

Biodegradable biomaterials for sustainable packaging: trends and challenges

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ABSTRACT

Conventional plastic packaging, derived from petrochemical sources, has long supported global food preservation and logistics but poses severe environmental risks due to its persistence and contribution to microplastic pollution. As the packaging industry accounts for nearly 40% of global plastic use, there is a growing demand for sustainable alternatives that can reduce ecological harm without compromising performance. Biodegradable biomaterials such as starch, cellulose, chitosan, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and protein-based polymers have emerged as viable candidates for replacing synthetic plastics in various packaging applications. These materials demonstrate favorable biodegradability, safety for food contact, and the capacity for enhancement through composite formulations with natural fibers, nanomaterials, or bioactive compounds. Applications span from food and medical packaging to e-commerce and edible films, with several systems offering functional benefits such as antimicrobial activity and improved barrier properties. Regulatory frameworks like EN 13432 and ASTM D6400, along with certification schemes including OK Compost and BPI, are critical in validating material claims and enabling market adoption. However, limitations persist, including high production costs, poor moisture resistance, limited mechanical durability, and the need for industrial composting infrastructure not widely available. Confusion over disposal and lack of consumer awareness further undermines the environmental potential of these materials. This review analyzes recent developments in biodegradable biomaterials for sustainable packaging, focusing on material classification, processing techniques, functional enhancements, and practical applications. It also outlines key challenges and regulatory considerations while highlighting future strategies including smart packaging and AI-driven design to improve scalability, safety, and circularity in biodegradable packaging systems.

KEYWORDS

Biodegradable biomaterials;
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Introduction

Conventional plastic packaging, largely derived from petroleum-based polymers, has played a pivotal role in ensuring food safety, prolonging shelf life, and reducing food waste. However, its long degradation timeline, environmental persistence, and contribution to microplastic pollution have raised global ecological and public health concerns. With the packaging industry being responsible for nearly 40% of global plastic usage, addressing the environmental burden of single-use plastics has become an urgent priority in environmental policy and materials science [1-3].

In response, biodegradable biomaterials have emerged as promising alternatives, capable of decomposing into non-toxic byproducts under natural environmental conditions. These materials include biopolymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), starch, cellulose, and protein-based films, which are increasingly being investigated for food packaging applications [4]. Recent advances in composite materials, integrating natural fibers, nanomaterials, or essential oils, have further enhanced the functional and mechanical properties of these biomaterials. In particular, nanocellulose, chitosan, and alginate-based formulations are gaining attention due to their favorable gas barrier,

antimicrobial, and biodegradation profiles. Notably, bio-packaging derived from agricultural and marine waste such as sugarcane bagasse, crab shells, and red seaweed presents a dual environmental benefit by simultaneously addressing waste valorization and plastic substitution [5].

According to recent market analyses, the global biodegradable packaging market is expected to surpass USD 25 billion by 2027, growing at a CAGR of approximately 14% from 2022 to 2027, driven by regulatory mandates in the EU, North America, and parts of Asia. However, despite these advances, several limitations restrict commercial scalability and widespread adoption. These include batch-to-batch variability, limited mechanical strength, high production costs, and a lack of standardization in biodegradability testing protocols. Moreover, incompatibility with existing recycling streams and ambiguous regulatory frameworks further complicate integration into mainstream packaging systems [6].

This review aims to critically analyze recent developments in biodegradable biomaterials for sustainable packaging, with a focus on material types, fabrication technologies, and real-world applications. Emphasis is also placed on identifying key challenges that hinder translation from laboratory

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innovation to market implementation. By evaluating current trends and obstacles, this review seeks to inform future interdisciplinary strategies for advancing sustainable materials in the packaging sector.

Types of Biodegradable Biomaterials

Biodegradable biomaterials have emerged as key alternatives to synthetic plastics in packaging due to their renewability, environmental degradability, and potential for circular economy integration. These materials fall into four major categories: polysaccharides, proteins, biodegradable polyesters, and bio-composite systems [7].

Polysaccharide-based materials

Polysaccharides such as starch, cellulose, chitosan, and alginate are naturally abundant, compostable, and suitable for food contact applications. Starch, derived from sources like maize,

potato, and jackfruit, forms transparent, flexible films with low oxygen permeability, but is inherently hydrophilic and lacks moisture resistance. Blending with polyvinyl alcohol (PVA) or crosslinking with citric acid can enhance its structural integrity [8]. Cellulose, typically sourced from agro-residues like sugarcane bagasse, is valued for its mechanical strength and film transparency. However, its poor solubility necessitates derivatization into carboxymethyl cellulose (CMC) or hydroxypropyl methylcellulose (HPMC) for packaging applications. Chitosan, a cationic polysaccharide from crustacean shells, exhibits film-forming ability, antimicrobial activity, and biodegradability, though its performance under high humidity remains limited. Alginate, derived from brown seaweed, provides excellent oxygen barrier properties and biocompatibility but suffers from water sensitivity unless reinforced or ionically crosslinked [9,10] [Table 1].

Table 1. Polysaccharide-Based Materials for Biodegradable Packaging.

Material	Source	Key Functional Properties	Limitations	Common Enhancements/Blends	Applications
Starch	Maize, potato, tapioca, jackfruit	- Good oxygen barrier under dry conditions	- Poor moisture resistance	- Blending with PVA or PLA	Food wraps, trays, compostable bags
		- Transparent and flexible films	- Brittle in dry conditions	- Crosslinking with citric acid	
		- Biodegradable and cost-effective	- Retrogradation over time	- Plasticization with glycerol or sorbitol	
Cellulose	Sugarcane bagasse, wood pulp, cotton linter	- High mechanical strength	- Insoluble in water	- Use of derivatives like CMC and HPMC	Coatings, multilayer films, rigid trays
		- Film transparency	- Limited processability in native form	- Blending with gelatin or PVA	
		- Biocompatible and compostable		- Nanocellulose reinforcement	
Chitosan	Crustacean shells (shrimp, crab), fungi	- Antimicrobial	- High moisture sensitivity	- Crosslinking with tripolyphosphate	Antimicrobial films, edible coatings, wound dressings
		- Good oxygen barrier	- Limited solubility at neutral pH	- Nanoparticle incorporation (e.g., ZnO)	
		- Biodegradable and film-forming		- Blending with essential oils	
Alginate	Brown seaweed (Laminaria, Macrocystis)	- Excellent gas barrier	- Water-sensitive	- Calcium ion crosslinking	Edible films, biodegradable pouches, coatings
		- Edible and biocompatible	- Poor mechanical integrity when hydrated	- Reinforcement with cellulose nanofibers or montmorillonite	
		- Ionically crosslinkable			
Pectin	Citrus peel, apple pomace	- Edible	- Low water resistance	- Plasticization with glycerol	Fruit coatings, edible wraps, active packaging
		- Film-forming	- Brittle without plasticizer	- Blending with starch or gelatin	
		- Can incorporate active compounds		- Crosslinking with Ca ²⁺	

Pullulan	Fermentation of <i>Aureobasidium pullulans</i>	- High transparency - Good oxygen barrier - Edible and tasteless	- High cost - Water solubility may limit shelf stability	- Blending with chitosan or gelatin - Crosslinking with sodium tripolyphosphate	Breathable films, edible coatings, pharmaceutical blisters
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Protein-based films

Protein-based materials such as gelatin, soy protein isolate (SPI), and casein possess film-forming capacity, moderate tensile strength, and functional versatility. Gelatin, derived from partial hydrolysis of animal collagen, forms elastic and transparent films but absorbs moisture readily. SPI, a plant-derived polymer, offers superior oxygen barrier properties and compatibility with antimicrobial agents and essential oils [11]. Casein, a milk phosphoprotein, is used in edible films and coating applications, forming amphiphilic networks conducive to water solubility control. Despite promising physicochemical performance, protein-based films often require blending with plasticizers to enhance flexibility and reduce brittleness [12] [Table 2].

Table 2. Properties and Characteristics of Protein-Based Biodegradable Films.

Protein Source	Origin	Film-Forming Ability	Barrier Properties	Mechanical Properties	Additives/Enhancers	Limitations	Typical Applications
Gelatin	Animal (collagen hydrolysate)	Forms elastic, transparent films	Moderate oxygen barrier; poor water vapor resistance	Moderate tensile strength; good elasticity	Glycerol, sorbitol (plasticizers)	Moisture sensitivity; poor heat stability	Edible coatings, flexible food films
Soy Protein Isolate (SPI)	Plant (soybeans)	Smooth, cohesive films	Excellent oxygen barrier; limited water barrier	Moderate to good TS; brittle without plasticizers	Essential oils, ZnO/Ag NPs, glycerol	Brittle without additives; limited humidity tolerance	Antimicrobial films, food wraps
Casein	Animal (milk protein)	Forms amphiphilic film networks	Good oxygen barrier; water solubility tunable	Moderate strength; flexible with plasticizers	Curcumin, lycopene, plant polyphenols	Sensitive to pH and enzymatic degradation	Edible films, coatings for dairy and meat products
Whey Protein Isolate (WPI)	Animal (milk by-product)	Glossy, smooth films	Good barrier to gases; poor moisture barrier	Good flexibility with plasticizers	Sorbitol, antioxidants	Hydrophilic; plasticizer-dependent	Bakery, confectionery wrapping
Corn Zein	Plant (corn endosperm)	Forms glossy, hydrophobic films	Good moisture resistance; poor oxygen barrier	Low elongation at break; moderate TS	Polyols, natural colorants	Poor mechanical resilience	Coating of nuts, confectionery items
Gluten (Wheat)	Plant (wheat protein)	Forms tough, film-like matrices	Moderate gas barrier; water-sensitive	Tough but brittle without plasticizer	Acids, plasticizers	Poor consumer acceptability (gluten-sensitive)	Packaging for dry foods
Pea Protein	Plant (legumes)	Acceptable with modification	Poor to moderate barrier performance	Moderate mechanical strength	Crosslinkers, glycerol	Requires denaturation; limited studies	Emerging alternative for plant-based packaging

Biodegradable polyesters

Biodegradable aliphatic polyesters such as PLA, PHA, and polybutylene succinate (PBS) are commercially scalable options for rigid and flexible packaging. PLA, produced via fermentation of starch-derived sugars, offers high transparency and mechanical strength, but has limited thermal resistance and tends to be brittle. Copolymerization and inclusion of plasticizers or fillers like talc improve its thermal and mechanical behavior. PHA, biosynthesized by microbial fermentation, exhibits full biodegradability in marine and soil environments and superior tensile properties, though its high production cost restricts widespread adoption. PBS, synthesized via polycondensation of succinic acid and butanediol, demonstrates good flexibility and processing compatibility, and is industrially compostable under controlled conditions [13,14] [Table 3].

Table 2. Key Biodegradable Polyesters for Sustainable Packaging.

Polyester Type	Source/Production	Biodegradability	Mechanical Properties	Barrier Properties	Processing Techniques	Applications
Polylactic Acid (PLA)	Fermentation of starch/sugar (e.g., corn, cassava); polymerized via lactide ring-opening	Industrial composting (EN 13432/ASTM D6400 compliant)	Tensile Strength: ~50–70 MPa; Brittle; Elongation at break: <10%	Moderate oxygen barrier; poor moisture barrier	Extrusion, Injection molding, Thermoforming, 3D printing	Rigid trays, flexible films, cutlery, medical packaging
Polyhydroxyalkanoates (PHA)	Biosynthesized via microbial fermentation of sugars, lipids, or wastewater	Biodegrades in soil, marine, and composting conditions	Tensile Strength: ~20–40 MPa; Elongation: 10–20%	Good moisture and oxygen barrier	Extrusion, Solvent casting, Blow molding	Food films, medical implants, coated paper
Polybutylene Succinate (PBS)	Chemical polymerization of succinic acid and 1,4-butanediol (can be bio-based)	Industrially compostable under controlled conditions	Tensile Strength: ~35–50 MPa; good elongation (~30–50%)	Good moisture resistance; moderate gas barrier	Injection molding, Blown film extrusion	Disposable cutlery, containers, mulch films
Polybutylene Adipate Terephthalate (PBAT)	Copolymer of adipic acid, terephthalic acid, and 1,4-butanediol (petro-based)	Biodegradable in industrial composting and soil	Highly flexible; Tensile Strength: ~20–30 MPa; Elongation >300%	Poor moisture barrier; high oxygen permeability	Blown film extrusion, Lamination	Compostable bags, agricultural films, packaging blends
Polycaprolactone (PCL)	Ring-opening polymerization of ϵ -caprolactone (petro-based)	Degrades in soil, compost, marine (very slow rate)	Low tensile strength (~10–20 MPa); highly elastic (elongation >400%)	Poor barrier properties	Electrospinning, Injection molding, Blending	Biomedical packaging, drug delivery films

Bio-composites and nanocomposites

Bio-composites and nanocomposites enhance the functional limitations of individual biopolymers. Reinforcement with lignin, flax fibers, zinc oxide nanoparticles (ZnO-NPs), or nanocellulose improves mechanical strength, UV shielding, antimicrobial activity, and moisture resistance. For instance, ZnO-incorporated starch–PVA films exhibit effective antibacterial properties against *E. coli* and *S. aureus* while maintaining high tensile strength. Similarly, nanocellulose derived from sugarcane bagasse enhances oxygen barrier properties and mechanical integrity when integrated into PLA matrices. While many such systems are promising, regulatory approval for nanoparticle migration and food-contact safety remains a critical consideration for real-world application [15,16].

Processing and Functional Properties

The functionality and commercial viability of biodegradable biomaterials for sustainable packaging are directly influenced by their processing conditions, additive incorporation, and resultant performance characteristics.

Processing techniques

Key fabrication methods for biodegradable packaging materials include extrusion, film blowing, solvent casting, and injection molding. Extrusion is commonly used for thermoplastic polymers such as PLA, PHA, and starch-polymer blends. During this process, polymer pellets are melted and shaped into films or sheets through controlled thermal and shear input. Film blowing, a subset of extrusion, is widely used for flexible packaging and allows the formation of thin, stretchable films with balanced mechanical properties and orientation. Solvent casting, suitable for hydrophilic polymers such as chitosan, gelatin, and alginate, provides good film uniformity but remains limited to lab-scale applications due to solvent recovery and drying constraints. Injection molding has been adapted for biodegradable trays, cutlery, and rigid containers, particularly with PBS and PLA, offering high throughput and design flexibility [17,18].

Additive technologies

To enhance processing feasibility and end-use performance, biodegradable polymers are often modified using plasticizers,

crosslinkers, and functional additives. Plasticizers such as glycerol and sorbitol improve flexibility by reducing hydrogen bonding and polymer chain rigidity, particularly in starch and protein-based films. Crosslinking agents, including citric acid and calcium ions, enhance water resistance and structural cohesion by forming covalent or ionic interpolymer networks. Additionally, antimicrobial additives like ZnO nanoparticles, silver ions, or essential oils inhibit microbial growth, extending product shelf life. Antioxidants such as tocopherol or polyphenolic compounds from natural extracts can be embedded in packaging to prevent oxidative degradation of lipid-rich foods. The compatibility of these additives with the base polymer matrix, as well as food safety approval, are critical parameters in formulation development [19,20].

Material performance

The suitability of biodegradable materials for packaging is assessed using parameters such as water vapor transmission rate (WVTR), oxygen permeability (OP), tensile strength (TS), and elongation at break (EB). PLA-based films exhibit low WVTR ($\sim 10\text{--}25\text{ g/m}^2/\text{day}$) and moderate OP ($\sim 150\text{ cm}^3/\text{m}^2/\text{day}/\text{atm}$), but limited flexibility, which can be mitigated using plasticizers or polymer blending. Starch and cellulose films are effective oxygen barriers under dry conditions but exhibit increased permeability and brittleness in high humidity environments [21,22]. The incorporation of nanocellulose, montmorillonite, or ZnO nanoparticles into PLA or starch matrices has been shown to reduce WVTR and enhance tensile properties by up to 50%. Functional improvements often correlate with the degree of filler dispersion, interfacial adhesion, and crystallinity enhancement [23].

Packaging performance also depends on processing parameters such as extrusion temperature, film thickness, and drying conditions, all of which influence crystallization, porosity, and structural uniformity. Furthermore, the degradation behavior of these films varies based on their exposure to moisture, microbial communities, and temperature underscoring the need for standardized biodegradability assessment protocols [24].

Applications in Packaging

Food packaging

Biopolymers such as starch PLA, chitosan, and cellulose are commonly formulated into flexible films, rigid trays, and food coatings. These materials serve as oxygen and moisture barriers, critical for preserving food quality and extending shelf life. For instance, chitosan films incorporated with silver or zinc oxide nanoparticles have demonstrated significant antimicrobial efficacy, with microbial growth inhibition zones exceeding 12 mm against common pathogens like *E. coli* and *S. aureus*. PLA-based trays and cellulose coatings also exhibit water vapor transmission rates (WVTR) in the range of $10\text{--}25\text{ g/m}^2/\text{day}$, providing protection for perishable items. Protein-based films formulated from casein or whey have been further enhanced with curcumin and lycopene to impart antioxidant properties, retarding lipid oxidation in high-fat food matrices by up to 40% [25,26].

Medical packaging

Biodegradable packaging is being adapted for medical applications such as sterilizable wraps, trays for surgical instruments, and bioresorbable pouches for wound dressings. Materials such as PLA, PHA, and gelatin-based composites provide structural durability and are compatible with ethylene oxide or gamma sterilization protocols. These systems meet functional sterilization standards while offering composability under controlled industrial conditions [27].

E-Commerce and consumer goods

Compostable mailers, molded fiber clamshells, and starch-based corrugated packaging are emerging in online retail and electronics logistics. These packaging types are engineered to sustain high mechanical stress and humidity variation during transit. Nanoclay-reinforced PLA and jute fiber composites have shown improvements in compressive strength by 35–45% compared to unfilled analogs. Furthermore, these systems are compatible with automated sealing, thermoforming, and lamination lines, facilitating seamless integration into existing supply chains [28].

Edible films

Edible packaging derived from polysaccharides or proteins has gained traction for use with fresh produce, bakery, and confectionery items. These films serve as primary barriers and can be safely ingested, eliminating waste altogether. For example, gelatin films enriched with pH-responsive anthocyanins have demonstrated real-time spoilage sensing capabilities by visually signaling protein degradation through color shifts. Moreover, their film-forming capacity is often enhanced using glycerol or sorbitol, resulting in tensile strengths of 15–30 MPa and elongation at break values above 20%, suitable for handling and wrapping perishable items [29].

Environmental and Regulatory Considerations

The transition toward biodegradable biomaterials in packaging necessitates rigorous environmental validation and compliance with standardized metrics. Key international standards such as EN 13432 (Europe) and ASTM D6400 (USA) define industrial composability criteria. According to these standards, a material is considered compostable if it biodegrades by at least 90% within 180 days under controlled aerobic composting conditions and does not release heavy metals or toxic residues that impair compost quality. In addition, EN 14995 extends composability testing to plastics not specifically intended for packaging applications [30].

Life cycle assessment (LCA) provides a comprehensive framework to evaluate the environmental footprint of biodegradable packaging across its production, use, and end-of-life phases. Studies comparing PLA, starch-based materials, and PHA with petroleum-based plastics consistently demonstrate reduced greenhouse gas (GHG) emissions and lower fossil energy consumption, provided that raw material sourcing and processing efficiencies are optimized. However, factors such as land use, water demand, and agricultural input for biomass cultivation may offset environmental gains if not carefully managed [31]. Figure 1 explains the cyclic biological process of biodegradable polymers.

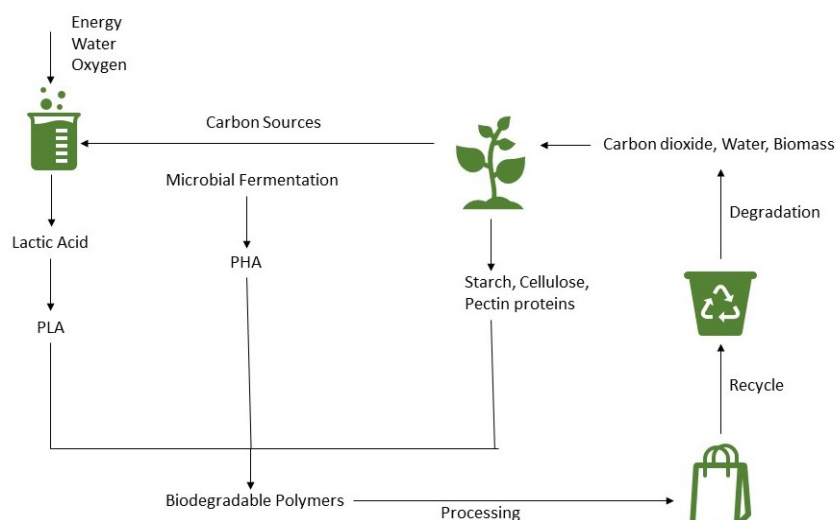


Figure 1. Cyclic biological process of biodegradable polymers.

Certification schemes such as OK Compost (TÜV Austria), Biodegradable Products Institute (BPI), and EU Ecolabel play a pivotal role in verifying environmental claims and ensuring compliance with compostability and sustainability benchmarks. These labels assess parameters including biodegradation rate, eco-toxicity, heavy metal content, and safe degradation in industrial composting systems. For end-users and manufacturers, such labels signify material credibility and regulatory approval across regional markets [32].

Despite these frameworks, inconsistencies in global standardization, absence of marine and soil degradation metrics, and limited access to industrial composting facilities continue to constrain widespread adoption. Harmonization of certification protocols and increased investment in decentralized composting infrastructure are essential to support the scalable and sustainable deployment of biodegradable packaging [33].

Challenges and Limitations

Despite their ecological appeal, biodegradable biomaterials face several practical and technical barriers that limit widespread adoption in commercial packaging. One of the primary constraints is economic feasibility. Biopolymer production often involves high raw material and processing costs compared to conventional petrochemical plastics. Materials such as PLA and PHA are derived from renewable resources but require energy-intensive processing steps, fermentation systems, and costly downstream purification, which raises the final product price [34].

Functionally, biodegradable materials present notable performance drawbacks. Polysaccharide- and protein-based films often exhibit high water sensitivity and limited mechanical durability. Their poor moisture and gas barrier properties make them unsuitable for long-term storage or humid environments unless reinforced with hydrophobic agents or nanofillers. Furthermore, their brittleness and restricted thermal stability pose challenges in thermoforming, sealing, and packaging machinery compatibility, reducing their adaptability in

automated systems used in industrial settings [35].

Another critical concern is the risk of contamination in the existing waste management stream. Biodegradable materials may visually resemble traditional plastics, leading to confusion among consumers and improper disposal. Most compostable biomaterials require specific industrial composting conditions like controlled temperature, humidity, and microbial activity which are not available in conventional recycling or landfill systems. The lack of standardized infrastructure and consumer awareness exacerbates this issue, leading to environmental inefficiencies [36].

Overcoming these limitations demands advancements in scalable biopolymer synthesis, functional performance optimization via composite engineering, and harmonization of waste processing frameworks supported by clear certification and labelling systems. These developments are essential to enable biodegradable biomaterials to replace conventional plastics in high-volume applications effectively.

Future Directions

The advancement of biodegradable biomaterials is poised to benefit significantly from innovations in smart packaging, sustainable sourcing, and computational material design. Smart packaging systems, particularly those embedded with biosensors, are being engineered to detect spoilage, microbial activity, or physicochemical changes in packaged products [37]. For instance, pH-sensitive films incorporating anthocyanins or metallic nanoparticles are under development for real-time freshness monitoring, enhancing safety and reducing food waste. Concurrently, waste-derived bioplastics produced from agro-industrial residues such as rice husk, shrimp shells, or potato peel starch offer a sustainable feedstock alternative that supports low-cost circularity and reduces environmental load [38]. Additionally, the integration of machine learning (ML) and artificial intelligence in material research is enabling accelerated prediction of biodegradation rates, blend miscibility, and barrier property optimization, thereby minimizing experimental iterations. These digital tools are particularly effective in screening polymer combinations and forecasting life-cycle performance. Lastly, embedding biodegradable materials into a circular bioeconomy demands harmonized regulatory frameworks and standardized labeling systems to support end-of-life recovery pathways. Progress in these areas will require synergistic collaboration between material scientists, process engineers, computational modelers, and policymakers to ensure scalable, safe, and sustainable packaging solutions [39,40].

Conclusion

Biodegradable biomaterials such as starch, cellulose, polylactic acid (PLA), and chitosan have gained substantial traction as

sustainable alternatives to conventional plastics in packaging. Their application in food films, molded trays, and active coatings is supported by their renewability, biodegradability, and moderate moisture and gas barrier properties. However, limitations in mechanical performance, cost competitiveness, and restricted post-use processing infrastructure continue to hinder large-scale implementation. Advances in nanocomposites, biosensor-integrated smart packaging, and machine learning-guided polymer optimization are expanding their functional potential. Regulatory frameworks including EN 13432 and ASTM D6400, along with certification systems, play an essential role in standardizing composability claims and building consumer trust. Integrating these materials into a circular bioeconomy through agricultural waste valorization, decentralized composting, and stakeholder collaboration across industry, academia, and policy sectors will be critical. Continued interdisciplinary research and policy incentives are necessary to ensure the safe, efficient, and economically viable transition to biodegradable packaging systems.

Disclosure statement

No potential conflict of interest was reported by the author.

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