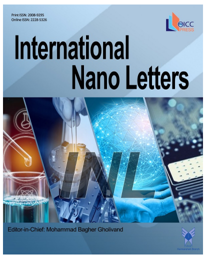

Int. Nano Lett. 2026; 16(1) : 36-50

International Nano Letters (INL)

https://doi.org/10.57647/inl.2026.1601.04

Review Article

Recent Insights into Biodegradable Nanocomposites for Food Packaging Applications: Prospects and Challenges

Maryam Salehian[1], Zeinab Salehi[2,*], Kianoush Khosravi-Darani[2,*]

[1] *Department of Biochemical and Pharmaceutical Engineering, School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran*

[2] *Department of Food Technology Researches, National Nutrition and Food Technology Research Institute, Faculty of Nutrition Sciences and Food Technology, Shahid Beheshti University of Medical Sciences, Tehran, Iran*

[*] **Corresponding authors:** zsalehy@ut.ac.ir, and k.khosravi@sbmu.ac.ir

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Article History

Received:
21 October 2025

Revised:
17 March 2026

Accepted:
26 March 2026

Published in Issue:
31 March 2026

Abstract:

Biodegradable nanocomposites have emerged as promising alternatives to conventional petroleum-based food packaging materials, offering enhanced mechanical strength, improved barrier performance, and active functionalities such as antimicrobial activity. By combining biopolymer matrices with nanoscale fillers, these materials aim to maintain food quality while reducing environmental impact. Numerous studies demonstrate that biodegradable nanocomposites can satisfy key functional requirements of traditional packaging while providing additional performance advantages.

However, despite significant laboratory-scale advancements, several critical challenges continue to limit large-scale implementation. These include scalable manufacturing and nanofiller dispersion control, regulatory compliance, migration safety evaluation, cost competitiveness, and long-term environmental assessment. Addressing these interconnected constraints is essential for translating material innovation into practical packaging solutions.

This review aims to bridge the gap between laboratory-scale material development and real-world packaging applications by addressing technical, safety, and commercialization constraints. By examining current limitations and emerging solutions, the review provides a realistic outlook on the future integration of biodegradable nanocomposites into sustainable food packaging systems.

Keywords: Biodegradable nanocomposites; Active food packaging; Nanofiller dispersion; Migration safety; Life cycle assessment; Commercialization challenges

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Cite this article: Salehian M, Salehi Z, Khosravi-Darani K. Recent Insights into Biodegradable Nanocomposites for Food Packaging Applications: Prospects and Challenges. Int. Nano Lett. 2026;16(1): 36-50. https://doi.org/10.57647/inl.2026.1601.04

1. Introduction

1.1 Importance of sustainable food packaging

Food packaging serves as a crucial element within the food supply chain and is increasingly vital in the final stages of food processing within the food industry [1]. The packaging sector significantly contributes to the global economy, with an estimated expenditure of around 55-65% of $130 billion on food and beverage packaging in the United States [2]. Approximately 30% of the total food production is predicted to be wasted due to spoilage during transportation and harvesting processes projections indicate that food waste could surpass 200 million tons by 2050, necessitating a 50% increase in food supplies worldwide [3]. The role of food packaging is essential in safeguarding food and food items from potential harm and deterioration, ensuring safety, maintaining hygiene, and actively reducing food wastage [1]. Indeed, Central to food packaging is its function in controlling gas and vapor exchange with the surrounding environment, preventing microbial and chemical contamination, thereby extending the shelf life of perishable foods like meats, fruits, and vegetables, and averting food safety concerns [4]. Consequently, the appropriate application of food packaging can aid in curbing and forestalling the generation of food waste [1]. Moreover, when designing packaging, convenience is a crucial aspect to consider, encompassing factors such as ease of opening, product dispensing, and resealing [5]. Packaging systems should be tailored to each food product, considering the food's specific qualities, factors contributing to quality deterioration (e.g., gas exchange, light exposure), distribution requirements, and marketing considerations, all while ensuring compliance with food-contact material regulations [4]. Primary packaging materials for food include paper, paperboard, plastic, glass, and metal, with combinations of these materials often used to enhance functionality [6]. Despite the successful performance of plastic packaging, their production from petroleum sources results in the release of greenhouse gases, primarily CO_2. Improper disposal of plastics leads to their accumulation in landfills, on land, and in water bodies, eventually contaminating oceans [7]. The degradation of marine and soil litter into micro- and nano-sized particles poses risks to various organisms, potentially entering the food chain and posing long-term adverse effects on human health. Without intervention, projections suggest that by 2050, the amount of plastic in the ocean may outweigh the total weight of fish if current production and consumption patterns persist in a linear fashion [3].

Food packaging serves as a prime illustration of the intricate aspects of sustainability. While some packaging innovations may align with sustainability from a certain standpoint, they may not be deemed sustainable from other perspectives. The sustainable development agenda gives rise to both synergies and trade-offs [8]. A comprehensive assessment of the sustainability of food packaging necessitates a broad outlook that encompasses various facets. This entails utilizing materials that produce no greenhouse gas emissions, exhibit potential for recycling or reusing, generate minimal landfill waste, reduce water consumption, are manufactured using renewable energy sources, do not emit air pollutants, do not pose risks to human health, among other factors [7]. In essence, contemporary food packaging must adhere to an additional criterion: environmental sustainability. Packaging significantly contributes to the sustainability of a food item and should be intricately designed in conjunction with the product to enhance overall environmental efficiency, while minimizing the likelihood of product spoilage, damage, and wastage [4].

A study carried out in Germany revealed that consumers place importance not only on the food's source and processing but also on the disposal of its packaging. A significant portion of respondents expressed willingness to pay a premium for environmentally friendly packaging [9].

Despite consumer concerns regarding environmental degradation, they believe that industries should spearhead initiatives for change by adopting and implementing sustainable practices. Notably, numerous companies, particularly those with substantial marketing influence like Walmart® and Amazon, are embracing more environmentally conscious approaches [5]. Consumers factor in various elements when making purchasing decisions related to packaging, including price, quality, safety, material composition, size, shape, convenience, functionality, protection, shelf life, environmental sustainability, biodegradability, reusability, and recyclability. This underscores the imperative need to gain a deeper understanding of consumers' obstacles to and perceptions of sustainable packaging, which can subsequently aid companies in crafting environmentally suitable food packaging for consumers [10].

1.2 A brief overview of biodegradable nanocomposites

Out of the four fundamental packaging materials, petroleum-based plastics have been extensively utilized since the mid-20th century. Their widespread use can be attributed to their affordability, ease of use, favorable processing characteristics, appealing aesthetic attributes, and excellent physicochemical properties. Over 40% of plastics are employed for packaging purposes, with nearly half of them dedicated to food packaging in the form of films, sheets, bottles, cups, tubs, and trays, among others. Ideally, packaging materials should biodegrade within a reasonable timeframe post-use without posing environmental challenges. Despite the prevalent use of synthetic plastic packaging materials across a variety of food products, they pose a significant environmental concern due to their resistance to degradation in the environment after disposal [11].

One of the most promising expectations within the realm of designing new materials for food packaging lies in the development of biodegradable systems with enhanced barrier characteristics. Some polymeric materials, depending on their chemical stability and additives, are deemed suitable for direct contact with food, as outlined in European Regulation (EC) No 1935/2004. Such applications require specific characteristics, including adequate mechanical strength, thermal resistance, transparency (when required), and compliance with food safety standards, particularly for fresh food packaging [12]. However, many conventional biodegradable polymers exhibit intrinsic limitations, such as relatively low mechanical strength, inferior gas and water vapor barrier properties, moisture sensitivity, and limited thermal stability, which restrict their broader application in demanding packaging conditions. In this context, nanocomposite technology has emerged as a promising strategy to enhance the functional performance of biodegradable polymers while preserving their environmental advantages [13]. Nanocomposite packaging materials exhibit significant potential as an advanced technology for food packaging, aiming to preserve food quality and prolong the shelf life of packaged products. Polymer nanocomposites primarily consist of a polymer matrix, nanofillers, plasticizers, and compatibilizers [14]. A variety of natural biopolymers like starch, cellulose, pectin, lignin, chitin/chitosan, alginates, hyaluronic acid, terpenes, gelatin, gluten, and polyhydroxyalkanoates (PHAs) from diverse sources, alongside synthetic biopolymers such as polycaprolactone (PCL), poly (butylene succinate), poly (lactic-co-glycolic acids), and polylactic acids (PLA), have been incorporated into nanocomposite materials for various applications [15].

Despite ongoing extensive research efforts in industry and academia, polymer nanotechnology within the realm of food packaging remains in the developmental stage. To advance polymer nanotechnology in food packaging, it is crucial to consider the entire life cycle of packaging (from raw material extraction and production to utilization and disposal), while integrating and balancing factors such as cost, performance, health, and environmental aspects. Multidisciplinary research efforts are pivotal in the field of polymer nanocomposite food packaging to address challenges related to safety, technology, regulations, standardization, skilled workforce, and technology transfer, ultimately leading to commercial success in the global market [14].

Although numerous review articles have addressed the material design and functional performance of biodegradable nanocomposites, relatively limited attention has been given to the integrated evaluation of scalability, commercialization constraints, nano-specific safety assessment, regulatory harmonization, and life-cycle-based sustainability verification. In particular, the transition from laboratory-scale optimization to industrial implementation remains underexplored in a holistic manner. This review aims to contribute to this perspective by connecting material innovation with safety, regulatory, environmental, and industrial feasibility considerations in food packaging applications.

2. Fundamentals of biodegradable nanocomposites

2.1 Definition and structural classification

The increasing demand from consumers for high-quality food and a growing awareness of healthy lifestyles are prompting researchers to seek ways to enhance food quality without compromising its nutritional value. Consequently, recent studies are concentrating on innovating methods, techniques, and protocols for processing, packaging, functionalization, quality control, and delivery systems for nutraceutical products [16]. Nanotechnology involves the manipulation of materials with at least one dimension at the nanometer scale (1-100 nm), enabling the creation of structures with unique properties attributed to their nanoscale dimensions. Nanocomposite food packaging, a rapidly expanding field within nanotechnology, offers a viable alternative to traditional packaging methods [17]. Nanocomposites are composite materials comprising blends of polymers and either organic or inorganic solids (fillers) like clays and oxides at the nanoscale level. The intricate structure of nanocomposites, where one phase (e.g., nanoparticles and nanotubes) possesses nanoscale morphology, imparts superior properties compared to microcomposites in an assembled configuration [18, 19]. The novel generation of composite materials demonstrates notable enhancements in modulus, dimensional stability, and resistance to solvents or gases compared to the original polymer. Nanocomposites also present additional advantages such as reduced density, transparency, enhanced flow, improved surface characteristics, and recyclability. It is important to note that these enhancements are achieved at very minimal filler concentrations (typically below 5%) [20]. Furthermore, these materials are cost-effective, easily processed, and contribute to prolonging the shelf life of food products [21]. Nanocomposites can be categorized into three groups based on the structure of the reinforcing nanoparticles: particulate/iso-dimensional (e.g., silica, metal NPs, metal oxides) exhibit three nanometric dimensions, elongated nanoparticles (e.g., cellulose nanofibrils, carbon nanotubes) which two dimensions are within the nanometer scale while the third dimension is larger s, and layered (e.g., monolayered clays, layered double hydroxides) that only one dimension falls within the nanometer range [15, 18].

2.2 Biopolymer matrices used in food packaging

Biopackaging is derived from biodegradable substances such as polysaccharides like chitosan, starch, and cellulose; proteins including gluten, gelatin, and zein; chemical polymers like polycaprolactones (PCLs), polyvinyl alcohol, copolymers (e.g., ethylene vinyl alcohol), and PLA; as well as polymers such as polyhydroxyalkanoates (PHAs) and polypeptides produced by natural or genetically modified microorganisms [22].

2.3 Functional nanofillers and active components

In order to maintain the freshness, safety, and quality of food items that are prone to spoilage and contamination by foodborne pathogens, antimicrobial packaging serves as a robust solution. By incorporating antimicrobial agents into materials that come in contact with food, the proliferation of microorganisms can be impeded, consequently extending the shelf life of food products [21]. Nanocomposite antimicrobial packaging systems prove to be effective due to the high surface area and energy of nanofillers, enabling strong interfacial interactions between polymer chains and nanofillers, thereby significantly enhancing the properties of bio/polymers such as mechanical strength, barrier properties, thermal resistance, and antimicrobial capabilities [23]. Additionally, biodegradable nanocomposites offer the advantage of biocompatibility, biodegradability, and functional attributes provided by biological or inorganic components. To develop eco-friendly materials, various biopolymers have been utilized in the production of biodegradable nanocomposites in recent times [24]. Particularly, metal and metal oxide nanoparticles (e.g., Ag, ZnO, Cu/CuO, TiO_2, and MgO NPs), mesoporous particles, graphene, and carbon dots have garnered significant attention in the food industry due to their inherent antibacterial properties. The integration of active antimicrobial nanoparticles into packaging materials results in lighter, stronger, and less oxygen-permeable packaging solutions [25].

Nanosized fillers encompass both organic and inorganic materials, including metal oxides (e.g., TiO_2, CuO, ZnO), metals (e.g., silver), natural antimicrobial agents (e.g., grape seed extract, nisin), natural biopolymers (e.g., chitosan), and clay (e.g., montmorillonite) [26].

The classification of nanocomposite materials into three distinct groups is based on the type of matrix materials used:

i Polymer matrix nanocomposites

ii Metal matrix nanocomposites

iii Ceramic matrix nanocomposites [21].

Additionally, nanocomposites can be further divided into non-polymer-based and polymer-based categories. Nonpolymer-based nanocomposites consist of Metal–Metal Nanocomposites, Metal–Ceramic Nanocomposites, and Ceramic–Ceramic Nanocomposites, while polymer-based nanocomposites involve materials with nanosized fillers such as carbon nanotubes, graphene, polystyrene, polypropylene, and cotton fabrics [27].

3. Processing and manufacturing techniques

3.1 Nanoparticle synthesis

Nanoparticle synthesis can be achieved through two main methods: the top-down method and the bottom-up method, as shown in Fig. 1. As illustrated in Fig. 1, top-down approaches involve the reduction of bulk materials into nanoscale structures through mechanical or physical forces, whereas bottom-up strategies assemble nanostructures from atomic or molecular precursors, typically enabling greater control over particle size and morphology.

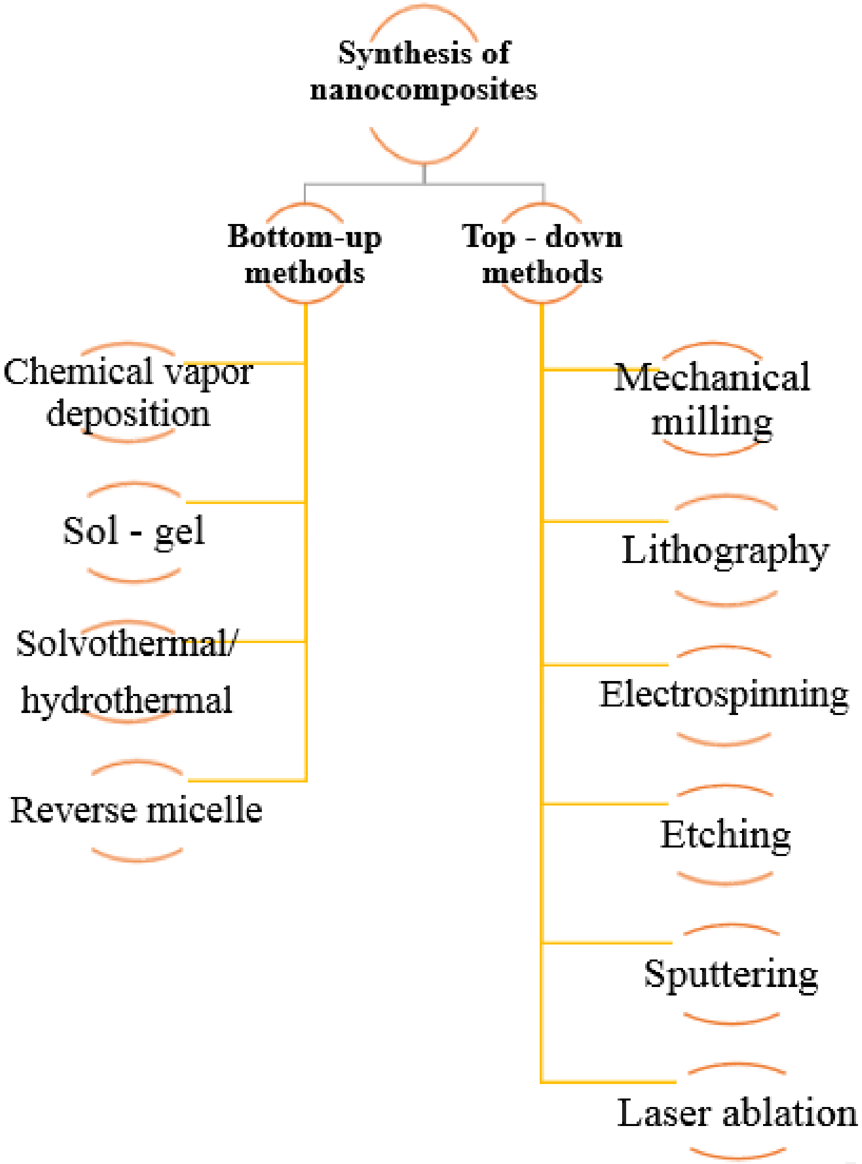

Figure 1. Classification of nanocomposite synthesis techniques into top-down and bottom-up approaches, highlighting representative fabrication routes commonly applied in material development.

https://doi.org/10.57647/inl.2026.1601.04

3.1.1 Top-down method:

In the top-down approach, larger compounds are reduced to nano-scaled materials using mechanical and chemical forces. Common top-down methods include mechanical milling, lithography, electrospinning, etching, sputtering, and laser ablation for nanoparticle synthesis [28].

3.1.1.1 Mechanical milling

Mechanical milling involves placing a suitable powder charge in a high-energy mill with a milling medium to reduce particle size and blend particles into new phases. It is an economical process for large-scale production of nano-sized grains and has been widely used for synthesizing noncrystalline metals, alloys, intermetallic compounds, ceramics, composites, and nanocomposites in various reactive atmospheres [29].

3.1.1.2 Lithography

Lithography is the process of printing a desired shape onto a light-sensitive material to selectively remove a portion of the sample and create the desired shape and configuration. Nanolithography offers advantages in creating custom-shaped nanoparticles, but it can be costly due to the complex equipment involved [30].

3.1.1.3 Electrospinning

Electrospinning is regarded as a straightforward, cost-effective, and highly promising method utilized for the fabrication of continuous nanoscale fibers derived from a variety of polymer materials with the assistance of a high-voltage electric field. Once the electrical force reaches a threshold to surpass the surface tension of the droplet located at the tip of the syringe, a charged polymer jet emerges from the Taylor cone and subsequently elongates, partly resembling an expanding helix. Ultimately, a fine fiber is obtained on the grounded collector through the stretching of a polymer solution droplet. The resultant fiber morphology is significantly impacted by a multitude of processing parameters including the characteristics of polymer solutions (such as polymer type, viscosity, concentration, conductivity, surface tension, and solvent polarity), the processing conditions (like flow rate, applied voltage, and distance to the collector), and the environmental factors (such as temperature and humidity [31].

3.1.1.4 Etching

Etching, a process commonly utilized in the microfabrication of metal, glass, and ceramic surfaces, serves as a key method for producing semiconductors, batteries, and electrical devices. Plasma etching and electrochemical etching are the primary techniques employed in food packaging systems. Plasma etching enables the creation of user-desired structures, while electrochemical etching facilitates rapid and sophisticated pattern formation on metal surfaces. Due to the rough nature of etched surfaces, they effectively inhibit bacterial adhesion. However, despite their applicability to diverse materials, these techniques are constrained by cost and efficiency considerations [32].

3.1.1.5 Sputtering

Sputtering is a widely adopted method for producing thin films of nanomaterials. One of its primary advantages is the ability to generate stoichiometric thin films, enhancing cost-effectiveness. By bombarding solid surfaces with high-energy particles, such as gas and plasma, thin films/nanoparticles are obtained. This phenomenon involves the deposition of nanoparticles through the bombardment of the target surface with highly energetic gaseous ions, leading to the physical ejection of small atomic clusters [33].

3.1.1.6 Laser ablation

Laser ablation is a conventional approach for creating nanoparticles from various solvents. Submerging a metal in a liquid solution and exposing it to laser light results in the condensation of a plasma plume, yielding diverse nanoparticles. This top-down method offers an alternative solution to traditional metallic chemical reduction for synthesizing nanoparticles, particularly in organic solvents and water, without the need for stabilizing agents or chemicals [30]. Laser ablation's benefits include its simplicity, lack of requirement for dispersion additives or reducible chemical compounds, and suitability for synthesizing polymer nanoparticle composites while avoiding the presence of reaction byproducts in the final nanocomposite [34].

3.1.2 Bottom-up method:

The bottom-up technique involves the creation of nanomaterials starting from atomic or molecular entities through diverse procedures. Various methodologies, such as chemical vapor deposition, sol-gel, solvothermal and hydrothermal methods, and reverse micelle methods are employed for the preparation of nanoparticles [28].

3.1.2.1 Chemical vapor deposition

Chemical vapor deposition is a commonly utilized technological process for materials fabrication wherein thin films are produced on a heated substrate via a chemical reaction involving gas-phase precursors. In comparison to physical vapor deposition techniques like evaporation and sputtering, chemical vapor deposition presents a distinct advantage by relying on chemical reactions that allow adjustable deposition rates and yield high-quality products with exceptional conformality [35].

3.1.2.2 Sol-gel

The sol-gel methodology stands as a traditional and industrial approach (known as the wet chemical method) for the production of diverse nanostructures, particularly metal oxide nanoparticles. The process involves dissolving the molecular precursor (often metal alkoxide) in water or alcohol, which is then transformed into a gel through hydrolysis/alcoholysis induced by heating and stirring. Due to the damp nature of the gel from the hydrolysis/alcoholysis process, appropriate drying techniques are necessary based on the desired properties and applications of the gel. The sol-gel technique is cost-efficient and offers precise control over the chemical composition of the resulting products owing to the low reaction temperature [36].

3.1.2.3 Solvothermal and hydrothermal method

Hydrothermal synthesis emerges as one of the widely employed strategies for nanomaterial synthesis, operating as a solution-based reaction approach. This method allows for the formation of nanomaterials over a broad temperature spectrum ranging from room temperature to elevated levels. To regulate the morphology of the targeted materials, either low-pressure or high-pressure conditions are applied depending on the vapor pressure of the primary composition in the reaction. Hydrothermal synthesis can yield nanomaterials that are unstable at increased temperatures [37].

3.1.2.4 Reverse micelle methods

Reverse micelles are composed of tiny water droplets surrounded by a dynamic yet well-defined layer of surfactant, and they are evenly dispersed in a nonpolar organic solvent. When considering an experimental approach, reverse micelles serve as a suitable and convenient molecular assembly on a nanoscale, with controllable experimental variables. The production of nanoparticles within reverse micelle microemulsions has been demonstrated to be a promising method due to the ability to regulate particle size, ensuring a narrow particle size distribution, along with a high level of uniformity in terms of concentration and morphology [38].

While numerous nanoparticle synthesis routes exist, not all techniques are equally suitable for food packaging applications. From an industrial perspective, scalability, cost-efficiency, reproducibility, and regulatory compatibility are critical selection criteria. Although both top-down and bottom-up methods provide precise structural control at the laboratory scale, their applicability in commercial food packaging depends largely on processing feasibility and integration into existing polymer manufacturing infrastructures.

3.2 Film fabrication and composite processing

Various techniques like casting, extrusion, melt-blending, polymerization, and vacuum drying are commonly utilized for the production of polymeric films with distinct physicochemical, mechanical, and biological properties. The selection of a specific technique is based on factors like food types, packaging size and type, and antibacterial agents [39].

Extrusion-based processing is among the most common techniques for biodegradable nanocomposites, as it enables continuous melt-processing and direct integration of nanoscale additives into thermoplastic matrices. Owing to its scalability, cost-efficiency, and compatibility with existing polymer manufacturing infrastructure, extrusion-along with injection molding—represents one of the most practical routes for large-scale food packaging production. However, its applicability remains largely limited to thermoplastic systems, and achieving uniform nanofiller dispersion during high-throughput processing continues to be a technical challenge [40].

However, from an industrial perspective, not all fabrication techniques demonstrate equal feasibility for large-scale food packaging production. Among these approaches, melt-blending and extrusion-based processes are generally considered more industrially relevant due to their compatibility with existing polymer processing infrastructure and continuous manufacturing lines [41]. In contrast, techniques such as vacuum-based or highly controlled laboratory-scale synthesis routes, while valuable for structural precision, may face economic and scalability constraints when translated to bulk packaging applications. Therefore, future developments should prioritize processing strategies that combine performance enhancement with scalability, reproducibility, and regulatory compatibility.

4. Structure-property relationships and characterization

Understanding the structure–property relationships in biodegradable nanocomposites requires comprehensive characterization across multiple length scales, as material structure directly governs mechanical, barrier, thermal, and functional performance [42].

In the context of food packaging, the selection of characterization methods is therefore guided not only by structural analysis requirements, but also by the need to correlate nanoscale features with application-specific performance indicators such as oxygen transmission rate, water vapor permeability, migration behavior, and durability under storage conditions.

The quantitative assessment of the dispersion and orientation of nanoparticles and the polymer matrix is crucial for establishing fundamental correlations between structure and properties. Various tools for structural characterization include force, optical, and electron microscopy; X-ray, neutron, and light scattering; chemical spectroscopic methods; electrical and dielectric characterization; and mechanical spectroscopy. Depending on the specifics of the nanoparticles and polymer matrix, each of these methods can provide distinct information about the dispersion state and the arrangement of polymers and nanoparticles across size scales from nanometers to millimeters; often, a combination of these techniques is employed to obtain detailed insights into the hierarchical morphology in nanocomposites [43].

An assortment of microscopic techniques, ranging from optical microscopy to electron microscopy and scanning probe microscopy, plays a crucial role in the analysis of the morphology of polymer nanocomposites at different length scales. These techniques are particularly vital in optimizing composite properties through structural characterization, offering direct insights not only into the filler's structure but also into filler-matrix adhesion, filler distribution, and the influence of the filler on the morphology and properties of the encompassing polymer matrix [44]. Optical microscopy has long been utilized in biopolymer research for sample analysis, owing to its straightforwardness and minimal sample preparation requirements. The utilization of optical microscopy aids in the observation of various characteristics such as dimensions, morphology, consistency, porosity, failure investigation, and quality assessment [42]. The conventional evaluation of polymer nanocomposites involves a combination of transmission electron microscopy (TEM) and wide-angle X-ray diffraction [45]. Transmission

https://doi.org/10.57647/inl.2026.1601.04

electron microscope TEM, being among the most advanced microscopes available presently, serves as an instrumental analytical device for the examination and visualization of samples at the nanoscale level. Despite operating on similar fundamental principles, TEM and light microscopes differ significantly in that TEM employs electrons instead of light [42]. Furthermore, atomic force microscopy is a scanning probe microscopy technique commonly employed for characterizing nanoscale features of surfaces, particularly in the assessment of nanocomposites. The process of topography imaging typically entails scanning the atomic force microscopy probe across the composite surface while monitoring the interaction response between the probe and the sample surface. Two distinct operational modes, namely contact and intermittent contact, can be employed, with measurements being conducted under various environments such as vacuum, vapor, or fluid [45].

Following material processing, physicochemical characterization is conducted to evaluate phase stability, interfacial interactions, and chemical modifications within the nanocomposite system. Common analytical techniques include X-ray diffraction, Fourier-transform infrared spectroscopy, Raman spectroscopy, and X-ray photoelectron spectroscopy, which provide insight into structural organization and material compatibility [46].

The mechanical characterization of nanocomposites encompasses a range of experimental and theoretical analyses, with commonly employed mechanical tests including tensile tests, compression tests, hardness tests, flexure tests, dynamic mechanical analysis, impact tests, shear tests, among others [47]. Thermal analysis comprises a well-established set of techniques aimed at acquiring qualitative and quantitative insights into the impact of thermal treatments on a wide array of materials, encompassing newly developed chemical compounds, polymers, ceramics, alloys, composites, nanocomposites, as well as food and pharmaceutical products. Thermal analysis techniques involve the measurement of a substance's physical properties as a function of temperature during controlled heating or cooling cycles and are extensively used for evaluating the thermal properties of materials [48]. The energy levels in nanomaterials are notably higher compared to bulk materials due to their increased surface area. Predictions regarding the melting temperature of nanomaterials are often based on size-dependent cohesive energy, with the melting temperature being directly proportional to the particle size [49]. Various theoretical and experimental investigations have been conducted to ascertain the thermal stability and response of nanocomposites, with common techniques encompassing thermo-mechanical analysis, thermo-gravimetric analysis, differential scanning calorimetry, dynamic mechanical thermal analysis, thermomechanical analysis, moisture absorption tests, and melt index rheology analysis [47].

Although electrical and dielectric characterization is more commonly associated with advanced smart or sensor-integrated packaging systems, understanding nanoparticle percolation networks and interfacial conductivity can support the development of intelligent or active food packaging applications. Due to the significant disparity in the electrical and dielectric characteristics of numerous nanoparticles and typical polymers, polymer nanocomposites have emerged as an appealing option for the advancement of lightweight materials with potential applications across various domains. Key considerations encompass the exploration of percolative structure nature, the emergence of hierarchical structures (e.g., fractals) and their influence on percolative performance, the alignment status of nanoparticles, their organized mesoscale structures, and their implications on electrical conductivity, as well as the interfacial resistance between the matrix and nanoparticles and among nanoparticles. These captivating principles necessitate substantial theoretical comprehension before becoming routinely implementable [43].

As a result of environmental deterioration, diverse reversible and irreversible repercussions can manifest in the tested materials, including diminished molecular weight (chain scissoring), compromised mechanical properties, embrittlement, cracks, fading of color, and the appearance of spots. It is important to highlight that the aging characteristics and mechanisms of unfilled polymers are often less intricate compared to those of filled composite materials. This discrepancy arises from the diverse constituents present in composites such as fillers, fibers, additives, plasticizers, and antioxidants, among others, each playing a role in the environmental deterioration of the composite entity as a whole [50].

5. Environmental impact assessment and regulations

With the expansion of nanotechnology commercialization, both the general public and governmental entities are increasingly concerned about the safety implications associated with the widespread utilization of nanocomposites in food packaging [51]. Various government bodies have issued directives concerning nanotechnology regulation. Recent directives and recommendations from regulatory bodies like the United States Food and Drug Administration (FDA) and the European Food Safety Authority deserve particular attention. In the United States, regulatory bodies, including the United States Environmental Protection Agency, FDA, and the Institute for Food and Agricultural Standards have implemented policies to address the potential hazards posed by nanomaterials and nanoproducts. The FDA conducted investigations to identify sources of nanomaterials while evaluating their environmental impact and effects on humans, plants, and animals, as well as exploring strategies for risk prevention or mitigation [52].

A notable issue of concern pertains to the environmental ramifications associated with the utilization of nanocomposites in food packaging applications. The environmental credentials of biodegradable nanocomposites are typically evaluated by scrutinizing their production processes, manufacturing of products, and eventual disposal. Various tools, such as environmental impact analysis, life cycle assessment, material flow analysis, and ecological footprint assessments, are employed to scrutinize the environmental consequences of different materials and manufacturing techniques [15]. The primary focus remains on packaging materials due to lingering uncertainties among the general public and policymakers regarding the safety of employing nanomaterials in direct contact with food. An in-depth exploration of risk assessment and safety concerns in this domain is crucial for gaining insights into the utilization of nanomaterials within this sector [53]. Life cycle assessment stands out as the most widely recognized approach for evaluating environmental impacts, offering a scientific method to compare the ecological consequences of product systems across various stages, including raw material extraction, manufacturing processes, product use, and disposal practices [15].

Yet another critical aspect to consider in the discourse surrounding the integration of nanofillers into biodegradable polymers is the preservation of their biodegradability, a highly valued trait in present times, along with the consequent implications on their environmental distribution [9]. The biodegradation of polymer materials has the potential to generate small molecules that may either temporarily or permanently accumulate in the environment. Oligomers, monomers, and metabolic byproducts formed during this process can interact with soil organisms, posing adverse effects on the surrounding ecosystem. Therefore, the environmental concerns regarding the persistence and ecotoxicity of these newly developed compounds become paramount in investigations related to the biodegradation process [50]. In order to enhance the flexibility, extensibility, and moisture resistance of packaging films, plasticizers are often incorporated into degradable polymers. However, the introduction of plasticizers may lead to certain drawbacks such as alterations in food aroma or increased permeability to oxygen in the films [25]. The significant benefit of utilizing biodegradable materials lies in their ability to undergo biodegradation swiftly after usage and disposal, with minimal or no ecotoxicity or adverse environmental effects. Nevertheless, the emergence of nanotechnology in this category of materials raises concerns regarding inadvertent environmental pollution due to the discharge of nanoscale compounds during the degradation process. Due to the incomplete comprehension of the distribution and destiny of NPs upon release into the environment, it is challenging to foresee whether these nano compounds will accumulate in the food chain or act as a source of environmental pollution. Consequently, conducting ecotoxicity assessments is imperative to ascertain the environmental risks posed by this technology to both the environment and future generations [9].

Three crucial considerations in assessing the sustainability and environmental aspects of packaging are as follows:

1- The selection of packaging materials should not necessitate transference from one location to another throughout the entire packaging duration to prevent indiscriminate disposal.

2- Efforts should be made to minimize the packaging of products as much as feasible to mitigate any detrimental impact on the ecosystem during the packaging production process.

3- The triple bottom line, encompassing impacts on the ecosystem, society, and business, should be taken into account, along with convenient packaging attributes such as efficiency, cleanliness, and recyclability [49].

The European Commission has issued a Union inventory of approved substances for manufacturing polymeric materials used in food contact, including nano-clay, titanium nitride, nano-silver, silanated silicon dioxide, titanium oxide, zinc oxide, and iron oxide NPs. Reports indicate that the migration of NPs from food packaging is expected to be minimal and gradual, with migration rates increasing as nanoparticle size and polymer viscosity decrease [54].

The United Nations Sustainable Development Goals (SDGs) provide a global framework for addressing environmental sustainability, responsible production, and waste reduction [55]. In this context, biodegradable nanocomposite packaging systems may support sustainability-oriented targets, particularly those related to responsible consumption and production. However, such contributions remain conditional upon verified life cycle performance, controlled nanoparticle release, and rigorous ecotoxicity evaluation to ensure that environmental benefits are not offset by unintended long-term impacts.

6. Prospects and challenges

6.1 Technical and processing barriers

Biodegradable nanocomposites incorporating nanoparticles such as montmorillonite, kaolinite, ZnO-NPs, TiO_2-NPs, Au-NPs, and Ag-NPs have demonstrated considerable improvements in mechanical strength, barrier properties, thermal stability, and reduced flammability while maintaining matrix transparency [56]. However, despite these promising advancements, several technical and processing-related challenges hinder their industrial-scale implementation. Several strategies have been considered to develop nanocomposites based on biodegradable polymers, which can generally be classified into solvent-based techniques and melt-mixing methods. Process technology plays a decisive role in determining the final nanostructure of the material, as it directly affects nanofiller dispersion, interfacial adhesion, and ultimately the functional performance of films or three-dimensional packaging structures [57].

Although solvent casting often enables relatively homogeneous nanoparticle distribution at laboratory scale, the high cost of solvents, the sensitivity of dispersion to solvent type and content, and the possibility of residual solvent acting as a plasticizer that alters polymer viscosity and mechanical properties represent significant drawbacks of this method [58]. In contrast, melt-mixing and extrusion techniques are more compatible with existing industrial infrastructure; however, achieving uniform nanofiller dispersion under melt-processing conditions remains a substantial challenge [41].

During scale-up of nanocomposite production, two critical challenges-dispersion and compatibility-become significantly more pronounced. At industrial scale, particularly under high-shear extrusion conditions, the inherent tendency of nanoparticles to agglomerate due to their high surface energy often results in non-uniform distribution within the polymer matrix, leading to void formation and stress concentration points [59]. Such structural heterogeneities may reduce barrier efficiency (e.g., oxygen transmission resistance) and compromise long-term mechanical stability [60]. Simultaneously, chemical incompatibility between nanofillers and polymeric resins can weaken interfacial adhesion, thereby impairing stress transfer efficiency. Excessive nanofiller loading further increases melt viscosity, hindering proper wetting and interfacial interaction. Therefore, successful scale-up requires precise control of processing parameters, optimization of filler loading, appropriate surface functionalization of nanomaterials, and careful selection of fabrication techniques to ensure uniform dispersion and strong interfacial bonding [59].

Furthermore, reproducibility at industrial scale remains a concern. Minor variations in shear rate, temperature gradients, or residence time during melt processing can significantly affect nanoparticle distribution and interfacial interactions [61]. Such variability may lead to batch-to-batch inconsistencies, which are unacceptable in food packaging applications requiring strict quality control standards. These technical barriers collectively explain why many biodegradable nanocomposites remain at laboratory scale despite promising functional properties.

6.2 Safety, migration and regulatory challenges

The migration of nanomaterials from food packaging into food products is an important safety concern. Nanoparticles may transfer into food through different mechanisms, including diffusion within the polymer matrix, dissolution, or surface abrasion of the packaging material. Since ingested nanoparticles may have potential adverse effects on the gastrointestinal tract and other organs, it is necessary to evaluate both the extent of their migration and their possible health impacts [62].

The migration of nanomaterials into food depends on several interacting factors. These factors include the properties of the nanoparticles themselves, such as their concentration, particle size, molecular weight, solubility, and their ability to move through the polymer matrix. Environmental conditions, including temperature and mechanical stress, can also influence the migration process. In addition, the characteristics of the food, such as its pH and composition, play an important role. Features of the packaging material, including polymer structure and viscosity, as well as the duration of contact between the food and the packaging, further affect the extent of migration.

Food storage and processing conditions may also impact nanoparticle release. For example, microwave heating has been reported to cause structural changes in packaging materials, which can increase the release of silver ions into food [17].

Regulations related to the use of nanomaterials in food packaging are not the same in Europe and the United States. In the European Union, any material that is intended to come into contact with food must be proven safe, and only substances that are included in authorized lists can be used within specific limits. In contrast, in the United States, a material is considered acceptable if it does not present a risk to consumer health under its intended conditions of use. In this approach, the estimated level of human exposure is an important factor in determining whether a substance is regarded as safe [63].

Regulation (EU) No. 10/2011 on plastic materials and articles is one of the main European regulations governing plastic food-contact materials. According to this regulation, the overall migration limit (OML) is 10 mg/dm^2, equivalent to 60 mg/kg of food [64]. For migration testing of plastic materials, six types of food simulants are defined in the regulation. These include 10% (v/v) ethanol, 3% (v/v) acetic acid, 20% (v/v) ethanol, 50% (v/v) ethanol, vegetable oil, and poly (2,6-diphenyl-p-phenylene oxide). These simulants are used to represent different types of food during laboratory testing [65].

In the United States, the use of nanomaterials in food packaging is regulated by FDA. Companies that intend to use these materials must obtain pre-market authorization before commercialization. This approval is typically obtained through either the Food Additive Petition process or the Food Contact Notification system [66].

The characterization of nanoparticles in composite materials is still a challenging task. Due to the complexity of these systems, accurately identifying and measuring nanoparticles is difficult. In addition, there are still limited methods available for reliable qualitative and quantitative analysis in such complex matrices.

Studies have shown that analytical methods are more effective when natural or engineered nanomaterials are present in simple matrices. However, in more complex samples, such as food products, analysis becomes more complicated and usually requires the use of multiple techniques. In these cases, a combination of methods is applied, including microscopy techniques such as atomic force microscopy, scanning electron microscopy, and TEM; chromatographic methods such as size exclusion chromatography; as well as spectroscopy, centrifugation, filtration, and related approaches [9].

Many studies have investigated the migration of nanomaterials from packaging materials into food products.

In particular, the migration of metal oxide nanoparticles such as TiO_2, ZnO, SiO_2, and aluminum oxide has been examined. Despite initial concerns about their potential release, the reported migration levels in most studies were found to comply with existing regulations and European directives. These findings indicate that, under normal conditions of use, such nanomaterials meet current regulatory standards for food packaging applications [62]. Although many studies have provided substantial short-term *in vitro* and *in vivo* data, information on the effects of long-term, low-dose oral exposure is still scarce. Overall, these findings emphasize the importance of conducting safety evaluations that take nanoparticle characteristics into account. Such assessments should include realistic migration data, improved gastrointestinal simulation models, and long-term dietary exposure studies to ensure the safe and responsible use of nano-enabled food packaging materials [67].

6.3 Economic and commercialization constraints

Despite the functional advantages of active and biodegradable nanocomposite packaging, their large-scale commercialization remains constrained by economic and regulatory barriers. Implementation costs, including the incorporation of nanofillers and the need to comply with complex legislative frameworks, represent significant challenges for large-scale industrial adoption [5].

Although biopolymer-based nanocomposites derived from natural sources demonstrate promising functional properties, their transition from conventional petroleum-based plastics requires overcoming several technical and practical obstacles [68]. These include the integration of antimicrobial agents into polymer matrices, compatibility between different components, and potential susceptibility to thermal and light-induced degradation [69]. Such factors may affect processing efficiency and long-term performance, thereby influencing production feasibility.

Furthermore, the advancement of active packaging systems depends on the establishment of clearly defined and standardized criteria for evaluating antimicrobial efficacy and safety [25]. Without harmonized assessment frameworks, regulatory approval processes may delay commercialization timelines. At the same time, increasing consumer demand for minimally processed and additive-free foods has encouraged innovation in antimicrobial packaging solutions [69]. Several companies have introduced bio-based packaging materials into the market. For example, Amcor PLC has developed cellulose-, starch-, and PLA-based biodegradable films for various food applications [55]. Nevertheless, broader implementation of nano-enabled systems will depend on achieving consistent regulatory approval, technological reliability, and market acceptance.

Biopolymer-based nanocomposite packaging materials derived from natural sources show great promise for a wide array of applications in the food industry, especially in the realm of advanced active food packaging with bio-functional attributes. Extensive research efforts are expected to focus on the development and utilization of biodegradable nanocomposite packaging with functional properties, aiming to supplant the use of conventional petrochemical-based packaging materials [68]. A key area of interest in active packaging pertains to enhancing the safety of antimicrobial nanofillers, given the limited exploration of the cytotoxic effects of these nanomaterials in packaging films. Current literature suggests that the toxicity of nanofillers is influenced by factors such as shape, size, surface-to-volume ratio, and doping, with toxicity levels varying based on concentration and duration of exposure. Furthermore, in order to create effective and long-lasting antibacterial packaging, it is essential to achieve a controlled release of antibacterial agents. Ongoing research is focusing on strategically incorporating nanofillers into packaging materials to facilitate gradual release and minimize excessive particle interaction with food products. The advancement of active packaging also hinges on the establishment of comprehensive, systematic, and clearly defined standards for assessing the antimicrobial efficacy and safety of nanofillers [25]. However, the transition from traditional non-compostable petroleum-based plastics to antimicrobial biodegradable packaging materials poses new challenges, including the integration of antimicrobials into the polymeric matrix, compatibility issues among different components, and increased susceptibility to degradation from heat and light. Certain antimicrobial agents experience significant loss rates due to inherent volatilization, as seen with essential oils, underscoring the need for further research to enhance the resilience and effectiveness of novel antimicrobial packaging materials [69]. Collaborative efforts among researchers, industry stakeholders, and governmental entities are crucial in addressing these challenges and expediting the progress of biodegradable film development for food packaging purposes [55]. The growing consumer demand for minimally processed and additive-free food products has also spurred the innovation of antimicrobial packaging solutions [69]. These next-generation packaging materials are envisioned to incorporate multiple beneficial functionalities, such as antimicrobial, antibiotic, biodegradable properties, and adaptive responses to environmental or chemical stimuli [56]. If successfully implemented at an industrial scale, such antimicrobial packaging may contribute to extended shelf life and improved product stability under controlled condition. Regulatory standards and consumer preferences are anticipated to steer the evolution of antimicrobial packaging towards novel, cost-effective, environmentally friendly materials that uphold food safety standards, preserve quality, and prolong shelf life with minimal additives [69]. Companies operating within the eco-friendly packaging sector are offering diverse packaging options tailored to various end-user industries, including custom-designed solutions to meet specific customer requirements. For instance, Amcor PLC (Zutphen, Netherlands) has successfully introduced cellulose-, starch-, and PLA-based biodegradable packaging films for a range of food products such as cheese, fresh meat, poultry, fruits, vegetables, and ready-to-eat meals. These packaging films exhibit excellent heat resistance and barrier properties against aroma, moisture, and oxygen, catering to the evolving needs of the food packaging industry [55].

6.4 Trade-off analysis across nanocomposite systems

Different classes of biodegradable nanocomposites offer distinct functional advantages, yet each system presents inherent limitations that influence its industrial applicability.

Nanoclays can improve the water barrier properties of bio-based films by creating a tortuous path within the polymer matrix. Among them, montmorillonite (MMT) is one of the most commonly used nanoclays due to its low cost and large surface area. MMT has been reported to enhance the mechanical strength and barrier performance of chitosan-based films.

However, while MMT enhances barrier performance, it generally does not improve the antimicrobial functionality. In addition, increasing nanoclay loading beyond an optimal concentration may lead to particle agglomeration within the polymer matrix, reducing dispersion efficiency and limiting further improvements in mechanical performance [73].

Therefore, clay-based systems offer a cost-effective solution for barrier enhancement, but may require additional functional additives when antimicrobial activity is desired. Nanocellulose is another type of nanomaterial widely used to reinforce bio-based films. It enhances their mechanical properties and reduces WVP and OP, which are among the main limitations of biopolymers in packaging applications. Nanocellulose is considered an environmentally friendly nanofiller due to its biodegradability, low density, non-toxicity, strong mechanical performance, and high aspect ratio, which provides a large interfacial area with the polymer matrix [73].

Although nanocellulose shows good mechanical strength and oxygen barrier performance under dry conditions, its resistance to moisture is relatively weak compared to petroleum-based plastics [74]. This humidity sensitivity may limit its effectiveness in high-moisture food packaging applications. Metal and metal oxide nanoparticles, such as Ag, ZnO, and TiO_2, are widely incorporated into biodegradable polymers to enhance mechanical strength and improve resistance to water vapor and oxygen transmission. In addition to reinforcing barrier performance, these nanoparticles can impart antimicrobial activity and light-blocking properties, making them attractive for active food packaging applications [62].

However, in some cases, especially for silver, the production method can influence the oxidation state of the nanoparticles. Silver nanoparticles are usually produced by reducing silver salts, which can result in different oxidation states, often similar to those of precursor compounds such as $AgNO_3$ or AgCl. Some studies have also reported the presence of silver oxides. Because noble metal nanoparticles are chemically stable, their interaction with the surrounding matrix may be relatively weak, making them more likely to migrate. Therefore, factors such as particle size and the use of barrier layers should be considered when designing food packaging materials to reduce migration [75]. Overall, while metal-based nanocomposites offer strong multifunctional performance at relatively low filler loadings, their industrial implementation requires a careful balance between antimicrobial efficiency, migration control, and regulatory compliance.

Overall, these comparisons demonstrate that no single nanocomposite system simultaneously maximizes barrier performance, antimicrobial efficiency, safety assurance, cost-effectiveness, and industrial scalability. Consequently, the selection of an appropriate nanofiller must be guided by application-specific requirements, regulatory considerations, and processing feasibility rather than laboratory-scale performance alone.

To further illustrate these trade-offs using quantitative food-packaging performance indicators, representative literature data are summarized in Table 1.

The comparative data presented in Table X demonstrate that biodegradable nanocomposites can achieve substantial improvements in oxygen barrier performance, with reductions reaching up to 60% depending on nanofiller type and loading level. However, the magnitude of improvement is strongly influenced by environmental conditions such as relative humidity, as observed in cellulose-based systems. While optimal nanofiller incorporation can simultaneously enhance mechanical strength and reduce permeability, excessive loading or high-moisture conditions may compromise performance. These results highlight that packaging performance must be evaluated quantitatively under application-relevant conditions rather than relying solely on laboratory-scale structural characterization.

Table 1. Comparative food-packaging performance indicators of selected biodegradable nanocomposite systems.

Matrix system	Nanofiller	OTR reduction	WVP change	References
CNF film[1]	Bentonite 15% (PNG)	62%↓	12%↓	[70]
Pullulan film	Starch 10% nanocrystals	Significant reduction	Significant reduction	[71]
PP coated system	Carrageenan + 1% Laponite/AgNPs	40%↓	Reduced	[72]

[1] Cellulose nanofibrils

https://doi.org/10.57647/inl.2026.1601.04

6.5 Strategic roadmap for future development

Research on biodegradable nanocomposites for food-related applications, including packaging and other food-contact surfaces, is expected to expand significantly in the coming years. However, future progress must extend beyond material innovation toward application-driven optimization. A comprehensive understanding of the physicochemical interactions between food products and packaging materials is essential for designing systems that not only exhibit antibacterial and antioxidant functionality but also maintain mechanical integrity and stable barrier performance under realistic storage conditions [76].

To strengthen sustainability goals, biopolymer production must adopt consistent, scalable manufacturing strategies that ensure reproducibility and cost-efficiency, thereby reducing long-term reliance on non-renewable resources. Moreover, materials developed at laboratory scale require systematic pilot-scale validation before implementation in industrial environments, in order to assess processing stability, performance consistency, and regulatory compliance.

At present, the relatively high production cost of biopolymer-based nanocomposites remains a major limitation for market competitiveness. Nevertheless, continued technological refinement, process optimization, and material standardization may gradually reduce costs and improve the feasibility of large-scale commercialization [77].

Future development should prioritize scalable material innovation and the formulation of nanocomposite systems that are compatible with existing extrusion, lamination, and film-processing technologies. Ensuring compatibility with current industrial infrastructure can significantly reduce additional capital investment and facilitate smoother commercial translation.

In parallel, the application of data-driven models (such as machine learning algorithms trained on food spoilage and storage datasets) can enable predictive shelf life estimation without relying solely on embedded sensing hardware. This approach may enhance packaging intelligence while maintaining affordability and design simplicity. Regulatory harmonization represents another essential component of future development. Establishing internationally aligned protocols for evaluating migration behavior, durability, and end-of-life impact would reduce uncertainty and accelerate commercialization. Streamlined evaluation frameworks for bio-based additives classified as generally recognized as safe, along with modular approval strategies for smart packaging components, may further support responsible innovation.

Finally, policy alignment and targeted investment strategies will play a pivotal role in enabling this transition. Incentive mechanisms promoting sustainable packaging, combined with support for small and medium-sized enterprises adopting green materials, can enhance competitiveness. Strategic investment in platform technologies (such as AI-assisted shelf life prediction systems) rather than isolated product solutions, may yield broader and more sustainable industry-wide impact [78]. Overall, translating biodegradable nanocomposites from laboratory innovation to industrial application requires coordinated advances in scalable processing, nano-specific safety assessment, and cost-effective production.

7. Conclusion

Biodegradable nanocomposites have advanced the field of sustainable food packaging by addressing the performance limitations of conventional bio-based polymers. The collective evidence indicates that nanoscale reinforcement can substantially improve barrier efficiency, mechanical integrity, and functional performance; however, these benefits introduce additional considerations related to safety evaluation, regulatory approval, processing scalability, and economic feasibility. The key challenge moving forward is not simply enhancing material properties, but achieving balanced optimization across performance, safety, environmental impact, and industrial viability. Current gaps persist in large-scale reproducibility, standardized nano-specific risk assessment, and long-term environmental verification. Future progress in this field will depend on integrated strategies that combine material innovation with scalable processing, harmonized safety protocols, and life-cycle-informed sustainability validation. Bridging these dimensions is essential for transitioning biodegradable nanocomposites from promising research concepts to commercially reliable and environmentally responsible packaging solutions.

Authors contributions
All authors contributed equally to the conception, design, execution, and writing of this work. All authors read and approved the final manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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