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Beyond fossil plastics: next-generation PLA-based bio-packaging for industrial applications – advances, challenges, and data-driven insights

Naja Hasoon K.T. and Unnikrishnan Gopalakrishna Panicker *

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The accumulation of conventional plastics has increased the need for sustainable alternatives, particularly those derived from renewable resources. Among these, polylactic acid (PLA)-based industrial materials have emerged as prominent candidates for replacing conventional plastics in various applications. PLA, a biodegradable and compostable polymer synthesized from renewable resources, such as cornstarch and sugarcane, offers several advantages, including environmental friendliness and lower greenhouse gas emissions. This review examines the current state of PLA-based bio-packaging materials, focusing on their features, production processes, and performance in comparison to traditional plastics. This review discusses advancements in PLA technology, including routes for enhancing its mechanical strength, thermal stability, and barrier properties, which are critical for its application in various packaging scenarios. Additionally, this review addresses the challenges associated with PLA, including its limited availability, higher cost compared to conventional plastics, and issues related to its end-of-life disposal and recycling.

1. Introduction

The global packaging industry is entering a transformative era in which bio-origin alone is no longer sufficient; materials must also be functional, intelligent, and circular by design. Polylactic acid (PLA) has emerged as a flagship biopolymer that bridges eco-performance and industrial feasibility. However, the next frontier lies not only in replacing fossil plastics but also in reprogramming the material behavior of PLA through molecular design, nanotechnology, and data-driven material informatics. This shift has transformed PLA from a biodegradable polymer to an engineered platform for smart and multifunctional packaging systems.

Packaging is indispensable across various industries because of its multifaceted role in protecting, preserving, and presenting products. It ensures physical, chemical, and biological safety; extends shelf life; and provides convenience to consumers.[1] Sustainable packaging solutions address environmental concerns, while cost-effective designs optimize economic efficiency.[2] The importance of packaging lies in its ability to maintain product integrity, promote consumer safety, and support competitive markets.

Packaging materials remain prevalent owing to their cost-effectiveness, durability, and versatility.[3] Plastic packaging is a significant contributor globally, with approximately 40% of the 368 million metric tons of plastic produced in 2019 being used for packaging.[4] Different packaging film processing techniques are used to produce films with specific properties that are suitable for various applications. Blown-film extrusion is a common technique in which molten plastic is extruded through a circular die, inflated into a bubble, and then flattened into a film. This method is widely used for creating bags and stretch films.[5–7] Cast film extrusion involves extruding molten plastic through a flat die, which is then rapidly cooled on a chill roll to produce a smooth and uniform film. This technique is ideal for applications requiring high clarity, such as food packaging. Co-extrusion is used to produce multilayer films by combining different materials into a single film, providing enhanced barrier properties and mechanical strength.[8] Lamination involves bonding layers of different materials, such as plastic, aluminum, or paper, to create composite films with combined properties, which are often used for packaging that requires moisture, oxygen, or light barriers.[9] Orientation processes, such as biaxial orientation, stretch the film in both the machine and transverse directions, improving the strength, clarity, and barrier properties, making it suitable for high-performance applications such as snack packaging.[10] Each of these techniques is selected based on the desired properties and end use of the packaging film. Blow molding and injection molding are key processes in packaging; however, they serve different purposes and are not typically used for film formation. Blow molding is used to create hollow plastic products, such as bottles and containers, by inflating a heated plastic parison inside a mold to take its shape.[11] Injection molding, on the other hand, is employed to produce solid plastic parts such as

Department of Chemistry, National Institute of Technology, Calicut, Kerala, India. E-mail: unnig@nitc.ac.in; naja_p220235cy@nitc.ac.in

caps and lids by injecting molten plastic into a mold cavity under high pressure.[12,13] Although both techniques are essential for forming three-dimensional packaging components, packaging films are created through processes such as blown film extrusion or cast film extrusion, where plastic is formed into thin, flexible sheets rather than solid or hollow shapes.

Non-biodegradable packaging materials are extensively used owing to their durability, versatility, and cost-effectiveness. Plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS) are commonly found in products ranging from plastic bags and bottles to food containers and protective packaging.[14,15] Metals, such as aluminum and steel, are also prevalent in beverage cans, food containers, and industrial packaging because of their strength and recyclability, although they are not biodegradable. Glass, widely used in bottles and jars, is another non-biodegradable material valued for its inertness and recyclability. Additionally, composites such as Tetra Pak and various laminates offer specific benefits for liquid and flexible packaging but pose challenges for biodegradability and recycling owing to their multilayered structures.[16] PLA composites enriched with bioactive compounds represent a sustainable and high-performance packaging solution that enhances food safety, extends shelf life, and meets modern preservation demands. Their biodegradability and functional versatility position PLA as a key material driving the food industry toward environmentally responsible packaging practices.[17] Bio-based polymers such as PLA, PHAs, starch-based, and cellulose-derived materials offer promising mechanical, barrier, and antimicrobial properties that support safer and more sustainable food packaging solutions. Despite existing challenges in processing and performance, their eco-friendly nature and ongoing advancements highlight strong potential for future adoption in the packaging industry (Table 1).

The shift toward biodegradable materials over non-biodegradable materials in packaging is primarily driven by environmental concerns, consumer demand, and regulatory pressure. Biodegradable materials offer significant advantages by reducing pollution and waste accumulation, as they decompose naturally and quickly, minimizing harm to wildlife and ecosystems.[1,3,33] They are often derived from renewable resources, contributing to a more sustainable and circular economy, and many can be composted to enrich the soil and reduce the need for chemical fertilizers. The growing consumer preference for eco-friendly products and increasing emphasis on corporate social responsibility are pushing brands to adopt sustainable and environmentally friendly packaging solutions. Stricter government regulations and international agreements aimed at reducing plastic waste have incentivized the use of biodegradable materials. Advances in biotechnology and materials science are making biodegradable options more competitive in terms of performance and cost, further driving their adoption.[34] Recent advances in enhancing the performance and reducing the costs of biopolymers for sustainable food packaging have focused on nanofiller dispersion, blending techniques, alternative feedstocks, and future research prospects for industrial scalability.[33] Bio-based and biodegradable packaging films improve food shelf life and quality, while emerging technologies enhance their performance and sustainability.[4,35]

Nanocomposites can incorporate antimicrobial properties, enhancing food safety by inhibiting the growth of bacteria and other microorganisms.[16,36,37] They also maintain or improve packaging transparency, which is important for product visibility and consumer appeal, and are recyclable. Their thermal stability renders them suitable for a wide range of processing and storage conditions. Active packaging features enabled by nanotechnology, such as smart packaging that interacts with the content or environment, add value. Sustainability is another significant benefit, as nanocomposites can be engineered to include biodegradable components or improve recyclability, contributing to more eco-friendly packaging solutions.[38–41] The adoption of nanocomposite materials in packaging addresses multiple industrial needs, from enhancing product protection and shelf life to improving sustainability and reducing the costs. These advanced materials offer versatile and effective solutions, making them attractive choices for packaging.[42,43] An edible, pH-sensitive gelatin–gellan gum film containing red radish anthocyanins was developed that combines electrochemical writing with robust mechanical, UV/oxygen barrier, and gas-sensing properties, enabling multicolor, pattern-preserving indicators that visibly respond to milk and fish spoilage for intelligent food packaging applications.[5]

In recent years, the integration of nanoscale fillers into polymer matrices has revolutionized the field of polymer nanocomposites.[44,45] Polylactic acid (PLA) is a biodegradable thermoplastic derived from renewable resources. PLA has gained significant traction because of its biocompatibility, transparency, and ability to be processed using conventional polymer processing techniques.[46] These attributes make PLA particularly attractive for applications ranging from packaging materials to biomedical implants and sustainable consumer products.

The incorporation of nanosized fillers into PLA matrices represents a promising avenue for enhancing their mechanical, thermal, and barrier properties, while maintaining their eco-friendly profile.[47,48] Nano fillers, typically inorganic or organic nanoparticles with at least one dimension of less than 100 nanometers, offer unique functionalities that can be tailored to specific application requirements.[43] Inorganic fillers such as montmorillonite clay, silica, and titanium dioxide nanoparticles reinforce polymers and improve tensile strength and modulus. Carbon-based nanomaterials, including carbon nanotubes and graphene, exhibit exceptional electrical conductivity and mechanical reinforcement capabilities. Incorporation of montmorillonite (MMT) into PLA or PLA-based blends produces composition-dependent mechanical enhancements. At low loading (1 wt%), MMT generally provides modest improvements in tensile strength and modulus (around 3–10%) while causing minimal embrittlement. Increasing the content to 3–5 wt% typically yields the most pronounced stiffness gains, with tensile modulus rising by about 10–19% and flexural modulus reaching improvements of 20–30% compared with neat PLA; some studies also report optimum impact

Table 1 Characterisation parameters, evaluation methods, and their relevance in PLA-based packaging

Parameters	Significance	Typical evaluation methods	Relevance to PLA-based packaging
Mechanical strength	Determines durability during handling, transport, and storage	Tensile (MPa), impact (kJ m^{-2}), and elongation (%) tests (ASTM D882, D638)	PLA: high modulus (3.4–3.7 GPa) and strength (50–60 MPa), low elongation (2.5–10%). PLA/EVA: lower modulus (1.2–2.0 GPa) and strength (30–40 MPa), high elongation (150–300%)[18]
Thermal stability	Defines heat resistance during processing and storage	DSC W/g, TGA%/min, and DMA analyses	DSC results: neat PLA shows $T_g = 59.2$ °C and $T_m = 153.5$ °C. The PLA/PBAT (70/30) blend has a slightly lower T_m (151.8 °C) and higher crystallinity (7.95%) TGA results: the PLA/PBAT blend exhibits lower thermal stability than neat PLA, with degradation beginning at approximately 280–320 °C (ref. 19)
Barrier properties	Controls permeability to gases (O_2, CO_2), vapors, and moisture	OTR (cc mm per m^2 per day·per atm), WVTR (g mm per m per day·per kPa) measurements (ASTM D3985, D1653)	Nanofillers like nanoclays, metal oxides (*e.g.*, MgO, TiO_2), and nanocellulose dramatically enhance PLA's barrier properties against oxygen, water vapor, and air—often by 25–87% at low loadings—making PLA composites ideal for sustainable food packaging despite neat PLA's high permeability limitations[20,21]
Optical properties	Clarity, gloss, and transparency affect consumer appeal	UV-vis spectrophotometry%, haze measurements%	Pure PLA: 50% UV blocking at 380 nm and 76% visible light transmittance Modified PLA systems: PLA + 5% PAHP 100% UV-B blocking; PLA/h-mTA20 shows strong UV shielding with high transparency; PLA + 7% POSS-BP blocks 76% UVA and ∼86% UVB while keeping high visible transmittance[22–26]
Food safety & migration behavior	Assesses the release of residual monomers, additives, or nanoparticles into food	Overall & specific migration tests mg dm^{-2} (EU 10/2011, FDA CFR 177)	PLA packaging is food-safe, approved by U.S. Food and Drug Administration and European Food Safety Authority, showing residual lactic acid monomer migration <0.35% (≪10 mg dm^{-2} overall limit) Nanoparticle migration (Ag/ZnO) remains <50 ppb at 40–60 °C, and blends like PLA/PBAT keep GRAS status with no off-flavor or toxic leachates in dry, fatty, or acidic food simulants[27]
Biodegradability/ compostability	Measures environmental degradation rate and end-of-life impact	ISO 14855, ASTM D5338, and soil or compost degradation studies%	PLA meets ASTM International D6400 and European Committee for Standardization EN 13432: 90% disintegration in 12 weeks and 90% mineralization in 6 months at ≥58 °C. PLA/PHB reaches 100% mineralization; PLA/PBS leaves only 0.3% mass (12 weeks, thin films), while thick PLA packs retain 55.7% mass after 12 weeks[28]
Antimicrobial & active properties	Ensures food preservation and extended shelf life	Microbial inhibition tests and zone of inhibition assays mm	ZnO nanofillers at 0.5–2.5 wt% in melt-mixed PLA films achieve >99% inhibition against *E. coli* and *S. aureus*, Ag nanoparticles with GO at 1–7 wt% *via* electrospinning provide 98–100% kill rates especially against *E. coli*, and 3% essential oil (cinnamaldehyde) in β-CD nanofibers yield the highest activity against both Gram-negative and Gram-positive bacteria[29–31]
Optical & sensory stability	Prevents discoloration, odor, or flavor migration	Colorimetry, GC-MS μg g^{-1}, and sensory analysis	Pure PLA offers >90% transmittance at 550 nm with neutral sensory profile (GRAS), PLA/PHB provides high clarity and low migration for UV protection, PLA/PCL achieves 50–80% transmittance while preserving fruit color/quality, and PLA/Starch maintains stable transparency without off-flavors[32]
Economic & processing feasibility	Determines industrial scalability and cost competitiveness	Techno-economic assessment MJ kg^{-1}, process simulation kg h^{-1}	PLA/EVA and PLA/PBAT blends enhance PLA's processability by improving elongation at break (*e.g.*, up to 200–500% for PLA/PBAT at 20–40 wt% PBAT *vs.* <10% for pure PLA) and melt flow index (*e.g.*, 15–30 g/10 min for PLA/EVA blends), while retaining biodegradability under industrial composting (90% mineralization in 6 months per EN 13432)[28]

strength at 5 wt% for specific organoclays (*e.g.* 1.44P). However, beyond 5 wt% MMT, nanoparticle aggregation becomes more prevalent, leading to reduced ductility and diminishing returns in strength enhancement despite continued increases in stiffness.[6–8,49] The incorporation of cellulose nanocrystals (CNC) into PLA has been shown to influence both mechanical and thermal performance in a loading-dependent manner. At low concentrations (around 1 wt%), CNC can increase the strain at break by approximately 20%, indicating improved ductility with only limited stiffening of the matrix. As the CNC content increases to about 3–5 wt%, more pronounced enhancements in thermal resistance and elastic modulus are typically observed due to the reinforcing effect of the rigid nanocrystals. However, at these higher loadings, there is a greater risk of CNC agglomeration particularly when dispersion or interfacial compatibilization is inadequate which can adversely affect toughness and overall mechanical balance.[10,50]

PLA/ZnO composite films show loading-dependent performance, with antimicrobial activity increasing as ZnO content rises; in some solvent-cast systems, ≥3 wt% ZnO achieves complete *E. coli* inhibition. Low to moderate loadings can also enhance mechanical and barrier properties, but excessive ZnO or poorly modified particles may cause agglomeration and defects, ultimately reducing tensile strength similar to other inorganic fillers.[12,51]

At low loadings (1–3 wt%), nanoclay and CNC mainly act as nucleating and reinforcing agents in PLA. Nanoclay offers greater stiffness and barrier improvements (*e.g.*, notable OP reduction and modulus increase) but is more prone to embrittlement if poorly dispersed.[13] Whereas CNC provides a more balanced stiffness–toughness profile with better ductility retention, though typically lower barrier gains.[10,50] For antimicrobial performance, metal oxides and Ag-based fillers are more effective: ZnO can fully inhibit *E. coli* above 3 wt% with added UV shielding, while Ag/ZnO hybrids show strong activity even at lower loadings, sometimes with trade-offs in transparency and water vapor barrier.[12,14]

Metal nanoparticles, such as silver and copper nanoparticles, possess antimicrobial properties, making them suitable for applications in food packaging and biomedical fields where microbial resistance is critical. Organic nanofillers derived from natural sources or synthesized polymers.

It is compatible with PLA and can enhance biodegradability without compromising its mechanical properties.[52]

Recent reviews on PLA focus either on broad overviews or on specific subthemes, but none integrate performance, processing, and techno-economic data the way this work does. For example, Tripathi *et al.* (2021) provide a comprehensive survey of durable PLA-based engineered blends and biocomposites, emphasizing stiffness–toughness balance and durability in structural applications rather than packaging-focused migration, sensory, and compostability constraints.[15] Other recent articles, such as the 2023–2024 reviews by Swetha *et al.* on PLA synthesis/processing for food packaging and by various authors on PLA production from food waste, largely catalog materials, processing routes, and general LCA trends without quantitative cross-comparison of blends, nanocomposites, and active systems.[1,53] Likewise, specialized reviews on PLA-based antibacterial packaging synthesize strategies for incorporating antimicrobials and bioactives but do not connect those formulations to industrial-scale economics, policy drivers, or full life-cycle trade-offs *versus* PLA blends and fossil plastics. In contrast, the present review explicitly positions itself as a data-driven synthesis that maps bibliometric trends, patents, compiles meta-analysis ranges for mechanical, thermal, barrier, and migration behavior of neat PLA, composites, and blends; couples these property datasets to processing–structure–property models (RSM, ANN, MD); and links them to region-specific economic and environmental metrics (policy scenarios, LCA indicators, and market growth), thereby filling a clear gap between descriptive narrative reviews and quantitatively benchmarked, decision-oriented analysis for next-generation PLA-based bio-packaging.[33–35,54,55]

This review focuses on the period from 2000 to 2024, encompassing the critical evolution of PLA-based packaging, from its early experimental stage to large-scale commercialization. During this period, global research, patent filings, and market expansion accelerated, particularly after 2015, driven by sustainability policies and advancements in biopolymer technology. The early 2000s marked limited innovation and niche applications, whereas the 2010–2015 phase saw growing academic and industrial engagement with biodegradable materials. From 2015 onward, a rapid surge in scientific publications (approaching 2000 per year) and patent activity was observed, indicating robust industrial adoption and diversified applications. Correspondingly, the PLA packaging market has expanded substantially and is projected to exceed USD 3.8 billion by 2034, underscoring its growing global significance in sustainable packaging solutions.[56,57]

This review provides an updated description of the production strategies for PLA, its blending with other polymers, and its reinforcement with a suitable filler for performance enhancement as a bio-packaging material.

The present review adopts a rigorously data-driven framework by mapping exponential PLA research expansion alongside industrial and performance datasets. Bibliometric analysis reveals a sharp post-2015 publication surge, with outputs rising from ∼500 papers in 2000 to >20 000 annually by 2024, accompanied by patent growth of ∼25% year-on-year and global production approaching 140 000 tonnes with 30% annual scaling. Techno-economic projections further contextualise this momentum, with the PLA packaging market forecast to expand from USD 2.01 billion in 2025 to USD 4.51 billion by 2030 (17.5% CAGR), where packaging constitutes 45% of demand. Beyond market mapping, the review compiles quantitative benchmarking tables spanning neat PLA, blends, and nanocomposites—for example, PLA/PBAT systems exhibiting 200–500% elongation compared with <10% for pure PLA, while nanocomposites demonstrate 50–80% oxygen permeability reductions. Processing–structure–property correlations are also synthesised, highlighting extrusion-induced crystallinity increases of 20–40% that yield tensile strengths of 50–70 MPa alongside permeability suppression. At the nanoscale, reinforcement metrics indicate modulus enhancements of 30–100% and antimicrobial efficiencies exceeding 99% in ZnO- and Ag-functionalised systems. These multiscale datasets are systematically integrated through statistical summaries, meta-analysis of over 100 studies, and life-cycle assessment modelling frameworks (*e.g.*, ReCiPe 2016), thereby transforming the article from a descriptive narrative into a quantitatively benchmarked, decision-oriented synthesis for next-generation PLA-based biopackaging.[16,36,38,58]

2. Salient properties of polylactic acid (PLA)

Biodegradable plastics offer significant potential to replace traditional petroleum-based plastics, which have detrimental effects on the environment, including pollution of land and water, and contribute to global warming.[39–41]

Polylactic acid (PLA) is a thermoplastic monomer derived from renewable organic sources such as corn starch and sugarcane.[44,59,60] PLA can be synthesized using direct condensation polymerization. Scheme 1 illustrates the synthesis pathway of PLA, showing the dehydration of lactic acid to form oligomers, followed by thermal cracking to lactide and subsequent ring-opening polymerization to produce high-molecular-weight PLA. Biodegradable PLA offers a sustainable solution for the biomedical and food packaging industries.[57,61,62] PLA has been applied in the production of tissue engineering scaffolds, materials for delivery systems, membranes for covering, various bioabsorbable medical implants, and in fields such as dermatology, cosmetics, and packaging. Owing to its renewability, biodegradability, biocompatibility, and outstanding thermomechanical properties, polylactic acid (PLA) is the best polymeric alternative to various petropolymers in ecologically friendly processes and products. Lactic acid fermentation of mulberry juice with different LAB strains alters color and phenolic composition and, particularly with L. plantarum, maximizes antioxidant activity by enriching key flavonols, anthocyanins, and phenolic acids linked to ABTS and DPPH radical scavenging.[42] Fig. 1 depicts the life cycle of PLA-based bioplastics, highlighting the conversion of renewable resources (corn starch) into lactic acid, polymerization into PLA, product utilization, and end-of-life degradation back into water and carbon dioxide through composting.

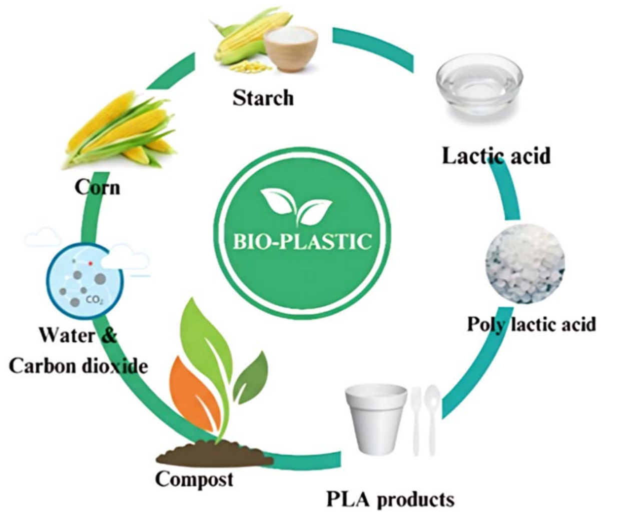
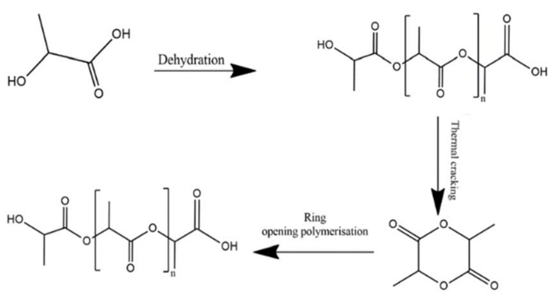


Fig. 1 Ideal lifecycle of polylactic acid.

2.1 Processing of PLA in packaging

Biopolymer production methods are well established, and their management and application must be adjusted to address certain challenges that affect their effective use. The basic production processes are similar, with significant differences depending on whether a thermoplastic or thermoset biopolymer is processed.[43] PLA resins are available in two forms: amorphous and crystalline. Owing to their amorphous structure, PLA resins are transparent, whereas semicrystalline PLA resin pellets appear opaque. Fig. 2 illustrates the technologies employed in the development of different packaging applications using PLA.

Recent PLA packaging research focuses on processing optimization, scalable production, and bio-based additives to improve mechanical and barrier performance cost-effectively. Active PLA packaging films are increasingly engineered using techniques such as solvent casting, extrusion, and combined casting/solvent methods to fine-tune properties such as crystallinity, barrier performance, and additive release kinetics. Processing conditions such as temperature, shear rate, solvent, and atmosphere control PLA crystallinity and thermal behavior, affecting food-contact suitability. Comparative analyses showed that the extrusion and casting methods yielded distinct barriers and mechanical outcomes owing to differences in phase morphology and crystallinity. Bio-based plasticizers have improved PLA's flexibility of PLA, reduced its brittleness, and enabled lower-temperature processing, enhancing its industrial compatibility. The incorporation of active agents such as antioxidants and antimicrobials introduces functional benefits, as well as trade-offs in barrier integrity and controlled release



Scheme 1 Preparation of PLA.

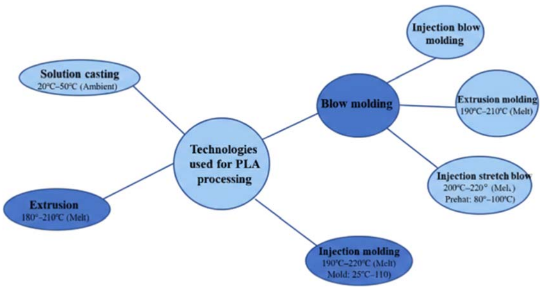


Fig. 2 Technologies used for processing of PLA in packaging.

behavior, both of which depend heavily on processing and dispersion quality. PLA continues to gain traction owing to sustainability policies and advances in heat resistance and toughness, although challenges persist in achieving cost parity, feedstock supply, and large-scale process optimization. Patent and market analyses have highlighted ongoing innovations in chemical recycling, process efficiency, and integration into existing packaging systems. Nonetheless, PLA's sensitivity of PLA to moisture, temperature, and shear demands precise process control and tailored formulations to ensure a consistent performance. Future opportunities lie in developing cost-effective blends, copolymers, and surface modifications to overcome inherent limitations, while strengthening industrial infrastructure for composting and recycling will further enhance PLA's role as a viable, sustainable packaging material.[63–65]

2.1.1 Types of technologies used in PLA processing. The polymer processing ability is significant for various applications.

2.1.1.1 Solution casting method. The solution casting method for producing PLA (poly lactic acid) film involves different steps [Fig. 3].

Solubilizing PLA in a compatible solvent, such as chloroform, dichloromethane, or a mixture of solvents, leads to a PLA solution, which is then cast onto a flat, clean glass dish to create a thin, uniform layer. The thickness of the film can be controlled by varying the amount of solution used. The cast PLA solution was left in a well-ventilated area to, allow the solvent to evaporate. As the solvent continued to evaporate, the PLA solidified, leaving behind a thin, transparent PLA film on the casting surface. The time required for the film to fully solidify depends on factors such as temperature, humidity, and the solvent used. Once the PLA film was completely dry and solid, it was carefully peeled from the casting surface. The obtained PLA film may undergo further processing steps such as cutting, shaping, or coating, depending on the intended application.[44]

Various processing techniques also affect mechanical strength. The melt-drawn PLA film exhibited enhanced mechanical properties compared to those of PLA synthesized *via* solvent casting. PLA blends created *via* solution casting exhibited a significant decrease in tensile strain, while Young's modulus remained constant[45,66]

2.1.1.2. Extrusion. Another processing technique employed in the development of PLA films is extrusion (Fig. 4). The extrusion process involves three primary phases: first, PLA is continuously melted; second, it is conveyed and discharged through a die. The hot-melt extrusion (HME) process effectively transforms raw plastic materials into uniform products by applying heat and pressure to force the material through a die.

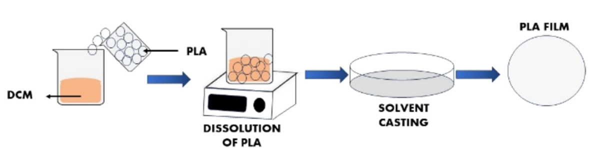


Fig. 3 Solution casting method of PLA film.

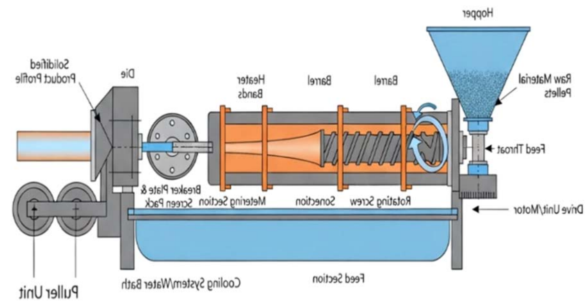


Fig. 4 Schematic diagram of extrusion molding machine.

This process is integral to various industries, particularly food processing and plastic manufacturing, owing to its ability to produce products with consistent shapes and densities.[67] The single-screw and twin-screw extruders used in this process are essential for achieving the desired material properties, with the twin-screw extruder offering enhanced material handling and a reduced risk of overheating.[68–70]

In the production of PLA products, the extrusion process plays a crucial role in converting PLA pellets into various forms such as sheets and containers.[71] The conditions for PLA extrusion, including the L/D ratio, melt temperature, and compression ratio were carefully controlled to optimize the mechanical properties of the material.[60,72] Adjusting the L-LA/D-LA ratio in PLA can significantly enhance its mechanical characteristics making it suitable for applications such as screws and fixation plates in fracture repair, potentially eliminating the need for additional support.[73]

2.1.1.3 Injection molding. This process involves heating thermoplastic polymers above their melting points and injecting the molten material into a mold, where it is cooled and solidified into the desired shape. The process is driven by critical mechanisms such as pressure flow and heat transfer, ensuring precise and consistent results. Plastic pellets are fed into a screw from a feed hopper melted, injected into the mold, and cooled using a dedicated cooling system that controls a solidification process.[74,75] The mold consists of two halves that are clamped together to form the cavity. Once the material cools and solidifies, the mold is opened to eject the finished component. This process is highly efficient, enabling the production of large quantities of small components at a reasonable cost, with minimal need for additional finishing if

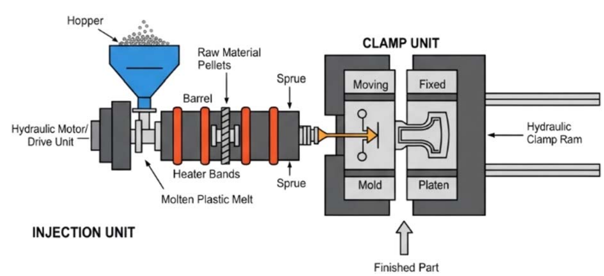


Fig. 5 Schematic diagram of an injection molding apparatus.

good manufacturing practices are followed.[76] Fig. 5 depicts a schematic representation of injection molding.

Various thermoplastics, including nylon, PP, LDPE, HDPE, PET, PVC, and PS, can be used in injection molding, each with specific characteristics and processing requirements. The screw action of the injection molding machine is similar to that of an extruder, with the key difference being that the screw in an injection molding machine not only rotates but also moves forward and backward to accommodate the different phases of the molding process. For materials such as PLA, which have a lower glass transition temperature, special care is required during processing and storage to prevent brittleness due to physical aging, a phenomenon that reduces molecular mobility and increases stiffness and brittleness over time.[77] Furthermore, advanced techniques, such as shear-controlled orientation injection molding (SCORIM) – can enhance the mechanical properties of semi-crystalline polymers by introducing in-mold shearing actions that alter the polymer structure during solidification, offering higher degrees of freedom and improved material properties compared to traditional injection molding.[78] Despite the complexity and need for specific handling of certain materials, injection molding remains an indispensable technique for the mass production of high-quality plastic products, offering unparalleled scalability, cost-effectiveness, and manufacturing versatility.[79,80]

2.1.1.4 Blow molding. Blow molding is a highly versatile and essential technique for producing hollow, three-dimensional plastic products, significantly impacting the food packaging industry. This process works by inflating a thermoplastic molten tube, known as a parison, within a mold cavity to shape it into the desired form, such as bottles and containers. As the parison conforms to the shape of the mold and solidifies upon cooling, it retains the intended structure.[77,81,82] Fig. 6 depicts a schematic representation of blow molding.

The three primary methods of blow molding—extrusion blow molding, injection blow molding, and injection stretch blow molding (ISBM)—cater to different manufacturing needs. Extrusion blow molding is the most prevalent method, primarily because of its cost-effectiveness and efficiency in producing containers that do not require exceptional precision or high-performance properties.[11] This method is widely used for creating polypropylene (PP) bottles, which are known for their clarity and hot-filling capability, and for producing containers made from materials such as PVC and HDPE. These polymers are often co-extruded with barrier materials such as nylon or ethylene vinyl alcohol (EVOH) to enhance their gas barrier properties, making them suitable for a variety of packaging applications.[83]

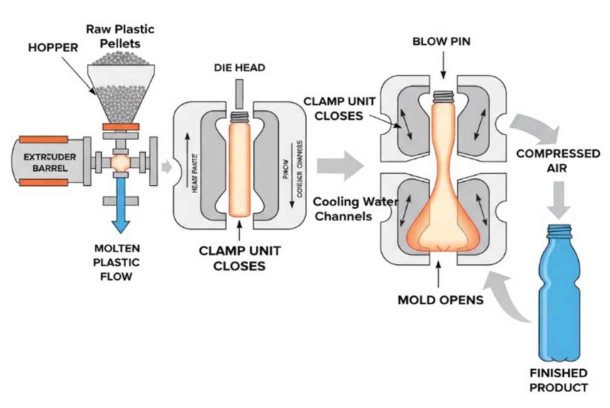


Fig. 6 Schematic diagram of a blow molding apparatus.

Injection blow molding, on the other hand, is particularly suited for producing smaller bottles and wide-mouth jars that require closer dimensional control and higher production volumes. This method involves creating a preform, which is then blown into the final shape, offering better mechanical strength and barrier properties than extrusion blow molding. Polymers such as HDPE, PVC, and PET are commonly used in this process, which is favored for its ability to produce containers with superior quality and performance.[84,85]

Injection stretch blow molding (ISBM), an advanced variation of injection blow molding, is widely used in the beverage industry to produce PET bottles. This process offers enhanced material properties, such as transparency, surface gloss, gas barrier characteristics, and impact strength, owing to the biaxial orientation achieved during the stretching and blowing phases. ISBM is particularly well-suited for producing high-performance bottles used for carbonated soft drinks, sports drinks, and other beverages that require durable, clear, and strong packaging.[86]

The adaptability of ISBM has extended to the use of polylactic acid (PLA) resins, which are increasingly employed in the food packaging sector for producing bottles and containers for liquids such as edible oils, fruit juices, and dairy products. PLA resins are processed at lower temperatures than PET, making them an eco-friendly alternative in the packaging industry.[87,88]

Blow molding is essential in food and beverage packaging because it produces containers with varied strength and barrier properties. Whether through the cost-effective extrusion blow molding process or the more specialized injection and stretch blow molding techniques, this method continues to evolve, meeting the demands of modern packaging requirements while incorporating sustainable materials such as PLA for environmentally conscious production.[85]

For future applications, such as electrochemical energy storage, energy conversion, and sensing, PLA-based systems can be employed using new techniques such as 3D printing.

PLA has excellent barrier properties and biodegradability, making it suitable for packaging applications. It is also becoming a popular food packaging material due to its good odour and flavour barrier, good retention twist or dead-fold property, and thermal shrink wrap quality.[46] Table 2 shows the properties of PLA required for food packaging.

Food safety and migration behavior are critical performance criteria for PLA and other bioplastic-based food packaging materials, as they determine the potential transfer of chemical components or additives from the packaging to the food, which can affect consumer health or food quality. Migration testing replicates real-use conditions, such as temperature, humidity, and storage duration, to ensure that any migrating substances remain within the regulatory safety limits established by

Table 2 Properties of PLA needed for food packaging

Sl. no.	Properties needed for food packaging: properties of PLA
1	Transparency—it has excellent transparency
2	Permeability—the CO_2 permeability relative to oxygen in PLA is higher than that of traditional fossil fuel-based polymers. This makes PLA particularly useful in food packaging applications where a strong oxygen barrier is required
3	Oxygen barrier capacity—compared to polystyrene, PLA offers superior oxygen barrier properties
4	Water-resistance capacity: it boasts superior water resistance and mechanical properties
5	Resistance against oils and fats—it has a good resistance capacity against oils and fats
6	Thermal processability—PLA offers excellent thermal processability compared to other bioplastics, thanks to its low melting temperature and low glass transition temperature
7	Resistant to UV radiation—PLA films are more resistant to UV radiation than low-density polyethylene films (LDPE)
8	Biodegradability—PLA is biodegradable and can be either incinerated or recycled. When PLA is exposed to boiling water or steam, it hydrolyzes into lactic acid, facilitating the molecular recycling of the packaging material

authorities such as the European Food Safety Authority (EFSA). PLA packaging generally exhibits favorable migration performance, with reported migration levels of additives, including nanoparticles, plasticizers, and antioxidants, well below the accepted safety thresholds. The extent of migration is influenced by several factors, including the chemical composition of the packaging, the type of additive used, processing conditions, and the storage environment of the food product. Processing approaches that enhance crystallinity and structural integrity, such as extrusion or high-pressure treatments, can effectively minimize migration. Moreover, parameters like crystallinity, moisture content, and phase morphology directly govern the rate and nature of substance migration, which may involve small molecules such as lactic acid oligomers. Beyond migration control, essential safety-related performance criteria for PLA food packaging include maintaining strong gas and moisture barrier properties to preserve food quality, ensuring chemical stability and inertness to prevent undesirable flavor or nutrient changes, and demonstrating compatibility with sterilization and regulatory standards to ensure safe and reliable use in food-contact applications.[47,52,89]

Modification of PLA *via* fillers, plasticizers, or blending changes its properties mainly through interfacial interactions and stress transfer. When nanoparticles such as cellulose nanofibers, nanoclay, graphene, or CNTs are well bonded to PLA (for example, by grafting PLA chains or forming strong hydrogen bonds), the interface can efficiently transfer load from the softer PLA matrix into the stiff filler, increasing tensile modulus and strength; if the interface is weak or fillers agglomerate, stress localizes, causing debonding, voids, and a loss in strength and toughness.[9,90,91]

A second key mechanism is crystallization and morphology change. Many fillers (CNC, NFC, nanoclay, CNTs, stereocomplex particles) act as heterogeneous nucleating agents, increasing nucleation density, reducing spherulite size, and raising crystallinity from about 5–15% in neat PLA to 25–40% in nucleated systems, which stiffens the material and lowers gas permeability by reducing free volume; however, excessive or aggregated filler can hinder chain mobility and suppress crystallization, reversing these benefits.[91–93]

Third, modifiers strongly affect polymer chain mobility and glass transition (T_g). Plasticizers like PEG or ATBC insert between PLA chains, weaken intermolecular interactions, increase free volume, and thus lower T_g by roughly 0.8–1.2 °C per wt% while greatly increasing elongation at break, whereas rigid, strongly bound fillers can immobilize chains in an interphase region, locally raising T_g and storage modulus, with the overall T_g response reflecting the balance between these plasticizing and constraining effects.[93–95]

Fourth, barrier performance is governed by a tortuous path mechanism. Plate-like fillers such as nanoclay or graphene, when exfoliated and oriented parallel to the film surface, force gas and water molecules to follow a longer, more convoluted path through the material, reducing oxygen and water vapor permeability by 30–80% at low loadings; poor exfoliation or high aggregation instead creates defects that limit or negate this barrier advantage.[91,96]

Fifth, with conductive fillers, property changes arise from network percolation and anisotropic structure. Above a critical loading, graphite, graphene, CNTs, or carbon black form continuous conductive networks, enabling electrical or thermal conductivity, and under processing flows these fillers can align and nucleate extended-chain crystals, simultaneously enhancing crystallinity, modulus, and directional conductivity.[97]

Some modifiers act *via* degradation and catalytic effects. Metal oxides and CaO can catalyze ester bond scission in PLA, lowering the onset of thermal degradation but accelerating hydrolytic or composting behavior, while appropriate surface modification (*e.g.*, silanization or fatty-acid treatment) improves particle dispersion and interfacial compatibility so that antimicrobial, mechanical, and degradability benefits are realized without excessive loss of stability.[91,98]

On the societal front, this study seeks to provide a valuable guide for industry professionals, policymakers, and stakeholders, promoting the adoption of biodegradable materials as a more environmentally friendly alternative to conventional plastics across a wider range of applications, ultimately reducing the environmental impact of plastic products.

3. PLA blends

Polylactic acid (PLA) is a prominent biopolymer for rigid applications owing to its stiffness. To enhance its properties, it is often blended with polybutylene adipate terephthalate (PBAT), another bio-based polymer.[56] PLA is inherently rigid but lacks impact resistance, making it a valuable complement to PBAT for developing high-performance and multifunctional biodegradable plastics (Fig. 7).

PLA–cassava starch blends exhibit enhanced water vapor barrier properties and can be employed for packaging applications.[99,100] Fig. 6 illustrates the application of polylactic acid (PLA) and cassava starch films as packaging materials for various types of food products. The incorporation of tapioca starch (TS) into polylactic acid (PLA) composites significantly improved their tensile strength. While TS enhanced the tensile modulus, it led to a reduction in the impact resistance as TS loading increased, making it suitable for applications requiring higher tensile strength but lower impact resistance. Blending PLA with tapioca starch is recommended for packaging applications due to its safety for humans and other organisms, as well as its cost-effectiveness and environmental benefits.[101] For PLA–PEG-based blends, increasing the concentration of PEG resulted in a decrease in the glass transition and cold crystallization temperatures of PLA, thereby enhancing crystallization. In addition, the tensile strength and elongation of the blended film increased, whereas at high concentrations, the tensile strength decreased but the elongation improved, indicating enhanced ductility. Higher PEG molecular weight and concentrations improved the oxygen barrier properties and transparency of the films, suggesting their suitability for use as biodegradable flexible packaging materials.[102] The addition of triacetin and PEG to PLA films improved the thermal stability of the films, resulting in the best performance for food packaging applications.[59] Radical polymerisation of PLA enhances its barrier properties by copolymerizing with suitable monomers to extend its applicability in food packaging.[60,102] The importance of selecting appropriate processing techniques and conditions for active PLA-based films, considering the properties of the active agents, such as volatility, solubility, and thermosensitivity, to effectively enhance food packaging cannot be overstated.[103] The study demonstrated that increasing the PLA content in the polypropylene/PLA blends decreased the melting temperature and crystallinity, while enhancing tensile modulus and strength, but reducing the elongation at break. The blends exhibited typical immiscibility, with PLA increasing water vapor permeability and decreasing oxygen permeability, indicating distinct phase separation, and varying properties depending on the PLA proportion.[61]

Fig. 7 PLA/cassava starch films applied as packaging for different food matrices.

The addition of chitosan to the material enhanced the PLA's mechanical qualities.[62] Incorporating cellulose acetate or chitosan into PLA significantly enhanced its thermal and mechanical properties. Among the two, PLA blended with chitosan showed the most notable improvement, particularly in elongation at break, which increased by 4.7%. This makes PLA/chitosan films the most promising for food packaging applications, offering a balance of improved flexibility and mechanical strength without the need for additional plasticizers or other additives.[57] The development of PLA/acetate and PLA/chitosan films demonstrated significant improvements in thermal and mechanical properties, with the PLA/chitosan films achieving the most notable enhancement in elongation at break. Consequently, PLA/chitosan films have emerged as the most promising option for flexible and improved packaging applications.[104].

Incorporating styrene–isoprene–styrene (SIS) triblock polymers into PLA can affect the stability and oxidative degradation of the material, with lower SIS concentrations offering better stability. This highlights that radiation processing is an effective method for sterilizing food packaging and medical products.[105] PLA–PHB blends offer a promising alternative to traditional petrochemical-based polymers for food packaging, owing to their enhanced processing performance, mechanical properties, and potential for active packaging applications.[63] Despite a reduction in viscosity with multiple recycling cycles of the PLA/PHB blends, the improved crystallinity and phase interaction, along with the stable tensile and impact properties, indicate that recycling enhances the blend morphology without significantly compromising the mechanical performance.[64] The transition from PLA to PHB in bio-based blends leads to decreased gas permeability and probe rotation mobility due to increased crystallinity, with both gas transport activation energy and probe mobility indicating that polymer segmental mobility governs gas permeability.[65] Recent advancements in compatibilizing biodegradable polymer blends through melt processing, emphasizing both *ex situ* and *in situ* strategies, have overcome limitations such as immiscibility and poor compatibility, thereby enhancing their performance for more sustainable packaging solutions.[106] The incorporation of compatibilizers into starch and synthetic biodegradable polymer blends effectively addresses immiscibility issues and enhances water resistance, thermo-mechanical properties, and chemical stability. These advancements lead to improved performance and greater potential for replacing non-biodegradable plastics with renewable polymers in various engineering applications.[107] The application of PALS for the degradation analysis of PLA/PBAT blends reveals dynamic changes in free volume holes, elucidating the degradation process and its impact on properties, thereby aiding in the advancement of PLA blend modification.[108] The life cycle assessment revealed that PLA films managed through landfills offer the lowest carbon footprint compared to other waste treatments, whereas PLA/PBAT blends subjected to incineration result in the highest carbon emissions. Therefore, careful consideration of the environmental impact of blending materials is essential, as PLA/PBAT blends may exacerbate carbon dioxide emissions relative to traditional materials such as LDPE.[109] Porous structures within poly(lactic acid)/gelatin foams have been created and have displayed a high level of biodegradability and cell viability, making them well-suited for a variety of biomedical applications.[67] The incorporation of *para*-phenylenediamine (*p*-SB) into PLA enhanced the mechanical properties and increased the hydrophobicity of the resulting film. Additionally, the PLA-*p*-SB films exhibited improved antimicrobial activity, suggesting their potential as viable alternatives to conventional synthetic packaging materials.[68] This study successfully developed flexible PLA materials plasticized with renewable and biodegradable epoxidized soybean oil methyl ester, achieving significantly enhanced elongation and improved properties, making them more suitable for food packaging applications.[69]

Life cycle assessments of PLA/PBAT blends (typically 60–80 wt% PLA) show environmental trade-offs *versus* pure PLA or PET: GHG emissions rise to 2.2–2.8 kg CO_2 eq per kg from PLA's 1.5–2.0 kg due to PBAT's fossil adipic acid (bio-PBAT variants drop to 1.2 kg), non-renewable energy increases 20–50% to 60–90 MJ kg^{-1}, and acidification climbs to 8–15 g SO_2 eq per kg; end-of-life composting achieves 85–92% mineralization in 6 months *via* selective PLA hydrolysis, with mechanical recycling viable for 3–4 cycles before 28% impact strength loss, making high-PLA blends (70+ wt%) 20–40% greener than PET overall.[37,70]

4. PLA composites

Polylactic acid (PLA) composites generally refers to binary material systems in with single primary filler or functional additive to tailor physicochemical performance. The addition of various fillers and additives may affect their mechanical properties. According to various studies, the increased layer height and extrusion width of PLA composites affect their mechanical properties.[71] PLA-based nanocomposites, incorporating various inorganic nanoparticles like metals, metallic oxides, graphite, and silica, demonstrate significant enhancements in storage modulus, tensile strength, crystallinity, glass transition temperature (T_g), and antimicrobial properties, and reductions in water vapor and oxygen permeability compared to pure PLA films. The increasing industrial acceptance of these nanocomposites presents promising prospects for replacing conventional petrochemical-based polymers in food packaging.[72] The incorporation of metal oxides into polylactic acid (PLA) films did not alter the chemical structure of PLA but affected its physical properties, with PLA/ZnO and PLA/MgO showing the widest and PLA/TiO_2 the smallest inhibition zones. While metal oxides increased the biodegradability and accelerated the thermal degradation of PLA, they also caused surface fractures, voids, and reduced tensile strength at concentrations above 0.1 phr.[110]

The PLA/curcumin composite film, developed through solution casting, demonstrated enhanced mechanical properties, UV-barrier protection, antioxidant activity, and potential for use in active food packaging without significantly compromising transparency or water vapor permeability.[73] In addition, Al/PLA composite specimens exhibited lower tensile strength and Young's modulus than pure PLA specimens.[74,75] The mechanical performance of Jute-reinforced PLA composites was found to be inferior to that of PLA–Flax materials.[76]

Owing to better interfacial interactions, the 25% PLA-loaded Ni–As material greatly outperformed the plain and other combinations in terms of tensile strength and modulus, elongation at break, impact characteristics, and flexural strength and modulus.[111,112] The mechanical strength of the printed PLA/n-HA scaffold depended on the percentage of *n*-HA component.[77] To improve the stiffness, strength, and thermal stability of pure polymer, polylactic acid (PLA) was reinforced with cellulose nanocrystals (CNC) and reduced graphene oxide (rGO).[77] Exploring ways to modify PLA by integrating renewable reinforcements presents an intriguing avenue for addressing PLA's constraints while preserving its transparency.[78] Composite films composed of PLA and chitosan exhibited higher water vapor permeability compared to pure PLA films. The PLA: CH composite displayed notable antimicrobial effectiveness against total aerobic and coliform microorganisms.[79] A conductive graphite/poly(lactic acid) filament with a graphite filler was fabricated and 3D-printed into electrochemical devices. Detailed scanning electrochemical microscopy investigations demonstrated the enhancement of conductivity and electrochemical performance due to the changed conducive filler/polymer distribution.[80] The surfaces of carbon black/poly(lactic acid) CB-PLA printouts were activated by electrolysis or enzymatic digestion. The detailed mechanism of CB-PLA hydrolysis supported by electrolysis is a promising new route for achieving a time-efficient and environmentally friendly activation procedure.[113] 3D printed PLA-graphene (PLA-G) based sensors were developed for dopamine determination. The sensor exhibited good repeatability and reproducibility. The method was successfully applied for dopamine determination in synthetic urine and human blood serum spiked samples, demonstrating good recovery.[81] The incorporation of hybrid GOCNT into PLA nanocomposite films significantly enhanced their mechanical strength, thermal properties, gas barrier performance, and UV protection, making them promising for diverse applications in packaging, life sciences, cosmetics, and synthetic plastics.[82] Pure starch produced from waste potato starch cross-linked with 3-(aminopropyl) trimethoxy silane (3-APTMS) blended with PLA is suitable for packaging applications owing to its enhanced durability.[11] Nano-cellulose-reinforced PLA bio-nanocomposites demonstrated improved thermal stability, low water absorption, UV-blocking properties, and enhanced mechanical strength, making them promising materials for packaging applications.[83] Incorporation of fenugreek essential oil (FEO) and curcumin into the PLA composite film resulted in enhancements in UV blocking ability, surface colour, tensile strength, flexibility, thickness, and water contact angle (WCA) and a slight reduction in water vapor permeability. The film also retained its thermal stability and displayed favourable antibacterial and antioxidant properties.[84] PLA films coated with active coatings such as chitosan or chitosan/caseinate blend, enriched with rosemary essential oil, are successful in delaying lipid oxidation and maintaining the quality of fresh chicken meat during storage. *In vivo* testing revealed that active films effectively mitigated meat oxidation during anaerobic modified atmosphere storage, maintaining stable levels of malondialdehyde and colour for up to 14 days and reducing heptanal and ethanol concentrations compared to control films.[85]

The sandwich-architectured PLA–graphene composite film significantly enhanced the water vapor and oxygen barrier properties of PLA food packaging, achieving an 87.6% reduction in water vapor permeability and a two-order-of-magnitude decrease in oxygen permeability. This improvement is due to the impermeable rGO core barrier, which creates a tortuous diffusion pathway, and the hydrophobicity of the material. The excellent barrier properties and good processability of the composite film make it a highly promising option for extending the shelf life of oxygen and moisture-sensitive food products.[86]

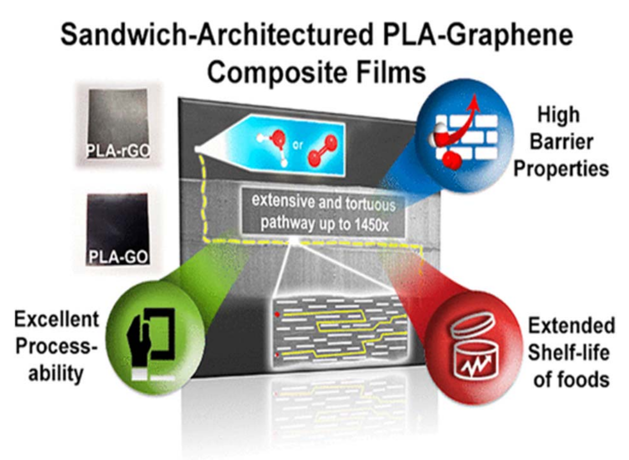


Fig. 8 Properties of PLA/graphene composites. Reprinted (adapted) with permission from. Copyright {2024} American Chemical Society.[86]

Fig. 8 presents the properties of the PLA/graphene composite films with a sandwiched architecture, demonstrating their potential for use in packaging applications.

Nano-cellulose from sugarcane bagasse fibers was isolated *via* a chemo-mechanical method, subjected to the preparation of its PLA-based bio-nanocomposites using an injection moulding process with varying weight percentages of nanocellulose.[87] An improvement in thermal stability, water resistance, and mechanical performance was observed in bio-nanocomposites with 2 wt% of nanocellulose and found that the contents of nanocellulose have a significant impact on the mechanical properties of the bio-nanocomposites.[88,114] Nano cellulose-based composites are widely used for energy storage applications such as supercapacitors, lithium-ion batteries, and other emerging electrochemical energy storage devices[115]

The diverse sources and extraction methods of nanocellulose (NC), its exceptional properties, and its role in advancing sustainable packaging materials, while addressing the processing of NC-based composites and associated health considerations.[116] The development of a one-pot process for incorporating cellulose nanofibers (CNF) into polylactic acid (PLA) demonstrated significant improvements in mechanical properties, with 3 and 5 wt% CNF increasing tensile strength, Young's modulus, and crystallinity. Additionally, the enhanced wettability of the PLA–CNF composites suggests their potential suitability for packaging, particularly for products with high-respiration rates.[117] Polylactic acid (PLA) and its natural fiber-reinforced composites, biodegradable, have high mechanical strength and are versatile in applications ranging from packaging to medicine. This review also addresses recent advancements, challenges, and future opportunities in developing and characterizing PLA-based green composites.[118]

The mechanical results clearly demonstrated a significant reinforcement effect of nanocellulose on the PLA matrix. This improvement can be attributed to the effective dispersion and stiffness between the filler and polymer matrix, which facilitated efficient stress transfer to the filler and consequently enhanced the tensile strength. The nanocomposites showed strong intermolecular interactions due to abundant hydroxyl groups and high surface area. These interactions improved stress transfer between the filler and PLA matrix. This mechanical behaviour is highly desirable and offers numerous benefits for various applications, including food packaging and biomedical applications.[119].

The development of PLA/GMS composite films using amine-functionalized green mesoporous silica sourced from rice husk significantly enhanced the flexibility, strength, antioxidant, and antibacterial properties of the films. These improvements led to a reduction in the oxygen transmission rate and extended the shelf life of the cut apple samples by seven days, demonstrating the potential of the composite films for effective active food packaging (Fig. 9).[120]

Incorporating nanocellulose offers significant advantages in improving the functional properties of TPS, PLA, and PBS for food packaging. The addition of nanocellulose to PLA and PBS enhances their oxygen barrier and mechanical properties, resulting in stronger mechanical performance and improved

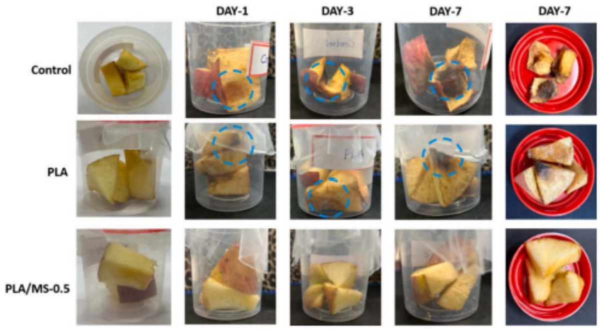


Fig. 9 Food packaging efficiency assessment of control, PLA, and PLA/GMS films. This figure has been reproduced from ref. 120 with permission from *International Journal of Biological Macromolecules*, Copyright 2024.

barrier properties while maintaining biodegradability. In the context of food packaging, where plastics are typically single-use but require adequate mechanical strength and barrier properties, nanocellulose-reinforced polymers hold promise for potential applications.[121] Nanocomposites based on PLA reinforced nanocellulose obtained from carrot pomace and silver nanoparticles were prepared using the solvent casting method. The obtained composites exhibited good transparency. Silver nanoparticles (AgNPs) synthesized using mango peel extract (MPE) were successfully incorporated into a polylactic acid (PLA) film, enhancing its mechanical properties, barrier ability, and antibacterial efficacy, with inhibition rates against *Escherichia coli* and *Staphylococcus aureus* exceeding 95%. The film was found to be safe, meeting silver migration and cytotoxicity standards, and effectively extended the shelf life of strawberries.[122] The addition of CCNF modified with AgNPs increased the hydrophilicity of the composites. Nanocellulose caused higher gas permeability and exhibited antibacterial activity only against *Escherichia coli* and *Bacillus cereus*. In addition, exhibited increased flexibility.[123] A novel nanocomposite film, referred to as PLA–ZnO, was developed by combining poly(lactic acid) (PLA) with rod-like zinc oxide (ZnO) nanoparticles. To achieve better dispersion and prevent a significant reduction in PLA's molecular mass, the nanofiller underwent surface treatment *via* silanization with triethoxy caprylyl silane. The resulting films were predominantly amorphous in nature. The changes in PLA's permeation properties were highly influenced by both the temperature and concentration of the nanofiller. In contrast to pure PLA, which lacked antimicrobial efficacy, the nanocomposites exhibited antibacterial activity against both Gram-positive and Gram-negative bacteria.[124] PLA/ZnO nanocomposites have potential applications in the medical and packaging sectors[125]

NCC-ZnO outperformed NCC as a filler in PLA by providing greater tensile strength, Young's modulus, UV shielding, and antibacterial activity, making it a promising alternative for active food packaging applications with enhanced performance in the future.[126]

Chitosan nanoparticles, modified with various derivatives through radiation-induced graft polymerization and chemical conjugation, exhibit sizes ranging from 25 to 60 nm and demonstrate enhanced antioxidant and antimicrobial properties, presenting promising potential as additives for bio-based active food packaging with tailored gas permeability and mechanical attributes.[127] Incorporating shellac nanoparticles into chitosan films improved their physicochemical properties, enhancing their thermal stability, mechanical strength, UV absorption, and color, while reducing water vapor permeability. This offers potential applications, such as preventing shrimp spoilage when curcumin is included.[128]

Chitosan nanoparticle-enriched PLA nanocomposites hold immense potential for biodegradable food packaging, offering properties comparable to conventional plastics while addressing environmental concerns and meeting the demand for sustainable materials.[129]

Calcium oxide nanoparticles sized 26 nm were organically modified with oleic acid (Ol-CaO), and both were incorporated into PLA at concentrations of 5 and 8 wt% by a melting process. Thermal analysis revealed that the presence of Ol-CaO in the PLA matrix decreased the glass transition temperature (T_g). The thermal stability of PLA/Ol-CaO decreased compared to that of neat PLA due to the catalytic activity of the nanoparticles, while the Vickers Microhardness (HV) of the nanocomposites PLA/Ol-CaO increased compared with the neat PLA due to the good dispersion of modified-surface Ol-CaO nanoparticles in PLA. PLA/Ol-CaO nanocomposites reached 99.9% of the antimicrobial effectiveness against *E. coli* for nanoparticles. The results showed that incorporating CaO nanoparticles into the PLA polymer matrix allows the future development of more sustainable materials as nanocomposites for food packaging or medical devices.[130]

The addition of titanium dioxide (TiO_2) nanoparticles to polylactic acid (PLA) composites significantly inhibited bacterial growth and biofilm formation by *E. coli*, with 1% TiO_2 showing the most pronounced effect. Despite the improved antibacterial performance, increasing the TiO_2 content beyond 1% did not result in further significant improvements.[131] The incorporation of Allium ursinum extract into poly(lactic acid) films enhanced both thermal and mechanical properties, with increased tensile strength and glass transition temperature observed for both 0.5% and 5% loadings. While the oxygen barrier properties remained largely unchanged, films with higher extract concentrations exhibited a notable color shift and effective antimicrobial activity against *E. coli*.[132]

4.1 PLA hybrid systems

PLA hybride are distinguished from conventional composites by their multiphase architectures, in which PLA is integrated with two or more functional component to achieve synergistic or multifunctional performance. These systems frequently combine polymers, nanofiller, plasticisers, compatibilisers, and bioactive agents within a single material platform. The surfaces of the carbon black/poly(lactic acid) CB-PLA printouts were activated by electrolysis or enzymatic digestion. The detailed mechanism of CB-PLA hydrolysis supported by electrolysis is a promising new route for achieving a time-efficient and environmentally friendly activation procedure.[113] Nanostructured membranes, composed of biodegradable poly(lactic acid) (PLA) and poly (ethylene glycol) (PEG), incorporating a covalently bonded lipophilic molecule (cholesterol), were specially designed as sensors. Bioinspired polymers may be used to incorporate antioxidant properties that allow the design of anti-stress biosensors and, electrodes for the detection of vitamin C or vitamin E in biomedical nutrition programs, among other applications.[133] To mitigate the environmental issues posed by non-biodegradable plastics, sustainable alternatives such as thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) are being developed for food packaging. Enhancing these materials with natural fibers and nanocellulose, along with the use of compatibilizers for better dispersion, addresses their weaknesses and improves their mechanical, barrier, and thermal properties, making them more viable for eco-friendly packaging solutions.[134] The addition of PLA and montmorillonite (MMT) to a PP/LDPE blend improved the tensile modulus and reduced the oxygen permeability, although it slightly increased the water vapor permeability. This new PP/LDPE/PLA/MMT composite effectively reduced tomato weight loss during low-temperature storage, demonstrating its potential as a high-performance packaging material for tomatoes.[135]

The addition of thymol and curry essential oil to both PLA and PLA/NFC films improved their mechanical, physical, and antimicrobial properties, thereby enhancing their effectiveness in preserving cherry tomatoes.[136] Biodegradable films of poly (butylene adipate-*co*-butylene terephthalate) (PBAT)/poly(lactic acid) (PLA) incorporated with nano-polyhedral oligomeric silsesquioxane ($POSS_{(epoxy)8}$) as a reactive compatibilizer with enhanced mechanical and barrier properties were developed to produce high-performance biodegradable plastic packaging films. The PBAT/PLA/$POSS_{(epoxy)8}$ films exhibited higher water vapor transmission rates and gas permeability than LDPE, making them more suitable for packaging moisture-sensitive produce such as strawberries, bananas, and mushrooms. These films' high perm selectivity and CO_2 permeability of these films help regulate the internal atmosphere, preventing CO_2 buildup and avoiding anoxic conditions, thereby extending the shelf life of fresh fruits and vegetables. The gas permeability scheme is shown in Fig. 10a.[137,138] Fig. 11b shows photographs of strawberries, bananas, and mushrooms stored in air and various types of plastic bags for 11 days. The image on the right highlights the cross-sections of bananas stored in different plastic bags.

The fabrication and characterization of nano-fibrillated cellulose (NFC) demonstrated its effectiveness in enhancing the tensile strength and impact toughness of plasticized PLA/ATBC bio-composites, with an optimal NFC addition of 4 wt%, resulting in significant improvements in mechanical properties, making them suitable for packaging applications requiring both load-bearing capacity and ductile functionality.[139] Incorporation of nanocrystalline cellulose derived from waste oil palm fibres into PLA/PHBV bio-nanocomposites significantly enhanced their mechanical properties and reduced oxygen permeability. The optimized bio-based composites outperform traditional polymer blends in terms of their structural integrity and barrier performance.[140]

The addition of ultrasonically exfoliated Boron Nitride (BN) to polylactic acid (PLA) composites significantly enhanced the

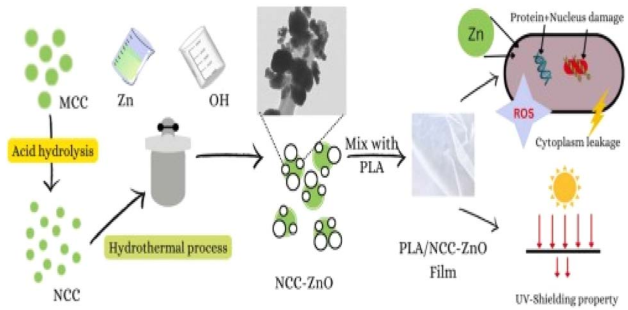


Fig. 10 Synthesis and application of PLA/NCC-ZnO films. This figure has been reproduced from ref. 126 with permission from *Food Packaging and Shelf Life*, Copyright 2023.

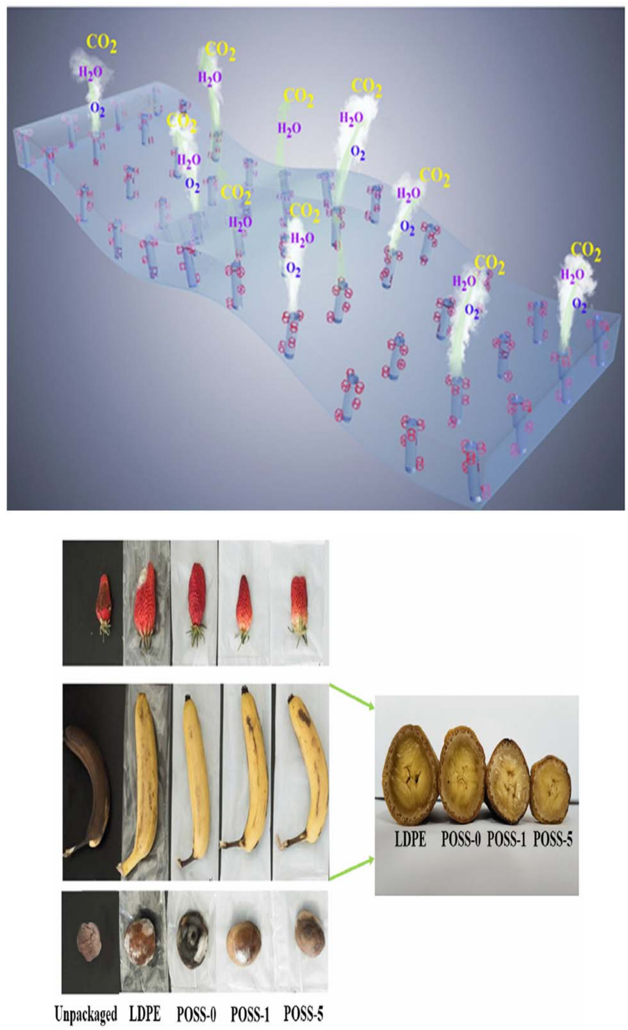


Fig. 11 (a) Schematic diagram of gas permeation in PBAT/PLA/$POSS_{(epoxy)8}$ films. (b) Photographs of strawberries, bananas, and mushrooms stored in air and in different types of plastic bags for 11 days. This figure has been reproduced from ref. 137 with permission from *Food Chemistry*, Copyright 2021.

tensile strength, with a peak value of 28.5 MPa at 2 wt% BN, representing a 132% increase compared to pure PLA. However, BN aggregation was observed at higher loadings, which could affect the uniformity of the composites.[141]

Antimicrobial films were created using poly(lactic acid) (PLA)/D-limonene/calcium oxide (CaO)-based nanocomposites through extrusion and successive thermocompression techniques. Despite CaO causing lower Young's modulus and reduced thermal stability in the nanocomposites, they displayed impressive antimicrobial efficacy. Consequently, these nanocomposites represent a significant advancement in the development of sustainable antimicrobial materials for applications in medicine and food packaging.[142]

PLA/limonene/CaO nanocomposites exhibit favourable thermal and mechanical properties, coupled with high antimicrobial efficiency against *E. coli*, making them promising and cost-effective options for medical and food packaging applications.[143] Incorporating PLA and MMT into a PP/LDPE blend improved the tensile modulus and reduced oxygen permeability, although it slightly increased the water vapor permeability and decreased the elongation at break. This new PP/LDPE/PLA/MMT composite effectively reduced tomato weight loss during low-temperature storage compared to standard PP films.[144] Biocomposites based on PLA, bio-plasticizers, and active agents such as vitamin E and chitosan-modified rosehip seed oil demonstrated varied physical-mechanical, thermal, barrier, antimicrobial, and antioxidant properties, enabling the development of eco-friendly food packaging materials with optimal features.[145]

The adoption of polylactic acid (PLA) materials offers substantial economic and environmental implications, with both benefits and ongoing challenges highlighted by recent life cycle assessments and market analyses.

4.2 Economic implications

The global PLA market is poised for rapid growth, with its size expected to more than double from USD 2.01 billion in 2025 to USD 4.51 billion by 2030, driven by the demand for sustainable packaging, medical devices, textiles, and automotive components. PLA production creates new agricultural value chains. Utilizing renewable sources such as corn, sugarcane, and cassava enables farmers to gain additional income streams, while industries benefit from secure and sustainable raw material supplies. Energy efficiency in manufacturing: PLA production consumes approximately 65% less energy than conventional plastics, resulting in notable cost reductions and lower operational emissions for manufacturers.

PLA economics vary by region. EU policies stimulate demand but increase resin costs. North American demand depends on oil and corn price fluctuations. Asia-Pacific benefits from feedstock availability and subsidies, although resin prices can remain 1.3–2× higher than PE or PET.[146–149]

4.3 Environmental implications

Lower greenhouse gas emissions over the lifecycle: PLA, being biobased, absorbs approximately 1.8 kg of CO_2 per kg produced—far greater than petroleum-based plastics. However, its conversion process stays energy-intensive and adds to CO_2 emissions. End-of-life advantages and limitations:[150,151] PLA can biodegrade under industrial composting conditions; however, its breakdown in home compost, soil, and marine environments is slow, sometimes taking decades. Under certain conditions, PLA may behave similarly to conventional plastics, contributing to microplastics if improperly managed. Reduced environmental footprint with optimization: life cycle assessments indicate that optimizing the conversion stage can lower CO_2 emissions associated with PLA by over 50%. Composting infrastructure and recycling improvements are vital for realizing PLA's full sustainability potential of PLA. Circular economy potential: integrating PLA into agricultural and industrial frameworks creates new links between waste valorization and material innovation, promoting more resilient, closed-loop resource cycles for bio-based materials.[151]

On the environmental side, regional policy frameworks (EU Green Deal, China's plastic value-chain controls, emerging EPR and compostability rules in Southeast Asia) strongly influence PLA's realized benefits by determining end-of-life routes and system boundaries in LCAs: EU markets with higher industrial composting and biowaste collection can capture lower GWP and reduced plastic leakage compared to regions where PLA is landfilled or incinerated; meanwhile, location and design of new PLA plants (feedstock sourcing, energy mix, co-product use) drive cradle-to-gate impacts, meaning the same kilogram of PLA can show substantially different GWP and cumulative energy demand in EU, US, or Asian LCAs depending on electricity carbon intensity, logistics, and integration with regional circular-economy infrastructure.[35,148,149,152,153]

These trends demonstrate that PLA adoption is key to sustainable material innovation; however, maximizing its positive impact depends on technological improvements, integrated policy frameworks, and infrastructure development for responsible disposal and recycling. Fig. 12 shows comparative study between PLA and conventional plastics.

Hybrid fiber-reinforced composites made from sisal and hemp fibers with polylactic acid (PLA) demonstrated enhanced mechanical properties, including improved tensile and flexural

Fig. 12 Comparative table: PLA *vs.* conventional plastics.

strengths and increased impact strength compared to neat PLA. These composites offer a promising, environmentally friendly alternative for applications in the automotive, packaging, electronics, interiors, and agricultural industries.[154]

5. Limitations and future outlook of PLA-based systems

Polylactic acid (PLA)-based systems, despite their appeal as bio-based and biodegradable polymers, continue to face several technical limitations that restrict their widespread use in advanced functional materials and sensor applications. These limitations span mechanical, thermal, chemical, environmental, and economic dimensions, prompting ongoing research into more sustainable and high-performance alternatives for their replacement.[155–157]

PLA possesses a relatively high tensile strength and elastic modulus comparable to PET; however, its low elongation at break and inherent brittleness limit its use in applications requiring flexibility or deformation under stress, such as wearable and implantable sensors. This poor toughness makes it susceptible to cracking and mechanical failure under repeated load or bending conditions. Similarly, its slow degradation rate—ranging from months to years—poses challenges for both biomedical and environmental applications. In medical contexts, controlled and predictable degradation is essential, whereas in environmental disposal, faster breakdown is desired to minimize waste accumulation.[158–165]

Another notable drawback of PLA is its hydrophobic nature, which reduces its interaction with water or biological fluids. This characteristic leads to poor cell adhesion and possible inflammatory reactions in biomedical applications. Furthermore, their lack of reactive side-chain groups makes surface modification or functionalization complex and often reliant on chemical grafting, plasma treatment, or mixing with functional fillers or co-polymers.[150,158]

Thermally, PLA displays low thermal stability and a low glass transition temperature ($\sim$60 °C), limiting its use in high-temperature environments or under prolonged heat exposure conditions. However, they also suffer from high flammability and the potential release of toxic gases upon combustion, restricting application in sectors such as electronics and automotive components unless modified with flame-retardant additives or 2D nanomaterials such as MXenes or graphene.[166,167]

6. Scope of review

Despite notable progress in PLA-based materials, key challenges remain in enhancing toughness and ductility without compromising biodegradability, achieving controlled and application-specific degradation rates, and improving interfacial compatibility with functional nanomaterials such as MXenes, graphene, and nanoclays to enable multifunctional capabilities in sensors, biomedical scaffolds, and structural composites. Research continues to investigate blending strategies, copolymerization, and chain extension to overcome brittleness, while surface and bulk modification approaches are being developed to adjust hydrophilicity, bioactivity, and interfacial chemistry. Additionally, integrating nanoparticles and fillers must be accomplished through scalable, cost-effective, and environmentally benign processes that preserve PLA's sustainability advantages. Blending PLA with PCL or PBSA accelerates biodegradation. Full degradation can occur within one year under home composting conditions. Enzymatic and crystallinity control further tune material lifespan. Ultimately, PLA's broader adoption in sustainable packaging, consumer electronics, and biomedical applications will be driven by its successful reinforcement through advanced fillers and green additives, the development of hybrid copolymer systems, and the establishment of robust circular economy and life-cycle assessment frameworks that support its end-of-life recovery and reuse.

In the short term, PLA food packaging development should focus on formulation and process optimization that can be adopted on existing industrial lines: fine-tuning PLA/PBAT, PLA/PCL, and plasticized PLA blends for thermoforming and film extrusion; engineering multilayer and coated structures (*e.g.*, PLA with bio-based barrier coatings or nanoclay/nanocellulose layers) to meet specific OTR/WVTR targets; validating active/antimicrobial PLA systems (essential oils, metal oxides, biopolymers) against harmonized food-safety and migration regulations (EU 10/2011, FDA, FSSAI); and implementing practical design-for-recycling protocols and mechanical recycling loops for post-consumer PLA in closed or semi-closed streams such as cups and trays.[48,168,169]

In the long term, PLA's role in food packaging should be framed within a circular, low-carbon system by diversifying feedstocks toward agricultural residues, lignocellulosic sugars, or algae to reduce pressure on food crops; scaling chemical recycling and depolymerization to lactic acid or higher-value monomers so PLA can be truly circular; developing high-performance PLA composites and hybrids (*e.g.*, lignin–PLA, nanocellulose–PLA, PBAT/PBS/PLA systems) tailored for region-specific policy regimes (EU PPWR, EPR schemes, compostability and recycling targets); and integrating intelligent packaging functions (sensors, indicators, RFID/digital IDs) that allow PLA-based packs to monitor food quality, enable dynamic shelf-life management, and interface with traceability and sorting systems needed for advanced circular-economy infrastructure.[48,170–172]

7. Conclusion

Polylactic acid (PLA) has recently evolved as a preferred candidate for sustainable packaging materials, offering a viable alternative to traditional petroleum-based plastics. Its inherent biodegradability and renewability address critical environmental concerns, providing a means to reduce plastic waste and reliance on fossil fuels. Strategies in PLA technology, such as the development of high-performance PLA-based composites and blends, have substantially enhanced its mechanical properties, barrier performance, and processing capabilities. These improvements make PLA suitable for a wide range of applications, from food packaging to industrial uses, in alignment with the growing consumer and regulatory demands for eco-friendly solutions.

Current modification strategies often improve one functional parameter at the expense of another, highlighting the need for system-level material design rather than single-property optimization.

From a structural standpoint, interfacial incompatibility in blends, filler aggregation in composites, and crystallinity control in processed films remain decisive factors governing performance reproducibility. Processing–structure–property relationships are still insufficiently standardized, leading to variability in reported optimal formulations. In addition, industrial scalability challenges such as narrow thermal processing windows, hydrolytic degradation during melt processing, and recycling–compostability trade-offs continue to limit commercialization potential.

Looking forward, future research must prioritize multifunctional hybrid architectures capable of delivering mechanical robustness (>60 MPa tensile strength), high flexibility (>150% elongation), and low oxygen permeability (<200 cc mm per m^2 per day per·atm) within a single material platform. Advanced compatibilization *via* reactive extrusion, bio-derived plasticizers, and surface-engineered nanofillers offers promising pathways. Integration of AI-assisted formulation design, predictive permeability modeling, and life-cycle-optimized material selection will further accelerate development.

Equally important is the transition toward circular bioeconomy frameworks, including closed-loop recycling, composting infrastructure compatibility, and carbon-footprint minimization validated through life-cycle assessment metrics. The convergence of material innovation, processing engineering, and sustainability analytics will ultimately define the future trajectory of PLA-based packaging systems.

Equally important is the transition toward circular bioeconomy frameworks, including closed-loop recycling, composting infrastructure compatibility, and carbon-footprint minimization validated through life-cycle assessment metrics. The convergence of material innovation, processing engineering, and sustainability analytics will ultimately define the future trajectory of PLA-based packaging systems.

Through these strategic directions, PLA can evolve from a biodegradable alternative into a high-performance, data-engineered packaging solution aligned with global environmental and industrial demands.

Author contributions

Naja Hasoon K.T.: conceptualization, writing – original draft preparation. Unnikrishnan Gopalakrishna Panicker: writing – reviewing and editing, supervision.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

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