1000–3000 g/m^2-day	3–10 g/m^2-day	10–20 mpa
Tensile Strength Elengation at Break	50–70 2–10 %	50–120 80–120 %	10–20 300 %

Figure 4: Overview of PLA Properties, Processing, and Packaging Applications [47]

The main features of Polylactic Acid (PLA) in contrast to traditional polymers are graphically summarised in Figure 4, which also emphasises the technology's potential for environmentally friendly food packaging. Comparing PLA's mechanical and barrier qualities to those of PET and PE, the top-left quadrant shows that although PLA has a comparable tensile strength, it is less flexible and has a higher permeability, which calls for modification for delicate packaging. In order to improve shelf life and food safety, PLA is functionalised with antibacterial and antioxidant agents in the top-right area of active packaging strategies. Common PLA processing methods include extrusion, electrospinning, and injection moulding are shown in the bottom-left quadrant. These methods allow for a variety of rigid and flexible packaging shapes. Last but not least, the bottom-right displays smart packaging systems that combine sustainability and food quality monitoring. These systems use PLA films with sensors to detect temperature, gas levels, or spoiling signs. When taken as a whole, the picture highlights PLA's many uses as an environmentally friendly and technologically flexible material for next-generation packaging.

Table 3: Comparison of Key Barrier and Mechanical Properties of PLA, PET, and PE [48]

Property	PLA	PET	PE
Oxygen Transmission Rate (OTR)	400–500 cc/m^2·day·atm	~3–5 cc/m^2·day·atm	~2000 cc/m^2·day·atm
Water Vapor Transmission Rate	1000–3000 g/m^2·day	~3–10 g/m^2·day	~10–20 g/m^2·day
Tensile Strength	50–70 MPa	50–80 MPa	10–20 MPa
Elongation at Break	2–10%	80–120%	300–600%

This comparison highlights that while PLA offers tensile strength similar to PET, it is significantly more brittle, as evidenced by its low elongation at break. Its high oxygen and water vapor transmission rates indicate inferior barrier properties compared to PET and PE, particularly under humid conditions. These limitations suggest that PLA, although biodegradable, requires enhancements such as coatings or blending to match the functional performance of conventional plastics in demanding food packaging applications.

2.3.Biodegradability and Compostability

Polylactic Acid (PLA) is a bio-based polymer known for its biodegradability and industrial compostability, making it an attractive alternative to conventional plastics in food packaging applications. Under industrial composting conditions, which typically involve temperatures above 58°C, high humidity, and active microbial populations, PLA undergoes hydrolysis followed by microbial assimilation, ultimately degrading into carbon dioxide, water, and biomass within a few months. This controlled biodegradation process prevents the accumulation of persistent plastic waste and supports the goals of a circular economy by ensuring that the material returns safely to the environment.

However, PLA’s biodegradation efficiency is highly dependent on environmental conditions. In natural environments such as soil, freshwater, marine water, or landfill settings, PLA degrades at a much slower rate due to lower temperatures and limited microbial activity. Therefore, effective waste management infrastructure and access to industrial composting facilities are essential to fully realise the environmental benefits of PLA packaging. Current research is focused on enhancing PLA’s biodegradability under home composting conditions by modifying its molecular structure or blending with other biodegradable polymers to accelerate degradation rates [49].

Overall, the environmental impact of PLA-based food packaging depends not only on its intrinsic biodegradability but also on developing adequate treatment systems, promoting responsible disposal practices, and innovating material formulations that enable efficient decomposition under diverse conditions.

2.4.Food Safety and Regulatory Compliance

FDA and EFSA has approved Polylactic Acid (PLA) as a safe substance to use in food packaging, owing to the non-toxic and biologically inert properties of the substance, not to mention its free of toxic additives (such as phthalates, bisphenol-A or heavy metals). The PLA-based materials are perfect in selling diverse food substances without the danger of chemical contamination [50]. PLA can be designed with tailored engineering which allows high levels of health and can be manufactured in clean manufacturing facilities and sterilised when required. Regulatory compliance makes it legally acceptable in most nations of the world and therefore, food manufacturing companies cannot find it difficult to use PLA-based packaging without violating regulations on trade and distribution [51]. The regularity of this support develops trust in consumers of its products, a fact that drives people towards knowing more about the materials that touch the food. To conclude, the ideal safety profile, absence of harmful ingredients, gaining the favourable reputation among regulatory bodies, makes PLA a stable and complaint material to be used in food packaging.

3. RECENT MODIFICATIONS AND BLENDS OF PLA

Several ideas associated with the modification of PLA and blending approaches through heavy research and development have been undertaken to enhance PLA products to beat its inherent shortcomings like brittleness, poor moisture protection, and low thermal resistivity (Table 4). Such innovations strive to improve the active characteristics of PLA, expanding its use in the construction of environmentally friendly packaging of food products. These are the most effective methods namely, copolymerization, plasticization, nano-reinforcement, polymer blending, and surface engineering [52].

Table 4: Comparative Properties and Applications of Major Biodegradable Polymers [53]

Property	PLA	PHA	PBS	Starch Blends
Source	Corn starch, sugarcane	Bacterial fermentation	Petroleum-derived + bio-based succinic acid	Corn, potato, cassava starch blended with PLA or PCL
Biodegradability	Industrial composting (fast), slow in natural conditions	Biodegradable in soil, marine, compost	Biodegradable under industrial composting	High biodegradability, including home composting
Mechanical Strength	Good tensile strength; brittle	Good flexibility and toughness	Moderate flexibility and toughness	Brittle unless plasticized or blended
Thermal Properties	Tg: 55–65°C; Tm: 150–180°C	Tm: 160–175°C	Tm: 90–120°C	Low thermal resistance
Barrier Properties	Moderate gas barrier, poor moisture barrier	Good moisture and gas barrier	Moderate barrier properties	Poor moisture barrier; improved with blends
Cost	Moderate	High	Moderate-high	Low
Applications	Rigid trays, cups, films	Films, bags, biomedical	Films, compost bags	Films, compostable bags, edible coatings

Limitations	Brittleness, low heat resistance	High cost of production	Limited supply chain	Poor mechanical and water resistance unless modified

3.1.Copolymerization and Plasticization Techniques (DES, Bio plasticizers)

The coropolymerization and plasticization processes are those needed to enable the enhancement of the PLA in its flexibility, toughness and its thermal performance as the material/polymer is naturally brittle. Copolymerization is the process of making PLA chemically binds with other monomers to make materials with higher mechanical properties and functions and still retain its biodegradability. The latter method is the plasticization where substances such as Deep Eutectic Solvents (DES) or bio-based plasticizers such as glycerol, citric acid, or vegetable oils are added to soften PLA matrix and enhance its process ability and elasticity [54]. These amendments in making PLA more adaptation with regards to flexible food packaging without the threat of losing its environmental-friendliness.

3.1.1. Copolymerization Techniques for PLA

The chemical process which joins PLA with other monomers so that the resultant copolymers exhibit custom properties is termed as copolymerization. This variant can resolve some of the impairments that come along with PLA because of its brittleness, low thermal resistance and poor impact strength [55]. When the PLA is copolymerised with other monomers such as polycaprolactone (PCL) or glycolic acid, researchers are able to produce materials that have not only a higher degree of mechanical flexibility, but with increased ductility and with better thermal properties [56]. Also, glass transition temperature, crystalline, and degradation rate of PLA can be altered by copolymerization, so that its behaviour can be tailored to suit particular requirements of food packaging, including rigid containers and uses more resistant to heat.

3.1.2. Plasticization of PLA Using DES and Bioplasticizers

Plasticization is a method that helps to improve the process ability and bends of PLA through the incorporation of various substances termed as plasticizers. This is either internal plasticizers (These covalently bond PLA chains) or external plasticizers (which are merely physically blended but not covalently bonded) [57]. The ultimate objective of the plasticization is to lessen intermolecular forces in the polymer matrix, therefore, making the material softer, less fractious, and easily processed [58]. A popular current environmental friendly method is Deep Eutectic Solvents (DES) and bio plasticizers based on renewable resources, e. g. bio plasticizers can be produced out of glycerol, citric acid, and vegetable oils. Not only do these additives enhance the ductility and elasticity of PLA, but also, they maintain the biodegradability and non-toxicity of PLA needed to ensure sustainable food packaging. Plasticized PLA finds special application in making flexible films, stretch wrap and bags, where flexibility by machine is almost as important as safety to the environment [59].

3.2. Nano-Reinforcement

Nano-reinforcement is the process of adding nonmaterial to the PLA matrix so that the barrier, mechanical and thermal properties of PLA is greatly improved [60]. For instance:

- Natural waxes (such as carnauba or beeswax) are in focus as having a potential of biodegradable modifiers according to its water resistance and PLA surface hydrophobicity. They also provide plasticizer effect to packaging films whereby they make the film less brittle and more flexible [61].
- Nano clay enhances the gas and moisture barrier effects, stability of dimensions, and stiffness due to the formation of a tortuous path which restrains the diffusion of the molecules within the PLA matrix.
- The cellulose nanofibers (CNFs) have a great mechanical reinforcement property and they are biodegradable. CNFs enhance the tensile strength, thermal stability and oxygen barrier attributes and therefore perfect in high performance packaging of foods.

3.3. Blending with Other Biopolymers

The idea of mixing PLA with other bio-degradable polymers is pragmatic and cost-efficient way of attaining palatable recesses in packaging. A few well-known mixtures are:

- **Starch:** Inexpensive, renewable and biodegradable, starch could lower the price of PLA and increase biodegradability. Nevertheless, it can decrease the water resistance and the mechanical resistance unless it is adjusted.
- **Polyhydroxyalkanoates (PHA):** PHA provides flexibility and heat stability to PLA and consequently the mixture is more usable in rigid packaging.
- **Polybutylene adipate terephthalate (PBAT):** PBAT is flexible, biodegradable polyester that can greatly enhance the impact resistance, elongation at break value, and process good flexibility of a PLA product and can thus be used in the fabrication of films and bags.

The mixtures can mitigate the inherent weaknesses of PLA without losing environmental advantages.

3.4. Surface Coating and Multilayer Structures

Coating and multilayer film production are also referred to as surface engineering technologies in an attempt to improve the moisture resistance, gas permeability, and functional stability of PLA without disturbing the original structure of the substance (Table 5). The water and oxygen barriers can be enhanced with the help of edible or biodegradable coatings, which are created with such substances as chitosan, waxes, or proteins. Multilayer structures, with PLA and other biopolymers or barrier layers in laminated combinations, can be used to achieve customized packaging according to food type, e.g. high-moisture or oxygen-sensitive food [62]. A combination of aesthetics, strength and biodegradability required to make packaging solutions ready in markets is also a possibility with such structures.

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Table 5: Types, Sources, and Functions of PLA Modifications [64]

Technique	Material/Type	Source	Function
Copolymerization	PLA-co-PCL, PLA-co-PGA	Synthetic monomers	Improves flexibility, thermal resistance
Plasticization	Glycerol, Citrate esters, DES	Biobased (e.g., natural solvents)	Enhances ductility, reduces brittleness
Nano-Reinforcement	Wax, Nanoclay, Cellulose nanofibers	Natural waxes, minerals, plant fibers	Enhances barrier, mechanical, and thermal properties
Blending with Biopolymers	Starch, PHA, PBAT	Corn, microbial fermentation, petro-based (PBAT)	Tailors flexibility, cost, and biodegradability
Surface Coating & Multilayers	Chitosan, Waxes, Protein films	Shellfish waste, plants, animal proteins	Improves moisture/gas barrier and food safety

3.5. Active Packaging Functionalization of PLA Films

Active packaging represents an advanced innovation in food packaging technologies, where the packaging system does not merely serve as a passive barrier but actively interacts with the food or its environment to extend shelf life, maintain quality, and enhance safety. When applied to polylactic acid (PLA)-based materials, this approach involves the incorporation of bioactive agents—such as antimicrobial, antioxidant, or moisture-absorbing compounds—either into the PLA matrix, as surface coatings, or within multilayer structures. Antimicrobial agents are among the most widely studied functional additives. Natural essential oils (e.g., oregano, thyme, cinnamon, and clove oil), chitosan, and metallic nanoparticles like silver (AgNPs) or zinc oxide (ZnO) can be embedded within PLA to actively inhibit microbial growth. These materials prevent bacterial colonization on the food surface and help reduce spoilage caused by pathogens like E. coli, Listeria monocytogenes, and Salmonella spp. For instance, electrospun PLA nanofibers containing oregano essential oil have been shown to significantly reduce microbial load in packaged poultry meat, thereby extending shelf life and reducing the need for synthetic preservatives [65].

Antioxidant agents play a critical role in combating oxidative degradation, particularly in fatty or lipid-rich foods. Incorporating antioxidants such as rosemary extract, ascorbic acid (vitamin C), green tea polyphenols, or tocopherols (vitamin E) into PLA matrices prevents lipid oxidation, discoloration, and off-flavor formation. These compounds function by scavenging free radicals, thereby preserving the food's nutritional and sensory attributes over time. PLA’s compatibility with electrospinning and solvent casting techniques allows fine control over the distribution and release of active agents, enabling the development of controlled-release systems that respond to environmental triggers (e.g., pH, moisture, or temperature). Moreover, functional PLA films can be tailored into smart packaging systems, which combine active properties with visual indicators that signal food spoilage or quality changes.

The functionalization of PLA with active compounds not only enhances food preservation and safety but also aligns with the growing consumer demand for natural, safe, and sustainable packaging solutions. Importantly, the use of natural bioactive agents ensures that the overall system remains non-toxic, biodegradable, and compliant with food safety regulations such as those of the FDA and EFSA. For example, Ramos demonstrated that PLA films embedded with oregano essential oil effectively reduced bacterial counts in refrigerated chicken meat by over 3 log CFU/g, showcasing the practical benefits of antimicrobial PLA packaging in real-world scenarios. As the global packaging industry shifts toward circular economy principles, active PLA packaging stands out as a viable solution that combines environmental responsibility with high-performance food protection.

4. PROCESSING TECHNIQUES AND PACKAGING FORMATS

The key to the effective use of PLA in food packaging is processing technologies, which allow shaping packages of many shapes and types without damaging or degrading their functionality. The developments of production processes and ideas of smart packaging have increased the horizons of PLA application and enabled it to surpass being a product of simple packaging and become a multifunctional system which maintained food quality, safety, and durability under conditions of storage. The most important points are examined hereunder:

4.1.Processing Techniques and Applications of PLA

Polylactic Acid (PLA) can be processed using conventional polymer processing methods compatible with existing industrial equipment, making it a versatile biopolymer for various food packaging applications [66]. The primary processing techniques include:

- **Extrusion:** PLA pellets are melted and extruded through a die to form continuous sheets or films, widely used in manufacturing thin wraps, laminates, and multilayer films for food packaging.
- **Thermoforming:** Extruded PLA sheets are heated to pliable temperatures and moulded using specific forms to produce rigid packaging products such as trays, clamshells, and cups**.** Thermoforming is extensively adopted due to its simplicity and cost-effectiveness in producing high-volume packaging formats.
- **Injection Moulding:** In this method, PLA granules are melted and injected under pressure into moulds to create complex, dimensionally precise items such as caps, closures, and small containers required in food packaging.

In addition to these standard processing techniques, solvent-based and advanced fabrication methods are used for specialized applications:

- **Solvent Casting:** Thin, uniform PLA films are produced by dissolving PLA in solvents such as chloroform or dichloromethane and casting the solution onto a surface, followed by solvent evaporation. This method is commonly employed in laboratory-scale research to develop biodegradable coatings or experimental packaging films [67].
- **Electrospinning:** PLA solutions are subjected to high voltage, resulting in ultra-fine nanofibers collected as films or mats with high surface area. Electrospun PLA is explored in applications such as active packaging, where increased surface area facilitates incorporation of antimicrobial or antioxidant agents to enhance food preservation.
- **Layer-by-Layer (LbL) Assembly:** This technique involves sequentially depositing PLA with other materials (e.g., polyelectrolytes or antimicrobial coatings) to create multifunctional composite structures with tailored barrier, mechanical, or bioactive properties. LbL assembly offers opportunities to design intelligent packaging with improved performance for specific food protection requirements.

Through these diverse processing techniques, PLA can be fabricated into a range of packaging formats including films, trays, containers, and functional coatings, effectively meeting varied needs in food preservation, protection, and shelf-life enhancement while ensuring environmental compatibility.

4.2.Active and Intelligent Packaging Integration

The process of food packaging is near-trivial as a barrier; modern food packaging is increasingly made an active participant in the shelf-life extension as well as the observation of food quality. Such smart technologies which can be compatible with PLA-based packaging are [68]:

- **Active Packaging:** This entails incorporation of antimicrobial agent (e.g., essential oils, silver nanoparticles, chitosan) or antioxidants into the PLA matrix or into the surface in order to actively prevent the growth of microbes, or prevent oxidation, thus maintaining food freshness of packaged food products.

- **Intelligent Packaging:** Intelligent packaging based on PLA material means inclusion to smart items such as a detector or indicator which observe and react to changing environmental conditions that alter the quality of foods. Examples of those indicators include ph indicators, which change colour when they notice that the level of acidity in the product is getting out of hand, and time, temperature indicators, the indicator that keeps track of how long the product has been exposed to different temperature changes to make sure it has been kept safe [69]. Also, gas sensors can determine the accumulation of such gas as CO 2 in closed packages, which helps to know the current state of freshness in real-time. These intelligent solutions increase the safety of food, minimize wastage and provide higher levels of transparency to consumers and retailers.

5. PHYSICOCHEMICAL AND MECHANICAL PROPERTY ENHANCEMENTS

Although it is a great addition to the market of sustainable and environmentally-friendly production with respect to its properties such as bio-degradability or eco-friendly footprint, in reality, Polylactic Acid (PLA) is also prone to several limitations regarding its physicochemical and mechanical characteristics [70]. This has necessitated the researchers to come up with various methods that can improve the efficiency of its barrier, thermal, mechanical stability and environmental impact to overcome these drawbacks and make its application more versatile in packaging food and other related industrial activities. This part expounds on the most significant property enhancements that are made by blending, through chemical adjudication, using nanotechnology, and via high-grade processing procedures.

5.1 Barrier Properties (Oxygen, Moisture)

The key property of food packaging is barrier properties which has a direct impact on the shelf life, freshness as well as safety of food products [71]. Unmodified PLA has moderate barrier to gas (like oxygen or carbon dioxide) but its relative barrier to moisture vapour is lower and thus it is not as good a moisture barrier. In order to increase its barrier, it is frequently combined with nonmaterial (e.g., nanoclays, cellulose nanofibers) or prepared as a multilayer film [72]. Nanocomposites introduce a tortuous channel in the movement of gas molecules, and this greatly blocks the oxygen and carbon dioxide permeability. Moreover, applying on the PLA films hydrophobic compounds such as waxes or lipids can enhance moisture resistance. These additions do not only increase the shelf life of perishable food but also tend to preserve the texture, odor and taste of food.

5.2 Thermal Stability

The relatively low thermal stability of PLA, a glass transition temperature of ~5565 C and melting point of 150180 C, precludes its application in hot-fill packaging, microwaveable trays and heat resistant containers. This is a major challenge in food packaging where the products can be either subjected to thermal processing or to different storage conditions. To addressing this, poly (lactide) may be copolymersed with thermally stable monomers or mixed with heat resistant biodegradable polymers such as poly hydroxyalkanoates (PHA) or poly butylene succinate (PBS) [73]. The other usual approaches occur when we enhance the crystallinity of PLA by means of controlled processing or nucleating agents and increase its thermal stability and dimensions stability. Such advancement renders PLA more fit in an expanded variety of packaging centres, such as those that necessitate heat doctoring or sterilisation.

5.3 Mechanical Strength and Flexibility

Although PLA is a tough and stiff material, it is also brittle and lacks any flexibility, which does not allow it to perform well under mechanical stresses, i.e., during transportation or handling the product. Mechanical property enhancement consists of alteration of PLA matrix to improve the elongation at break, impact resistance and tough mechanical properties. Plasticization (in the form of agents such as glycerol, citrate esters or deep eutectic solvents) and polymer blends (PBAT, PCL and thermoplastic starch) are amongst the methods with proven results to enhance the mechanical flexible properties of PLA [74]. Besides, the tensile strength and impact strength are enhanced through reinforcement using nanofillers such as cellulose nanocrystals and carbon nanotubes among others. Such adaptations have given PLA packaging additional strength that has the ability to resist mechanical loads, piercing and flexion, which is crucial both in rigid and flexible packaging products.

5.4 Biodegradability and Environmental Fate

Along with the other pretentious features, the biodegradability of PLA is one of the most appreciated aspects associated with possibility to decompose into harmless end products that include carbon dioxide, water, and bio-mass under the controlled conditions of composting [75]. The rate of degradation of PLA in the natural conditions (such as in the soil, oceans, landfills) is however much lower because of a lack of high temperatures and particular microbial activity. Improvements of PLA degradation refer to blending with some faster-decomposing materials (such as starch or PBS) which lead to an enhancement of the degradation in the ambient conditions. Break down can also occur in a non-industrial environment through the addition of bioactive substances and enzymes that stimulate microbial activity. Moreover, the molecular weight, crystalline of PLA also impacts on the hydrolysis rate and microbial attack rate of PLA. This effect enhances the biodegradability of PLA, making it compatible to the global notion of circular economy and encourages the waste management strategies that help to reduce plastic pollution in the terrestrial and aquatic ecosystem.

6. CHALLENGES AND LIMITATIONS

Although Polylactic Acid (PLA) has quite many benefits as a biodegradable, renewable, and sustainable packaging product, there still exist some technical, economical, and environmental constraints that restrict its further application especially in high-performance food packaging products [76]. The market should overcome these limitations in order to fully exploit the potential of PLA and greatly integrate the system into the market. The most important issues are listed as follows:

- **Polymer-Nan filler Matrix compatibility:** The compatibility of the PLA matrix and nanofillers added to the PLA matrix is one of the significant scientific challenges in the enhancement of PLA. Nanofillers are common to enhance the mechanical, thermal and barrier properties of PLA, however the dispersions of them in the PLA matrix is not always easy to attain. Weak interfacial chemistry or nanoparticle agglomeration can potentially result in phase separation, mechanical inhomogeneity, and localized behaviour. This interaction could be enhanced by surface treatment of nanofillers or compatibilizers, but this means of manipulation adds complexity and cost to the process, something that makes industrial-scale production challenging.
- **Cost and Scalability of Production:** PLA is not less costly when compared to traditional plastics such as polyethylene (PE), polypropylene (PP), or polystyrene (PS) however. Thanks to its renewable nature it can be derived at a larger scale as well. Use of PLA requires various energy-consuming processes that are involved in the production such sugar fermentation, purification of lactic acid and polymerization which increases the cost of manufacturing. Moreover, the PLA production infrastructure is not that mature and widespread as the fossil-based plastic one. Consequently, there will be no full realization of economies of scale which make PLA to be less appealing to low cost and high volume food packaging applications. Lowering the prices of raw materials, efficient processing, and production capacity are key measures to improving the competitiveness of the PLA in the market.
- **Brittleness and Barrier Limitations, Functional Properties Regarding Food Packaging:** The brittle and moderate barrier performance of PLA provides a serious drawback in its use in packaging. It cannot be used in some dynamic applications without any modification due to its low impact resistance, poor flexibility and limited stretchability. Also, PLA has poor oxygen and moisture barrier in comparison to the petroleum-based plastics despite its excellent transparency and printability. Such setbacks make it less effective when it comes to packaging moisture sensitive or highly perishable food products. These problems can be overcome by blending, coating and reinforcement techniques but these are usually complex, expensive and may affect biodegradability [77].
- **Recycling and Disposal Issues:** PLA can be industrially composted but it does not easily decompose in the natural environment, including landfills, in marine environments, or in home composting systems. In addition, PLA cannot be recycled into the conventional plastic waste streams; when commingled with other typical

plastics, it may pollute the recycling process. This poses a serious problem to the waste management system which is not designed to segregate and treat PLA-based materials in a different manner. There is little public awareness and infrastructure to dispose of PLA and mismanaged waste leads to less environmental benefit. To maximize on its biodegradability there is an urgent need to expand industrial composting facilities and educate people on proper disposal methods.

- **Migration and Interaction with Food Contents:** PLA is a food contact approved material by regulatory authorities such as the FDA and EFSA, but the migration of additives, plasticizers, or degradation products into food under specific conditions (e.g. high temperature or low pH) is of concern. In particular where PLA is compounded with other polymers or nonmaterial reinforced, there is a necessity to test and guarantee the safety of the entire components by carrying out stringent migration tests and toxicology studies. Unregulated contact between the PLA packaging and food may jeopardize food safety and consumer confidence. This is especially crucial when it comes to risky or tender products like dairy, meat, or baby food.

7. APPLICATIONS IN THE FOOD INDUSTRY

The Polylactic Acid (PLA) due to its biodegradable, biocompatible and food contact permitted by regulators is becoming more and more used in various applications in the food packaging industry [78]. It can serve many different product types, including fresh produce, beverages, and has environmental advantages. Other than functional packaging, PLA is also useful in shelf life extension, consumer attractiveness and compatibility with sustainability objectives of food industries and regulatory bodies in different parts of the world.

7.1.PLA in Packaging of Dairy, Meat, Bakery, Fruits, and Beverages

As a result of its compost ability, clarity, and stiffness, PLA has been widely used in the packaging of various food types. This is the usage of PLA in the key food categories [79]:

- **Dairy Products:** PLA is applied in yogurt containers, milk bottle linings and cheese containers. It is highly transparent and printable, which is good in branding. Nonetheless, because of its medium moisture barrier, multilayer structures or coatings are frequently applied to maintain product freshness.

- **Meat and Processed Meat Products:** In these products, thermoformed PLA trays, and vacuum-sealable films are used. The antimicrobial additives incorporated in modified PLA can stop bacteria growth and keep the hygiene. Thermal restrictions can however necessitate extra packaging layers of hot or cooked meats.

- **Bakery Items:** PLA films can be used to package bread, cookies and pastries and provide visibility and physical protection. Its biodegradable characteristic is also in line with the current consumer preference to sustainable bakery packaging.

- **Fresh Fruits and Vegetables:** PLA clamshells, stretch wraps and flow packs are common in the fresh produce market where they help to lower respiration rates and keep fragile fruits intact. The readability and the strictness of PLA are attractive in the shelf display.

- **Beverages:** PLA is incorporated in the production of cold drinks cups, straws and lids. PLA can only be used on cold drinks because of its low tolerance to heat. Another frequent alternative found in food service establishments is coated PLA paper cups.

7.2.Shelf-Life Extension and Consumer Acceptance

Though the intrinsic barrier performance of PLA is not as high as conventional plastics, the shelf life has been demonstrated to increase both by blending and coating and by the addition of active additives (e.g., antimicrobials, oxygen scavengers) to PLA to slow the growth of microorganisms, loss of moisture, or oxidation [80].

Also, the importance of sustainability and eco-friendly packaging is growing among the consumers and this has had a positive impact on the acceptance of PLA-based products. Research has shown that visual attractiveness (transparency, tactile), compostable labels and food safety are important factors that influence consumer appeal to PLA-packed products. PLA is also preferred by retailers and food manufacturers because of its branding potential and green certifications compliance.

7.3.Case Studies or Commercial PLA-Based Products

There are a number of commercially successful products which note the increased presence of PLA in the food packaging market (Table 6) [81]:

- Danone and Stonyfield Farm have employed PLA-based yogurt cups to decrease carbon footprint and enhance sustainability of packaging.
- One of the biggest PLA producers (under the brand IngeoTM) is NatureWorks LLC, which sells PLA resins to various food brands to produce trays, containers and films.
- Vegware and BioPak have a wide range of certified compostable PLA catering and food delivery packaging, cutlery, cups, salad boxes, and clamshell.
- Delhaize is one of the largest European food retailers that launched PLA-packed baked goods and fruit packaging, stating that they have decreased the plastic consumption and enhanced consumer feedback.

Table 6: Commercially Available PLA-Based Products and Their Applications [82]

Product Name	Company/Brand	Application
Ingeo™ PLA Resins	NatureWorks LLC	Trays, containers, films
PlantBottle™	Coca-Cola	Beverage bottles (30% bio-based PET)

PLA Yogurt Cups	Danone, Stonyfield Farm	Yogurt packaging
PLA Cutlery and Containers	Vegware	Catering disposables
PLA Cold Cups and Lids	BioPak	Cold beverage packaging
PLA Bakery Trays	Delhaize	Bakery and fruit packaging

These examples highlight the way in which PLA has already breached the niche and the mainstream markets and is proving to be effective when its functional, environmental, and economic drivers are in play.

7.4.Real-World Applications and Market Adoption

The increasing global demand for sustainable and eco-conscious food packaging has prompted numerous companies to adopt PLA-based packaging solutions in response to both regulatory pressures and shifting consumer preferences [81]. The transition from conventional, petroleum-derived plastics to compostable, bio-based alternatives such as PLA has seen substantial momentum in recent years, with major brands integrating these materials into their supply chains. These real-world case studies highlight the practical feasibility, consumer acceptance, and environmental relevance of PLA packaging in diverse food service and retail settings [83].

One notable example is Just Salad, a U.S.-based fast-casual restaurant chain that has embraced sustainability as a core operational principle. The company introduced PLA-based compostable cutlery and food bowls as part of its broader initiative to reduce single-use plastic waste. By replacing traditional plastic disposables with items made from PLA, Just Salad aims to minimize landfill-bound waste while maintaining functional performance and food safety [84]. This move not only supports waste reduction goals but also enhances the brand's eco-conscious image among its urban, environmentally aware clientele.

Similarly, HelloFresh, a globally recognized meal-kit delivery service, has adopted compostable PLA liners for packaging its temperature-sensitive products [85]. In 2023, HelloFresh made a strategic shift towards PLA-based thermal liners to align with its corporate sustainability targets. The use of compostable liners offers dual benefits: reducing dependency on expanded polystyrene (EPS) and other non-biodegradable materials, and lowering the carbon footprint associated with last-mile food delivery. This innovation reflects the scalability of PLA in insulated food logistics and demonstrates how biodegradable polymers can meet the complex needs of modern e-commerce supply chains [86].

In the United Kingdom, Marks & Spencer (M&S), a major food and retail conglomerate, piloted the use of PLA-sealed produce pouches with integrated freshness-enhancing coatings. These pouches are designed to preserve fruits and vegetables by maintaining an optimal microclimate, leveraging PLA's transparency and biodegradability while improving shelf-life performance through active barrier enhancements. The initiative is part of M&S's 'Plan A' sustainability roadmap, which commits to eliminating non-recyclable plastic packaging and supporting circular material use. The deployment of PLA in high-volume fresh produce packaging signifies a promising shift from trial-scale implementations to full-scale commercial application.

Collectively, these real-world examples demonstrate the increasing market penetration and practical adoption of PLA-based packaging solutions by mainstream companies across sectors—from dine-in food services to subscription-based meal delivery and large-scale retail. These implementations showcase the adaptability of PLA to different packaging formats (e.g., bowls, liners, pouches), underline its role in brand differentiation and regulatory compliance, and affirm its potential as a cornerstone material in sustainable packaging transformations [87].

8. FUTURE PROSPECTS AND RESEARCH DIRECTIONS

Polylactic Acid (PLA) has already become a viable biopolymer in food packaging that is sustainable. Nevertheless, to achieve its full potential and address the current shortcomings, future research and industrial advances have to be directed towards the improvement of its performance, the compatibility with the environment, and the incorporation of PLA into the wider circular economy and sustainability approaches [88]. The technological innovations, the green chemistry, the intelligent packaging system, and the favourable regulatory environment are some of the techno-future of the PLA.

8.1.Improvement in Mechanical and Functional Performance

Among the most urgent and important future research on PLA, there is the one that would improve its mechanical and functional properties, especially to enhance its ductile nature, thermal and barrier properties, and still maintain its original strength of biodegradability. The current drawbacks of PLA such as brittle nature, low moisture barrier, and low thermal stability limit its applicability to various industrial and food packaging applications which demand greater durability and strength [89]. To cope with these problems, scientists are actively engaged in creating new copolymers that will be as environmental friendly as PLA, but will be more impact resistant and bendable, to be used in more demanding applications. The other important area of consideration is the use of sophisticated plasticizers and polymer blending, which is aimed at enhancing flexibility and elasticity, but with no adverse effects of leaching and degradation in the long run. It has also been demonstrated that advances in processing methods of controlling crystallization in PLA processing could be used to improve its thermal stability and structural integrity, and expand its use in hot-fill packaging, microwaveable containers, and reusable bio plastics [90]. Collectively, these developments will help turn PLA into a mainstream material rather than a niche biopolymer capable of being used in a variety of high-performance, environmentally friendly packaging applications.

8.2.Green Nanofiller Synthesis

Green nanofiller production is an emerging and sustainable domain in terms of improving the performance of PLA-based material [91]. With nanotechnology still playing a decisive role in enhancing the mechanical, thermal and barrier characteristics of biopolymers, the focus is increasingly directed at the development of nanofillers that are not only functional, but also sustainable and biodegradable. Conventionally, reinforcement of PLA has involved inorganic or synthetic nonmaterial, which may affect the compost ability of the latter and increase environmental or toxicity issues. To counter this, researchers are resorting to the exploitation of bio-based sources to develop nanofillers. Agricultural waste-derived cellulose nanocrystals (CNCs), starch nanoparticles, lignin, and chitosan are emerging as materials due to their renewability, biodegradability and excellent reinforcing properties [92]. Also, natural wax nanoemulsions are under investigation in terms of their potential in increasing the surface hydrophobicity and moisture Water Barrier in PLA films. The main goal of the application of these green nanofillers is to guarantee that the improved PLA will still be non-toxic and compostable in nature and will be cost-effective and functionally superior. This solution corresponds to the principles of green chemistry and circular design, which helps to create the next-generation of environmentally friendly packaging with a low environmental impact.

8.3.Integration with Circular Economy Principles

The future of PLA research is slowly but surely moving towards producing systems where materials are reused recycled or safely biodegraded so that waste and environmental pollution is minimal as the world moves towards a circular economy model. The paradigm focuses on the entire lifecycle of products and PLA, as a biodegradable polymer, has great prospects of fitting into these concepts when suitably handled [93]. A large scale creation of closed-loop composting and collection systems is one of the main areas of development as it would secure that post-consumer PLA packaging could be efficiently collected and directed to the industrial composting facilities instead of ending up in landfills or polluting the recycling streams [94]. Simultaneously, scientists and other stakeholders in the industry are developing solutions to mechanical and chemical recycling of PLA, and thus, lactic acid monomers or other recyclable materials can be returned to the production process [95]. Moreover, in the future, the PLA packaging design will probably include multicomponent systems, such as films, coatings, inks, and adhesives, each of which is either compostable or recyclable, so that the materials can be used in a circular waste management system [96]. The PLA integration in a circular economy environment not only helps the world to mitigate the reliance on fossil-based plastics but also leads to developing regenerative, low-impact industrial ecosystems where the importance of long-term environmental sustainability is considered.

8.4.Smart Packaging and Sustainability Goals

The other promising trend is the integration of smart technologies with PLA-based packaging. These include [97]:

- Biosensors and indicators (pH, temperature, gas changes, etc.) to advise the consumer about the freshness of the product.
- Additives that are antimicrobial and antioxidants and actively maintain food quality.
- Compost ability labels in QR code or interactive packaging aspects that encourage consumer education and proper disposal practices.

Smart PLA packaging can help achieve wider sustainability and food safety objectives by minimizing food waste, increasing consumer confidence, and allowing real-time quality tracking [98].

8.5.Industrial and Policy-Level Integration

To go global, PLA needs industrial support and policies. Study should be in line with [99]:

- Government policies to promote the use of bioplastics in terms of incentives, subsidy, or a ban on single-use plastics.
- Normalization of composting facilities, such as labelling standards and biodegradability tests.
- Public-private partnerships to facilitate innovation, manufacturing and supply chain development of PLA.

Policy frameworks and industrial ecosystems need to change in the future so that PLA is not only one of the materials of choice but a system solution to sustainable packaging, in every sector [100].

9. CONCLUSION

The recent breakthrough in Polylactic Acid (PLA) has made it a very good candidate in terms of sustainability and high-performance material in food packaging. The previous shortcomings of PLA, including brittleness, low thermal resistance, and poor barrier properties have been successfully overcome by means of new technologies like copolymerization, bio-based plasticization, nano-reinforcement, and multilayer film structures, which have led to enhanced mechanical strength, thermal stability, and moisture and gas barrier performance. Such advancements have increased the scope of PLA in the different food industries such as dairy, meat, and bakery, fresh produce, and beverages. In addition to functional enhancements, PLA also has considerable environmental benefits since it is biodegradable, compostable under industrial conditions, and made of renewable sources, making it one of the most important materials in the transition to eco-friendly and circular economy-based packaging systems worldwide. The combination of smart packaging technologies, including biosensors and antimicrobial agents, further increases the usefulness of PLA in the shelf-life extension, food waste reduction, and consumer safety. Along with these improvements, however, there are still challenges: cost-competitiveness, inability to break down in home composters, and the lack of infrastructure to deal with the waste. Consequently, the future research should aim at the development of low-cost, scalable production processes, green nanofillers synthesis, enhancement of environmental degradability, and the development of efficient composting and recycling. As long as innovation and policy continue to support it, PLA will become a pillar of sustainable packaging industry, with environmental and economic benefits.

9.1.Research Gaps and Future Directions

While significant progress has been made in enhancing the properties and processing of PLA for food packaging, research gaps remain in improving its biodegradation under home composting conditions, developing cost-effective green nanofillers, and scaling up recycling and composting infrastructures to handle PLA waste effectively. Additionally, long-term migration studies assessing food safety, economic feasibility analyses of advanced PLA modifications, and integration of smart technologies (e.g., sensors, indicators) with minimal environmental impact require further exploration. Future research should also focus on designing fully circular systems for PLA production, use, and end-of-life treatment to establish it as a mainstream sustainable packaging material globally.

REFERENCES

1. Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020). Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials. *Materials*, *13*(21), 4994.
2. Mangaraj, S., Yadav, A., Bal, L. M., Dash, S. K., & Mahanti, N. K. (2019). Application of biodegradable polymers in food packaging industry: A comprehensive review. *Journal of Packaging Technology and Research*, *3*, 77-96.
3. Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Syafiq, R. S. F. K. S., & Sherwani, S. F. K. (2020). Nanocellulose reinforced thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications. *Frontiers in chemistry*, *8*, 213.
4. Arora, A., & Padua, G. W. (2010). Nanocomposites in food packaging. *Journal of Food science*, *75*(1), R43-R49.
5. De Azeredo, H. M. (2009). Nanocomposites for food packaging applications. *Food research international*, *42*(9), 1240-1253.
6. Siracusa, V., Rocculi, P., Romani, S., & Dalla Rosa, M. (2008). Biodegradable polymers for food packaging: a review. *Trends in food science & technology*, *19*(12), 634-643.
7. Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Peeters, R., Cardon, L., ... &Devlieghere, F. (2013). Application of bioplastics for food packaging. *Trends in Food Science & Technology*, *32*(2), 128-141.
8. Wang, H., Qian, J., & Ding, F. (2018). Emerging chitosan-based films for food packaging applications. *Journal of agricultural and food chemistry*, *66*(2), 395-413.
9. **Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Syafiq, R. S. F. K. S., & Sherwani, S. F. K. (2020).** Nanocellulose reinforced thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications. *Frontiers in Chemistry*, **8**, 213.
10. Marano, S., Laudadio, E., Minnelli, C., & Stipa, P. (2022). Tailoring the barrier properties of PLA: a state-of-the-art review for food packaging applications. *Polymers*, *14*(8), 1626.
11. Swetha, T. A., Bora, A., Mohanrasu, K., Balaji, P., Raja, R., Ponnuchamy, K., ... & Arun, A. (2023). A comprehensive review on polylactic acid (PLA)–Synthesis, processing

and application in food packaging. *International Journal of Biological Macromolecules*, *234*, 123715.
12. Rodríguez-Núñez, J. R., Madera-Santana, T. J., Burrola-Núñez, H., & Martínez-Encinas, E. G. (2018). Composite materials based on PLA and its applications in food packaging. *Composites materials for food packaging*, 355-399.
13. Wu, J. H., Hu, T. G., Wang, H., Zong, M. H., Wu, H., & Wen, P. (2022). Electrospinning of PLA nanofibers: Recent advances and its potential application for food packaging. *Journal of Agricultural and Food Chemistry*, *70*(27), 8207-8221.
14. Shao, L., Xi, Y., & Weng, Y. (2022). Recent advances in PLA-based antibacterial food packaging and its applications. *Molecules*, *27*(18), 5953.
15. Sorrentino, A., Gorrasi, G., & Vittoria, V. (2007). Potential perspectives of bio-nanocomposites for food packaging applications. *Trends in food science & technology*, *18*(2), 84-95.
16. Arrieta, M. P., Fortunati, E., Burgos, N., Peltzer, M. A., López, J., &Peponi, L. (2016). Nanocellulose-based polymeric blends for food packaging applications. *Multifunctional polymeric nanocomposites based on cellulosic reinforcements*, 205-252.
17. Mihindukulasuriya, S. D. F., & Lim, L. T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology*, *40*(2), 149-167.
18. Siracusa, V. (2012). Food packaging permeability behaviour: A report. *International Journal of Polymer Science*, *2012*(1), 302029.
19. Espitia, P. J. P., Soares, N. D. F. F., Coimbra, J. S. D. R., de Andrade, N. J., Cruz, R. S., & Medeiros, E. A. A. (2012). Zinc oxide nanoparticles: synthesis, antimicrobial activity and food packaging applications. *Food and bioprocess technology*, *5*, 1447-1464.
20. Espitia, P. J. P., Otoni, C. G., & Soares, N. F. F. (2025). Zinc oxide nanoparticles for food packaging applications. In Antimicrobial food packaging (pp. 603-610). Academic Press.
21. Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., ... & Coma, V. (2018). Active packaging applications for food. *Comprehensive Reviews in food science and food safety*, *17*(1), 165-199.
22. Silvestre, C., Duraccio, D., & Cimmino, S. (2011). Food packaging based on polymer nanomaterials. *Progress in polymer science*, *36*(12), 1766-1782.
23. Avella, M., De Vlieger, J. J., Errico, M. E., Fischer, S., Vacca, P., & Volpe, M. G. (2005). Biodegradable starch/clay nanocomposite films for food packaging applications. *Food chemistry*, *93*(3), 467-474.
24. Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. *Progress in Polymer Science*, *117*, 101395.
25. Pankaj, S. K., Bueno-Ferrer, C., Misra, N. N., Milosavljević, V., O'donnell, C. P., Bourke, P., ... & Cullen, P. J. (2014). Applications of cold plasma technology in food packaging. *Trends in Food Science & Technology*, *35*(1), 5-17.

26. Marsh, K., &Bugusu, B. (2007). Food packaging—roles, materials, and environmental issues. *Journal of food science*, *72*(3), R39-R55.
27. Elsawy, M. A., Kim, K. H., Park, J. W., & Deep, A. (2017). Hydrolytic degradation of polylactic acid (PLA) and its composites. *Renewable and Sustainable Energy Reviews*, *79*, 1346-1352.
28. Onyeaka, H., Obileke, K., Makaka, G., & Nwokolo, N. (2022). Current research and applications of starch-based biodegradable films for food packaging. *Polymers*, *14*(6), 1126.
29. Said, N. S., Howell, N. K., &Sarbon, N. M. (2023). A review on potential use of gelatin-based film as active and smart biodegradable films for food packaging application. *Food Reviews International*, *39*(2), 1063-1085.
30. Altan, A., Aytac, Z., & Uyar, T. (2018). Carvacrol loaded electrospun fibrous films from zein and poly (lactic acid) for active food packaging. *Food Hydrocolloids*, *81*, 48-59.
31. Mellinas, C., Ramos, M., Jiménez, A., & Garrigós, M. C. (2020). Recent trends in the use of pectin from agro-waste residues as a natural-based biopolymer for food packaging applications. *Materials*, *13*(3), 673.
32. Zhao, X., Cornish, K., & Vodovotz, Y. (2020). Narrowing the gap for bioplastic use in food packaging: an update. *Environmental science & technology*, *54*(8), 4712-4732.
33. Abdul Khalil, H. P. S., Banerjee, A., Saurabh, C. K., Tye, Y. Y., Suriani, A. B., Mohamed, A., ... & Paridah, M. T. (2018). Biodegradable films for fruits and vegetables packaging application: preparation and properties. *Food Engineering Reviews*, *10*(3), 139-153.
34. Priyadarshi, R., Ezati, P., & Rhim, J. W. (2021). Recent advances in intelligent food packaging applications using natural food colorants. *ACS Food Science & Technology*, *1*(2), 124-138.
35. Bumbudsanpharoke, N., & Ko, S. (2019). Nanoclays in food and beverage packaging. *Journal of Nanomaterials*, *2019*(1), 8927167.
36. Basavegowda, N., & Baek, K. H. (2021). Synergistic antioxidant and antibacterial advantages of essential oils for food packaging applications. Biomolecules, 11(9), 1267.
37. Cheng, J., Lin, X., Wu, X., Liu, Q., Wan, S., & Zhang, Y. (2021). Preparation of a multifunctional silver nanoparticles polylactic acid food packaging film using mango peel extract. *International Journal of Biological Macromolecules*, *188*, 678-688.
38. Fahmy, H. M., Eldin, R. E. S., Serea, E. S. A., Gomaa, N. M., AboElmagd, G. M., Salem, S. A., ... & Shalan, A. E. (2020). Advances in nanotechnology and antibacterial properties of biodegradable food packaging materials. RSC advances, 10(35), 20467-20484.
39. Niranjana Prabhu, T., & Prashantha, K. (2018). A review on present status and future challenges of starch based polymer films and their composites in food packaging applications. *Polymer Composites*, *39*(7), 2499-2522.
40. Aman Mohammadi, M., Ramezani, S., Hosseini, H., Mortazavian, A. M., Hosseini, S. M., & Ghorbani, M. (2021). Electrospun antibacterial and antioxidant zein/polylactic

acid/hydroxypropyl methylcellulose nanofibers as an active food packaging system. *Food and Bioprocess Technology*, *14*(8), 1529-1541.

41. Yang, W., Weng, Y., Puglia, D., Qi, G., Dong, W., Kenny, J. M., & Ma, P. (2020). Poly (lactic acid)/lignin films with enhanced toughness and anti-oxidation performance for active food packaging. *International journal of biological macromolecules*, *144*, 102-110.
42. Niu, X., Liu, Y., Song, Y., Han, J., & Pan, H. (2018). Rosin modified cellulose nanofiber as a reinforcing and co-antimicrobial agents in polylactic acid/chitosan composite film for food packaging. *Carbohydrate polymers*, *183*, 102-109.
43. Gaikwad, K. K., Singh, S., & Lee, Y. S. (2018). Oxygen scavenging films in food packaging. *Environmental Chemistry Letters*, *16*(2), 523-538.
44. Kim, I., Viswanathan, K., Kasi, G., Thanakkasaranee, S., Sadeghi, K., & Seo, J. (2022). ZnO nanostructures in active antibacterial food packaging: Preparation methods, antimicrobial mechanisms, safety issues, future prospects, and challenges. *Food Reviews International*, *38*(4), 537-565.
45. Vieira, I. R. S., de Carvalho, A. P. A. D., & Conte-Junior, C. A. (2022). Recent advances in biobased and biodegradable polymer nanocomposites, nanoparticles, and natural antioxidants for antibacterial and antioxidant food packaging applications. *Comprehensive Reviews in Food Science and Food Safety*, *21*(4), 3673-3716.
46. Costa, S. M., Ferreira, D. P., Teixeira, P., Ballesteros, L. F., Teixeira, J. A., & Fangueiro, R. (2021). Active natural-based films for food packaging applications: The combined effect of chitosan and nanocellulose. *International Journal of Biological Macromolecules*, *177*, 241-251.
47. Roy, S., Ezati, P., & Rhim, J. W. (2021). Gelatin/carrageenan-based functional films with carbon dots from enoki mushroom for active food packaging applications. *ACS Applied Polymer Materials*, *3*(12), 6437-6445.
48. Wrona, M., & Nerín, C. (2020). Analytical approaches for analysis of safety of modern food packaging: A review. *Molecules*, *25*(3), 752.
49. Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z., & Younis, K. (2022). Application of nanotechnology in food packaging: Pros and Cons. *Journal of Agriculture and Food Research*, *7*, 100270.
50. Kumar, L., Ramakanth, D., Akhila, K., & Gaikwad, K. K. (2022). Edible films and coatings for food packaging applications: A review. *Environmental Chemistry Letters*, *20*(1), 875-900.
51. Qasim, U., Osman, A. I., Al-Muhtaseb, A. A. H., Farrell, C., Al-Abri, M., Ali, M., ... & Rooney, D. W. (2021). Renewable cellulosic nanocomposites for food packaging to avoid fossil fuel plastic pollution: a review. Environmental Chemistry Letters, 19(1), 613-641.

52. Alehosseini, A., Gómez-Mascaraque, L. G., Martínez-Sanz, M., & López-Rubio, A. (2019). Electrospun curcumin-loaded protein nanofiber mats as active/bioactive coatings for food packaging applications. *Food Hydrocolloids*, *87*, 758-771.
53. Jayakumar, A., Heera, K. V., Sumi, T. S., Joseph, M., Mathew, S., Praveen, G., ... & Radhakrishnan, E. K. (2019). Starch-PVA composite films with zinc-oxide nanoparticles and phytochemicals as intelligent pH sensing wraps for food packaging application. *International Journal of Biological Macromolecules*, *136*, 395-403.
54. Zhong, Y., Godwin, P., Jin, Y., & Xiao, H. (2020). Biodegradable polymers and green-based antimicrobial packaging materials: A mini-review. *Advanced Industrial and Engineering Polymer Research*, *3*(1), 27-35.
55. Cvek, M., Paul, U. C., Zia, J., Mancini, G., Sedlarik, V., & Athanassiou, A. (2022). Biodegradable films of PLA/PPC and curcumin as packaging materials and smart indicators of food spoilage. *ACS Applied Materials & Interfaces*, *14*(12), 14654-14667.
56. Peighambardoust, S. J., Peighambardoust, S. H., Pournasir, N., & Pakdel, P. M. (2019). Properties of active starch-based films incorporating a combination of Ag, ZnO and CuO nanoparticles for potential use in food packaging applications. *Food Packaging and Shelf Life*, *22*, 100420.
57. Dash, K. K., Ali, N. A., Das, D., & Mohanta, D. (2019). Thorough evaluation of sweet potato starch and lemon-waste pectin based-edible films with nano-titania inclusions for food packaging applications. *International journal of biological macromolecules*, *139*, 449-458.
58. Xie, J., Wang, Z., Zhao, Q., Yang, Y., Xu, J., Waterhouse, G. I., ... & Jin, G. (2018). Scale-up fabrication of biodegradable poly (butylene adipate-co-terephthalate)/organophilic–clay nanocomposite films for potential packaging applications. *ACS omega*, *3*(1), 1187-1196.
59. Vasile, C. (2018). Polymeric nanocomposites and nanocoatings for food packaging: A review. *Materials*, *11*(10), 1834.
60. Asgher, M., Qamar, S. A., Bilal, M., & Iqbal, H. M. (2020). Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Research International*, *137*, 109625.
61. Azeredo, H. M., Barud, H., Farinas, C. S., Vasconcellos, V. M., & Claro, A. M. (2019). Bacterial cellulose as a raw material for food and food packaging applications. *Frontiers in Sustainable Food Systems*, *3*, 7.
62. Moustafa, H., Youssef, A. M., Darwish, N. A., & Abou-Kandil, A. I. (2019). Eco-friendly polymer composites for green packaging: Future vision and challenges. *Composites Part B: Engineering*, *172*, 16-25.
63. Huang, Y., Mei, L., Chen, X., & Wang, Q. (2018). Recent developments in food packaging based on nanomaterials. *Nanomaterials*, *8*(10), 830.
64. Sánchez-Safont, E. L., Aldureid, A., Lagarón, J. M., Gámez-Pérez, J., & Cabedo, L. (2018). Biocomposites of different lignocellulosic wastes for sustainable food packaging applications. *Composites Part B: Engineering*, *145*, 215-225.

65. Muthuraj, R., Misra, M., & Mohanty, A. K. (2018). Biodegradable compatibilized polymer blends for packaging applications: A literature review. *Journal of Applied Polymer Science*, *135*(24), 45726.
66. Kakadellis, S., & Harris, Z. M. (2020). Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment–A critical review. *Journal of Cleaner Production*, *274*, 122831.
67. Liu, Y., Wang, S., & Lan, W. (2018). Fabrication of antibacterial chitosan-PVA blended film using electrospray technique for food packaging applications. *International Journal of Biological Macromolecules*, *107*, 848-854.
68. Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. *RSC advances*, *10*(33), 19309-19336.
69. Gupta, V., Biswas, D., & Roy, S. (2022). A comprehensive review of biodegradable polymer-based films and coatings and their food packaging applications. *Materials*, *15*(17), 5899.
70. Shao, L., Xi, Y., & Weng, Y. (2022). Recent advances in PLA-based antibacterial food packaging and its applications. *Molecules*, 27(18), 5953.
71. Rodríguez-Núñez, J. R., Madera-Santana, T. J., Burrola-Núñez, H., & Martínez-Encinas, E. G. (2018). Composite materials based on PLA and its applications in food packaging. In *Composites materials for food packaging* (pp. 355-399). Elsevier.
72. Marano, S., Laudadio, E., Minnelli, C., & Stipa, P. (2022). Tailoring the barrier properties of PLA: a state-of-the-art review for food packaging applications. *Polymers*, 14(8), 1626
73. Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Syafiq, R. S. F. K. S., & Sherwani, S. F. K. (2020). Nanocellulose reinforced thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications. *Frontiers in Chemistry*, 8, 213.
74. Guo, Z., Zhang, Y., Cao, J., & Li, H. (2021). A review on the recycling of waste PET bottles: Strategies and technologies. *Polymer Degradation and Stability*, 190, 109638.
75. Yildirim-Yucel, Z., Yesil-Celiktas, O., & Bedir, E. (2022). Biodegradable polymers for food packaging applications. *Food Science and Technology*, 42.

76. **Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020).** Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials. *Materials,* **13**(21), 4994.
77. **Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Peeters, R., Cardon, L., et al. (2013).** Application of bioplastics for food packaging. *Trends in Food Science & Technology,* **32**(2), 128-141.
78. **Vink, E. T., Rabago, K. R., Glassner, D. A., & Gruber, P. R. (2003).** Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production. *Polymer Degradation and Stability,* **80**(3), 403-419.

79. **Rodríguez-Núñez, J. R., Madera-Santana, T. J., Burrola-Núñez, H., & Martínez-Encinas, E. G. (2018).** Composite materials based on PLA and its applications in food packaging. In *Composites Materials for Food Packaging* (pp. 355-399).
80. **Arrieta, M. P., Samper, M. D., Aldas, M., & López, J. (2017).** On the use of PLA-PHB blends for sustainable food packaging applications. *Materials*, **10**(9), 1008.
81. Sin, L. T. (2012). *Polylactic acid: PLA biopolymer technology and applications*. William Andrew.
82. Ubeda, S., Aznar, M., Alfaro, P., & Nerín, C. (2019). Migration of oligomers from a food contact biopolymer based on polylactic acid (PLA) and polyester. *Analytical and bioanalytical chemistry*, *411*(16), 3521-3532.
83. Gan, I., & Chow, W. S. (2018). Antimicrobial poly (lactic acid)/cellulose bionanocomposite for food packaging application: A review. *Food packaging and shelf life*, *17*, 150-161.
84. Mohamad, N., Mazlan, M. M., Tawakkal, I. S. M. A., Talib, R. A., Kian, L. K., Fouad, H., & Jawaid, M. (2020). Development of active agents filled polylactic acid films for food packaging application. *International Journal of Biological Macromolecules*, *163*, 1451-1457.
85. Siracusa, V., Blanco, I., Romani, S., Tylewicz, U., Rocculi, P., & Rosa, M. D. (2012). Poly (lactic acid)-modified films for food packaging application: Physical, mechanical, and barrier behavior. *Journal of Applied Polymer Science*, *125*(S2), E390-E401.
86. Marra, A., Silvestre, C., Duraccio, D., & Cimmino, S. (2016). Polylactic acid/zinc oxide biocomposite films for food packaging application. *International journal of biological macromolecules*, *88*, 254-262.
87. Malek, N. S. A., Faizuwan, M., Khusaimi, Z., Bonnia, N. N., Rusop, M., & Asli, N. A. (2021, April). Preparation and characterization of biodegradable polylactic acid (PLA) film for food packaging application: A Review. In *Journal of Physics: Conference Series* (Vol. 1892, No. 1, p. 012037). IOP Publishing.
88. Swaroop, C., & Shukla, M. (2018). Nano-magnesium oxide reinforced polylactic acid biofilms for food packaging applications. *International Journal of Biological Macromolecules*, *113*, 729-736.
89. Makhijani, K., Kumar, R., & Sharma, S. K. (2015). Biodegradability of blended polymers: A comparison of various properties. *Critical Reviews in Environmental Science and Technology*, *45*(16), 1801-1825.
90. Patwary, M. S., Surid, S. M., & Gafur, M. A. (2020). Properties and applications of biodegradable polymers. *Journal of Research*, *9*, 33.
91. Taib, N. A. A. B., Rahman, M. R., Huda, D., Kuok, K. K., Hamdan, S., Bakri, M. K. B., ... & Khan, A. (2023). A review on poly lactic acid (PLA) as a biodegradable polymer. *Polymer Bulletin*, *80*(2), 1179-1213.
92. Singhvi, M., & Gokhale, D. (2013). Biomass to biodegradable polymer (PLA). *RSC advances*, *3*(33), 13558-13568.

93. Chen, C. C., Chueh, J. Y., Tseng, H., Huang, H. M., & Lee, S. Y. (2003). Preparation and characterization of biodegradable PLA polymeric blends. *Biomaterials*, *24*(7), 1167-1173.
94. Baran, E. H., & Erbil, H. Y. (2019). Surface modification of 3D printed PLA objects by fused deposition modeling: a review. *Colloids and interfaces*, *3*(2), 43.
95. Cheng, Y., Deng, S., Chen, P., & Ruan, R. (2009). Polylactic acid (PLA) synthesis and modifications: a review. *Frontiers of chemistry in China*, *4*(3), 259-264.
96. Standau, T., Zhao, C., Murillo Castellón, S., Bonten, C., & Altstädt, V. (2019). Chemical modification and foam processing of polylactide (PLA). *Polymers*, *11*(2), 306.
97. Kay, I. P., Herskovitz, J. E., & Goddard, J. M. (2022). Interfacial behavior of a polylactic acid active packaging film dictates its performance in complex food matrices. *Food Packaging and Shelf Life*, *32*, 100832.
98. Rojas, A., Velásquez, E., Patiño Vidal, C., Guarda, A., Galotto, M. J., & López de Dicastillo, C. (2021). Active PLA packaging films: effect of processing and the addition of natural antimicrobials and antioxidants on physical properties, release kinetics, and compostability. *Antioxidants*, *10*(12), 1976.
99. Martins, C., Vilarinho, F., Silva, A. S., Andrade, M., Machado, A. V., Castilho, M. C., ... & Ramos, F. (2018). Active polylactic acid film incorporated with green tea extract: Development, characterization and effectiveness. *Industrial crops and products*, *123*, 100-110.
100. Papadopoulou, E. L., Paul, U. C., Tran, T. N., Suarato, G., Ceseracciu, L., Marras, S., ... & Athanassiou, A. (2019). Sustainable active food packaging from poly (lactic acid) and cocoa bean shells. *ACS applied materials & interfaces*, *11*(34), 31317-31327.

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