Design and Characterization of Biodegradable Nano Composite Packaging Films with Active and Intelligent Functions for Food Quality Monitoring and Waste Reduction

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Abstract

Food loss and waste pose significant global challenges with profound environmental, economic, and social consequences, driving the need for advanced food preservation and monitoring strategies. Packaging plays a critical role in mitigating food spoilage; however, conventional petroleum-based plastics raise serious environmental concerns due to their persistence and accumulation in ecosystems. In response, biodegradable packaging materials have emerged as sustainable alternatives, though their widespread adoption is hindered by inherent limitations in mechanical strength, barrier performance, and functional versatility. This review critically examines recent advances in biodegradable nanocomposite packaging films that integrate active and intelligent functions for food quality monitoring and waste reduction. Emphasis is placed on biodegradable polymer matrices, nanofillers, nanocomposite design strategies, active packaging mechanisms (antimicrobial and antioxidant), intelligent indicator systems (pH- and gas- responsive), fabrication methods, and performance evaluation. The review highlights how nanocomposite approaches can overcome material limitations while enabling multifunctionality. Key challenges related to stability, safety, scalability, regulatory acceptance, and lack of standardized performance metrics are discussed, along with emerging research gaps. Future perspectives focus on multilayer designs, safe-by-design nanomaterials, digital integration, and the need for quantitative waste-reduction assessment. Overall, biodegradable active and intelligent nanocomposite packaging systems represent a promising pathway toward sustainable food packaging, provided that interdisciplinary efforts bridge the gap between laboratory innovation and real-world implementation.

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1. Introduction

Food loss and waste represent one of the most critical global sustainability challenges, with approximately one-third of all food produced for human consumption lost or wasted annually (FAO, 2019; Gustavsson *et al*., 2011) [7]. This inefficiency not only undermines global food security but also contributes significantly to environmental degradation through unnecessary consumption of natural resources, increased greenhouse gas emissions, and excessive waste generation (FAO, 2019). A substantial proportion of food waste arises from spoilage during storage, transportation, and retail stages, driven primarily by microbial growth, oxidative reactions, and the lack of effective tools for monitoring food quality in real time (Robertson, 2016; Singh *et al*., 2018). Packaging therefore plays a central role in mitigating food losses by protecting products from external contamination and environmental stresses, extending shelf life, and providing information on product condition throughout the supply chain (Marsh & Bugusu, 2007) [12].

Conventional food packaging systems are predominantly based on petroleum-derived plastics such as polyethylene, polypropylene, and polyethylene terephthalate (Siracusa *et al*., 2008). These materials offer excellent mechanical strength, barrier properties, and processability, which have supported their widespread use in the food industry (Robertson, 2016). However, their resistance to degradation has led to severe environmental accumulation, long-term pollution, and growing ecological concerns (Geyer *et al*., 2017) [6]. Increasing regulatory pressure, heightened consumer awareness, and global sustainability initiatives have accelerated the search for environmentally friendly alternatives that can reduce reliance on fossil-based plastics (European Commission, 2018) [4]. Within this context, biodegradable and bio-based polymer materials have emerged as promising candidates for next-generation food packaging systems, offering the potential to reduce environmental impact while maintaining essential packaging functions (Siracusa *et al*., 2008).

Despite their environmental advantages, replacing conventional plastics with biodegradable polymers presents several technical challenges. Many biopolymers exhibit relatively poor mechanical strength, high sensitivity to moisture, and inferior gas barrier properties, which limit their direct application in demanding food packaging scenarios (Rhim *et al*., 2013; Sorrentino *et al*., 2007) [14,]. In addition, traditional packaging systems—whether based on conventional plastics or biodegradable materials—are largely passive in nature and do not adequately address the dynamic and complex processes involved in food spoilage (Duncan, 2011) [3]. Food deterioration is influenced by multiple factors, including storage temperature, microbial activity, oxygen availability, and product-specific biochemical reactions (Singh *et al*., 2018). As a result, there has been growing interest in packaging technologies that go beyond passive containment and are capable of interacting with food and its surrounding environment to actively preserve quality and provide information on freshness (Yam *et al*., 2005) [19].

Active packaging systems are designed to deliberately incorporate functional components that can extend shelf life or enhance food safety by releasing or absorbing specific substances within the package (Yam *et al*., 2005; Realini & Marcos, 2014) [13,19]. Typical examples include antimicrobial agents that inhibit the growth of spoilage and pathogenic microorganisms, antioxidants that delay lipid oxidation, and moisture or oxygen scavengers that help maintain a favorable internal package environment (Duncan, 2011) [3]. In parallel, intelligent packaging systems aim to monitor the condition of packaged foods and communicate information about freshness, spoilage, or storage history through indicators or sensors (Kerry *et al*., 2006) [9]. When combined, active and intelligent functions offer a powerful strategy for reducing food waste and improving consumer confidence by linking preservation performance with real-time quality monitoring (Realini & Marcos, 2014) [13]. In recent years, biodegradable nanocomposite packaging films have attracted substantial attention as versatile platforms capable of integrating both active and intelligent functionalities (Rhim *et al*., 2013; Sorrentino *et al*., 2007) [13]. By incorporating nanoscale fillers into biodegradable polymer matrices, nanocomposite systems can achieve significant improvements in mechanical strength, thermal stability, and gas and moisture barrier properties (Azeredo *et al*., 2017) [1]. At the same time, these nanostructured materials can act as carriers for active agents or sensing components, enabling multifunctional packaging designs (Duncan, 2011) [3]. As such, nanocomposites provide a promising pathway to overcome the intrinsic material limitations of many biopolymers while expanding their functional capabilities (Rhim *et al*., 2013) [13].

Biodegradable polymers used in food packaging are commonly derived from renewable resources and can be broadly classified into polysaccharide-based, protein-based, and aliphatic polyester- based materials (Siracusa *et al*., 2008). Polysaccharides such as starch, chitosan, cellulose derivatives, and alginate are widely studied due to their biodegradability, abundance, and film- forming ability (Bourtoom, 2008) [2]. Among these, chitosan has received particular attention because of its intrinsic antimicrobial activity, biocompatibility, and ability to form transparent films (Zhang *et al*., 2014) [20]. However, chitosan-based films often exhibit high water vapor permeability and limited mechanical flexibility, which necessitate modification, blending, or reinforcement strategies (Rhim *et al*., 2013) [14]. Starch-based films are attractive due to their low cost and widespread availability but are inherently brittle and highly sensitive to moisture (Jiang *et al*., 2020) [8]. Cellulose derivatives, including carboxymethyl cellulose and hydroxypropyl methylcellulose, offer improved mechanical properties but still require reinforcement for use in high-performance packaging applications (Rhim *et al*., 2013) [14]. Protein-based films, such as those derived from gelatin, whey protein, or soy protein, typically provide good oxygen barrier properties but suffer from poor water resistance and long-term stability (Bourtoom, 2008) [2].

Among biodegradable polyesters, polylactic acid (PLA) stands out as one of the most commercially successful bioplastics. PLA exhibits good transparency, mechanical strength, and compatibility with conventional processing techniques such as extrusion and thermoforming (Siracusa *et al*., 2008). Nevertheless, its brittleness, relatively low gas barrier performance compared to petroleum-based plastics, and lack of inherent antimicrobial or antioxidant activity limit its standalone use in food packaging (Sorrentino *et al*., 2007). Consequently, blending PLA with other biopolymers or reinforcing it with nanofillers has become a widely adopted strategy to tailor its properties for specific packaging applications (Rhim *et al*., 2013) [14].

Nanocomposites are formed by dispersing nanoscale fillers, typically with at least one dimension below 100 nm, within a polymer matrix (Sorrentino *et al*., 2007). In biodegradable packaging films, nanofillers play multiple roles, including mechanical reinforcement, enhancement of gas and moisture barrier properties, modulation of optical characteristics, and facilitation of functional activity (Duncan, 2011) [3]. Among the various nanofillers investigated, cellulose nanocrystals and cellulose nanofibers have emerged as particularly attractive due to their renewable origin, high aspect ratio, low density, and excellent mechanical performance (Azeredo *et al.*, 2017; Xu *et al.*, 2024) [18]. The incorporation of nanocellulose into biopolymer matrices can significantly improve tensile strength and reduce gas permeability by creating tortuous diffusion pathways (Xu *et al.*, 2024) [18]. Furthermore, the surface chemistry of nanocellulose enables functionalization and strong interfacial interactions with polymer matrices (Azeredo *et al.*, 2017) [1]. Layered silicate clays, such as montmorillonite, have also been extensively used to enhance barrier properties by increasing the effective diffusion path length for gases and vapors (Sorrentino *et al.*, 2007). In contrast, metal and me3tal-oxide nanoparticles, including silver, zinc oxide, and titanium dioxide, are primarily incorporated for their antimicrobial activity (Llorens *et al.*, 2012) [11]. While these inorganic nanoparticles can be highly effective, concerns related to nanoparticle migration, potential toxicity, and regulatory acceptance have stimulated increasing interest in safer, bio-based nanofillers and strategies to immobilize active components within the polymer matrix (Duncan, 2011) [3]. Overall, the integration of nanofillers into biodegradable polymers not only improves structural performance but also enables multifunctional platforms capable of hosting active agents and sensing elements (Rhim *et al.*, 2013) [14].

Active biodegradable packaging systems aim to interact with packaged food or its environment in a controlled manner to extend shelf life and maintain quality (Yam *et al.*, 2005) [19]. Antimicrobial packaging is a major focus in this area, targeting the inhibition of spoilage and pathogenic microorganisms on food surfaces (Realini & Marcos, 2014) [13]. Chitosan-based films naturally exhibit antimicrobial properties due to their polycationic structure, which can disrupt microbial cell membranes (Zhang *et al.*, 2014) [20]. This activity can be further enhanced by incorporating natural antimicrobial agents such as essential oils, plant extracts rich in polyphenols, or antimicrobial nanoparticles (Duncan, 2011) [3]. Essential oils are particularly attractive because of their natural origin and broad-spectrum activity; however, their volatility, strong aroma, and rapid release often require encapsulation or controlled-release strategies to ensure sustained effectiveness and minimize sensory impacts (Realini & Marcos, 2014) [13].

Antioxidant-active packaging systems are designed to slow oxidative degradation, which is particularly relevant for lipid-rich foods (Kerry *et al.*, 2006) [9]. Natural antioxidants, including tocopherols, flavonoids, and phenolic compounds, are commonly incorporated into biodegradable films to scavenge free radicals and delay oxidation (Duncan, 2011) [3]. The nanocomposite structure of these films can modulate the release kinetics of antioxidants, enabling prolonged protective effects during storage (Rhim *et al.*, 2013) [14]. Nevertheless, the overall performance of active biodegradable packaging systems depends strongly on controlled release behavior, compatibility between active agents and polymer matrices, and the preservation of mechanical and barrier properties, highlighting the importance of systematic material design and characterization (Realini & Marcos, 2014) [13].

In contrast to active packaging, intelligent packaging systems are intended to provide information about the condition of packaged foods rather than directly influencing preservation (Kerry *et al.*, 2006) [9]. Intelligent systems typically incorporate indicators or sensors that respond to changes in the internal package environment, such as temperature fluctuations, pH variation, gas composition, or the presence of microbial metabolites (Yam *et al.*, 2005) [19]. Among these, colorimetric indicators have been most widely studied due to their simplicity, low cost, and ease of visual interpretation (Kerry *et al.*, 2006) [9]. pH-sensitive indicators based on natural dyes, particularly anthocyanins extracted from fruits and vegetables, have attracted considerable interest (Kuswandi *et al.*, 2011) [10]. Anthocyanins exhibit distinct color changes across a wide pH range and can respond to volatile basic nitrogen compounds produced during the spoilage of protein-rich foods (Kuswandi *et al.*, 2011) [10]. Their natural origin and consumer-friendly appearance make them particularly suitable for food packaging applications (Realini & Marcos, 2014) [13].

In addition to pH-sensitive systems, gas indicators targeting ammonia, carbon dioxide, hydrogen sulfide, or oxygen have been developed to monitor spoilage progression or package integrity (Yam *et al.*, 2005) [19]. These indicators are often incorporated as discrete patches or printed elements within packaging systems (Kerry *et al.*, 2006) [9]. More recently, digital approaches that combine colorimetric indicators with smartphone-based image analysis have enabled semi-quantitative assessment of food freshness, offering opportunities for enhanced traceability and consumer engagement (Kuswandi *et al.*, 2011) [10]. Despite these advances, challenges remain in improving indicator stability under exposure to light and temperature, enhancing selectivity toward specific spoilage compounds, and establishing standardized calibration protocols that reliably link indicator responses to microbiological and chemical spoilage parameters (Realini & Marcos, 2014) [13].

The integration of active and intelligent functions within biodegradable nanocomposite packaging films represents a promising strategy for addressing food waste in a holistic manner (Rhim *et al.*, 2013) [14]. Active components can slow spoilage processes, while intelligent indicators provide timely and accessible information on food quality, enabling better decision-making by producers, retailers, and consumers (Kerry *et al.*, 2006) [9]. This combination not only extends shelf life but also reduces the premature disposal of safe, consumable food driven by uncertainty regarding freshness (Realini & Marcos, 2014) [13]. However, achieving seamless integration of these functions within a single biodegradable system poses significant challenges related to material compatibility, processing conditions, safety, regulatory compliance, scalability, cost-effectiveness, and end-of-life performance (Duncan, 2011) [3].

Given the rapid growth and interdisciplinary nature of research in biodegradable active and intelligent packaging, a comprehensive and critical review is necessary to consolidate current knowledge, identify key challenges, and outline future research directions (Rhim *et al*., 2013) [14]. This review focuses on biodegradable nanocomposite packaging films that combine active and intelligent functionalities for food quality monitoring and waste reduction. It critically examines biodegradable polymer matrices, nanofillers, active agents, intelligent indicator systems, fabrication strategies, characterization approaches, and safety and sustainability considerations, with particular emphasis on recent advances and remaining research gaps.

2. Materials and Nanocomposite Design

The performance and multifunctionality of biodegradable active and intelligent packaging systems are fundamentally governed by the selection of polymer matrices and the design of nanocomposite architectures. Biodegradable polymers used in food packaging are largely derived from renewable resources and are capable of undergoing biological degradation into environmentally benign products. While these materials offer significant environmental advantages over conventional petroleum-based plastics, their intrinsic physicochemical properties often fail to meet the stringent mechanical, thermal, and barrier requirements demanded by modern food packaging applications (Siracusa *et al*., 2008; Rhim *et al*., 2013) [14]. As a result, rational material selection and nanocomposite design strategies are essential to develop biodegradable packaging films that combine sustainability with functional performance.

Biodegradable polymers employed in food packaging can be broadly categorized into polysaccharide-based, protein-based, and aliphatic polyester-based materials (Siracusa *et al*., 2008). Polysaccharides such as starch, chitosan, cellulose derivatives, and alginate have attracted extensive attention due to their abundance, renewability, biodegradability, and film-forming capability (Bourtoom, 2008) [2]. Starch-based films are among the most widely investigated because of their low cost and wide availability; however, their high hydrophilicity leads to brittleness and strong sensitivity to moisture, which significantly limits their barrier and mechanical performance (Jiang *et al*., 2020) [8]. Consequently, plasticization, chemical modification, and blending strategies are frequently employed to improve their flexibility and durability. Cellulose derivatives, including carboxymethyl cellulose and hydroxypropyl methylcellulose, exhibit improved film-forming behavior and optical transparency but still display limited moisture resistance under high-humidity conditions (Rhim *et al*., 2013) [14]. Chitosan has emerged as a particularly promising polysaccharide for food packaging applications due to its intrinsic antimicrobial activity, biocompatibility, and ability to form transparent films (Zhang *et al*., 2014) [20]. The antimicrobial properties of chitosan originate from its polycationic structure, which interacts with negatively charged microbial cell membranes, leading to cell disruption. Despite these advantages, chitosan-based films typically exhibit high water vapor permeability and relatively poor mechanical strength, necessitating blending or reinforcement to enhance their performance (Zhang *et al*., 2014) [20].

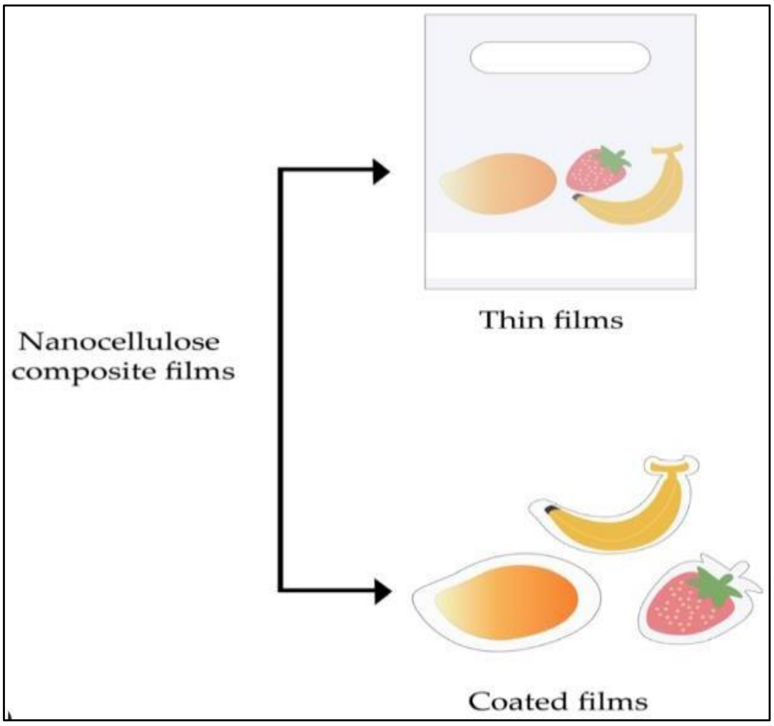

Fig 1: Usage of nanocellulose composite films in food packaging *Adapted from Xu et al.* (2024) [18].

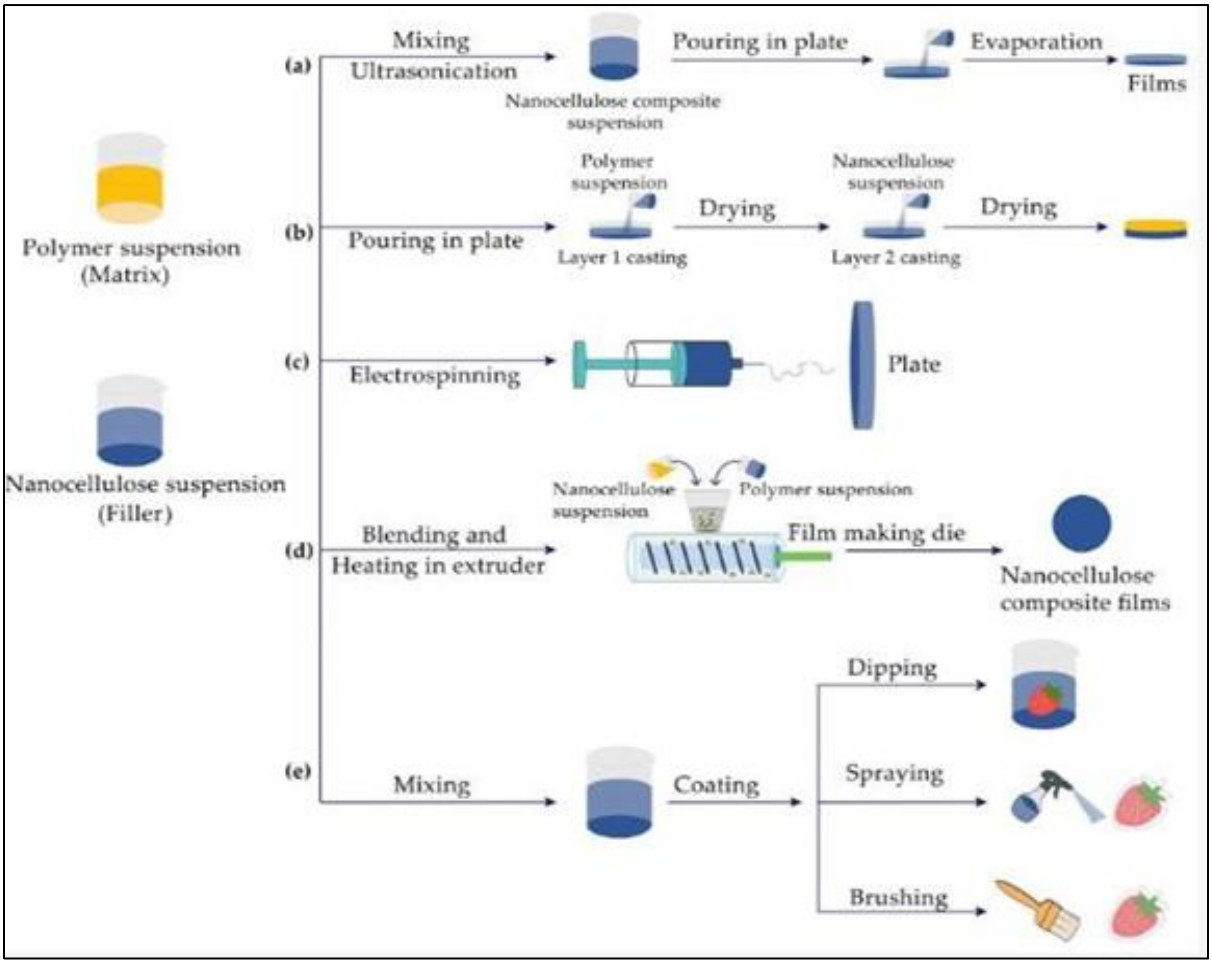

Fig 2: Preparation methods of nanocellulose composite films: (a) solvent casting method, (b) layer-by-layer assembly, (c) electrospinning, (d) melt process, (e) coating Representative morphology and schematic illustration of nanocellulose-reinforced biodegradable composite films and their gas barrier enhancement mechanism. *Adapted from Xu et al.* (2024) [18].

Protein-based biodegradable films derived from gelatin, whey protein, soy protein, and zein have also been explored for food packaging applications. These materials generally exhibit excellent oxygen barrier properties due to their dense polymer networks, making them suitable for protecting oxidation-sensitive foods (Bourtoom, 2008) [2]. However, protein-based films are often characterized by high moisture sensitivity, limited mechanical stability, and potential allergenicity, which restrict their industrial applicability. Crosslinking, blending with polysaccharides, and nanocomposite reinforcement are therefore commonly employed to improve their functional properties (Rhim *et al*., 2013) [14].

Among aliphatic polyesters, polylactic acid (PLA) is currently the most commercially successful biodegradable polymer used in food packaging. PLA exhibits good transparency, mechanical strength, and compatibility with conventional processing techniques such as extrusion and thermoforming (Siracusa *et al*., 2008). Nevertheless, PLA is inherently brittle, exhibits relatively poor gas barrier properties compared to petroleum-based plastics, and lacks intrinsic antimicrobial or antioxidant functionality (Sorrentino *et al*., 2007). These limitations have driven extensive research into PLA-based blends and nanocomposites to tailor its properties for advanced food packaging applications. Other biodegradable polyesters, including polyhydroxyalkanoates (PHAs) and polybutylene succinate (PBS), have also attracted interest due to their favorable biodegradation profiles and mechanical performance, although their higher production costs and limited commercial availability remain challenges (Rhim *et al*., 2013) [14].

To overcome the intrinsic limitations of biodegradable polymers, nanocomposite design has emerged as an effective strategy. Nanocomposites are formed by incorporating nanoscale fillers, typically with at least one dimension below 100 nm, into a polymer matrix. Due to their high surface area and strong interfacial interactions, nanofillers can significantly enhance mechanical strength, thermal stability, and gas and moisture barrier properties even at low loading levels (Sorrentino *et al*., 2007; Duncan, 2011) [3]. In food packaging applications, nanocomposites also provide multifunctional platforms capable of hosting active agents and intelligent sensing components, enabling advanced packaging systems with preservation and monitoring capabilities.

Among the various nanofillers investigated, nanocellulose—including cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs)—has emerged as one of the most promising candidates for biodegradable food packaging applications. Nanocellulose is derived from natural cellulose sources and exhibits exceptional mechanical properties, low density, high aspect ratio, and renewability (Azeredo *et al*., 2017) [1]. When incorporated into biodegradable polymer matrices, nanocellulose significantly improves tensile strength and elastic modulus while reducing gas permeability through the formation of tortuous diffusion pathways that hinder molecular transport (Azeredo *et al*., 2017) [1]. Furthermore, the abundance of hydroxyl groups on nanocellulose surfaces promotes strong hydrogen bonding with polymer chains and enables chemical functionalization, making nanocellulose an attractive carrier for active agents and intelligent indicator compounds.

Layered silicate clays, such as montmorillonite, have also been widely used as nanofillers in biodegradable packaging films. These plate-like nanomaterials enhance barrier performance by increasing the effective diffusion path length for gases and vapors within the polymer matrix (Sorrentino *et al*., 2007). The degree of barrier improvement is strongly dependent on the dispersion state of the clay layers, with exfoliated nanocomposites generally providing superior performance compared to intercalated or aggregated structures (Rhim *et al*., 2013) [14]. However, excessive clay loading or poor dispersion can adversely affect film transparency and processability, which are critical considerations for consumer-facing food packaging. Metal and metal-oxide nanoparticles, including silver, zinc oxide, and titanium dioxide, have been incorporated into biodegradable nanocomposite films primarily for their antimicrobial activity. These nanoparticles can inhibit microbial growth through mechanisms such as reactive oxygen species generation, membrane disruption, and metal ion release (Duncan, 2011; Llorens *et al*., 2012) [3,11]. Despite their effectiveness, the use of inorganic nanoparticles raises concerns related to migration into food matrices, potential toxicity, and regulatory acceptance. As a result, recent research increasingly emphasizes immobilization strategies, reduced nanoparticle loadings, and the development of safer bio-based alternatives to minimize potential risks (Llorens *et al*., 2012) [11].

Nanocomposite design in biodegradable packaging extends beyond mechanical reinforcement and barrier enhancement, playing a crucial role in enabling active and intelligent functionalities. Nanofillers can act as carriers for antimicrobial and antioxidant agents, modulate release kinetics, and stabilize sensitive indicator compounds. For instance, encapsulation of essential oils or natural dyes within nanostructured domains can protect them from premature degradation and allow controlled release in response to environmental stimuli (Rhim *et al*., 2013) [14]. Similarly, nanocomposite architectures can be engineered to spatially separate active and intelligent components, minimizing undesirable interactions while maintaining overall film integrity.

The dispersion and interfacial compatibility of nanofillers within biodegradable polymer matrices are key determinants of nanocomposite performance. Poor dispersion or weak interfacial bonding can result in filler aggregation, reduced mechanical performance, and compromised barrier properties (Sorrentino *et al*., 2007). Surface modification of nanofillers, polymer blending, and optimization of processing conditions are therefore commonly employed to achieve uniform dispersion and strong interfacial interactions. Fabrication techniques such as solution casting, melt compounding, and in situ polymerization have been widely used to produce biodegradable nanocomposite films, each offering distinct advantages and limitations in terms of scalability, energy consumption, and compatibility with functional additives (Rhim *et al*., 2013) [14]. From a sustainability and safety perspective, nanocomposite design must also consider end-of-life behavior, food-contact safety, and regulatory compliance. The incorporation of nanomaterials into biodegradable polymers should not compromise compostability or biodegradation performance. In addition, migration of nanofillers and associated active agents into food matrices must be carefully evaluated to ensure consumer safety and regulatory acceptance (Duncan, 2011) [3]. These considerations highlight the importance of selecting nanofillers that are not only functionally effective but also environmentally benign and suitable for food packaging applications.

The rational selection of biodegradable polymers and the thoughtful design of nanocomposite structures form the foundation for advanced active and intelligent packaging systems. By combining renewable polymer matrices with functional nanofillers, biodegradable nanocomposites offer a versatile and scalable platform capable of meeting the mechanical, barrier, and multifunctional requirements of modern food packaging while contributing to sustainability and food waste reduction goals.

3. Active and Intelligent Packaging Functions

Active and intelligent packaging technologies represent a paradigm shift from conventional passive food packaging toward systems that can interact with food and its surrounding environment to enhance safety, extend shelf life, and provide real-time information on product quality. In the context of biodegradable nanocomposite packaging films, the integration of active and intelligent functions offers a particularly attractive approach for addressing food spoilage and waste while maintaining environmental sustainability. Active packaging focuses on preserving food quality through controlled interactions, whereas intelligent packaging aims to monitor and communicate changes in food condition. When combined within a single biodegradable system, these functions provide complementary benefits that align with modern demands for safer, smarter, and more sustainable food packaging solutions (Yam *et al*., 2005; Realini & Marcos, 2014) [13,19]. Active packaging systems are designed to deliberately incorporate components that release or absorb substances in order to maintain or improve food quality and safety. The most widely studied active functions in biodegradable packaging films include antimicrobial activity, antioxidant activity, and barrier modification (Duncan, 2011) [3]. These functions are particularly relevant for perishable foods, where microbial growth and oxidative degradation are the primary mechanisms of spoilage. Biodegradable polymer matrices reinforced with nanofillers provide an effective platform for hosting active agents while simultaneously improving the structural and barrier properties of the packaging material (Rhim *et al*., 2013) [14].

Antimicrobial active packaging has attracted extensive research attention due to its direct impact on food safety and shelf-life extension. Antimicrobial agents incorporated into packaging films can inhibit or delay the growth of spoilage microorganisms and foodborne pathogens on food surfaces. In biodegradable systems, antimicrobial activity can originate from the polymer matrix itself, incorporated natural compounds, or inorganic antimicrobial agents. Chitosan-based films are a prominent example, as chitosan exhibits intrinsic antimicrobial activity arising from its polycationic nature, which disrupts microbial cell membranes and interferes with cellular metabolism (Zhang *et al*., 2014) [20]. However, the antimicrobial efficacy of chitosan alone is often insufficient for high-risk foods, prompting the incorporation of additional antimicrobial agents.

Natural antimicrobial compounds, particularly essential oils and plant-derived extracts, are among the most commonly used active agents in biodegradable packaging films. Essential oils such as thyme, oregano, clove, and cinnamon oils exhibit broad-spectrum antimicrobial activity against bacteria, yeasts, and molds due to their phenolic constituents (Singh *et al*., 2018). Their natural origin and consumer acceptance make them attractive alternatives to synthetic preservatives. Nevertheless, essential oils are highly volatile, sensitive to heat and light, and may impart strong aromas that affect food sensory quality. To address these limitations, encapsulation strategies using nanocomposite structures have been widely explored. Nanofillers can act as carriers or reservoirs for essential oils, enabling controlled release and prolonged antimicrobial effectiveness while minimizing sensory impact (Rhim *et al*., 2013; Realini & Marcos, 2014) [13,14].

Inorganic antimicrobial agents, including metal and metal-oxide nanoparticles such as silver, zinc oxide, and titanium dioxide, have also been incorporated into biodegradable nanocomposite films. These nanoparticles exhibit antimicrobial activity through mechanisms such as reactive oxygen species generation, metal ion release, and direct interaction with microbial cell membranes (Duncan, 2011; Llorens *et al*., 2012) [3,11]. While highly effective, concerns regarding nanoparticle migration into food, potential toxicity, and regulatory acceptance have limited their widespread application. Consequently, recent research emphasizes low nanoparticle loadings, immobilization within the polymer matrix, and the use of bio-based nanofillers to reduce safety risks while maintaining antimicrobial performance (Llorens *et al*., 2012) [11]. Antioxidant active packaging represents another important strategy for extending the shelf life of foods, particularly those rich in lipids. Oxidative reactions lead to rancidity, off-flavors, nutrient loss, and color changes, significantly reducing food quality. Antioxidant-active biodegradable films incorporate compounds capable of scavenging free radicals or chelating pro-oxidant metals. Natural antioxidants, including tocopherols, flavonoids, and phenolic compounds extracted from plant sources, are commonly used due to their effectiveness and consumer-friendly perception (Kerry *et al*., 2006) [9]. Similar to antimicrobial agents, the effectiveness of antioxidants depends on controlled release behavior, which can be modulated through nanocomposite design. The incorporation of nanofillers can slow the diffusion of antioxidants, enabling sustained protection throughout storage (Rhim *et al*., 2013) [14].

Beyond antimicrobial and antioxidant functions, active packaging systems may also include moisture absorbers, oxygen scavengers, and ethylene absorbers to regulate the internal package environment. Although these functions are more commonly implemented in conventional packaging formats, recent studies have demonstrated their feasibility in biodegradable systems through the incorporation of functional fillers and reactive compounds (Yam *et al*., 2005) [19]. The challenge lies in integrating these functions without compromising biodegradability, mechanical performance, or food-contact safety. In contrast to active packaging, intelligent packaging systems are designed to monitor the condition of packaged foods and provide information about quality, freshness, or safety without directly altering the food itself. Intelligent systems typically incorporate indicators or sensors that respond to changes in environmental conditions or the accumulation of spoilage-related metabolites. Among the various intelligent packaging approaches, colorimetric indicators have gained the most attention due to their simplicity, low cost, and ease of interpretation by consumers and stakeholders throughout the supply chain (Kerry *et al*., 2006).

pH-sensitive indicators based on natural dyes are among the most widely studied intelligent packaging systems for biodegradable films. Anthocyanins, extracted from fruits and vegetables such as red cabbage, berries, and purple sweet potato, exhibit distinct and reversible color changes across a wide pH range. These color changes are particularly useful for monitoring the spoilage of protein-rich foods, where microbial activity leads to the production of volatile basic nitrogen compounds that increase pH (Kuswandi *et al*., 2011) [10]. The natural origin, visual readability, and compatibility with biodegradable polymers make anthocyanins attractive candidates for intelligent packaging applications. However, anthocyanins are sensitive to light, temperature, and oxygen, which can result in color fading and reduced reliability over time. To improve stability, nanocomposite matrices and encapsulation strategies have been employed to protect anthocyanins and enhance their operational lifespan (Xu *et al*., 2024) [18]. Gas-sensitive indicators represent another important class of intelligent packaging systems. These indicators respond to changes in the concentration of gases such as ammonia, carbon dioxide, hydrogen sulfide, and oxygen, which are associated with microbial spoilage, respiration of fresh produce, or package integrity. Gas indicators are typically incorporated as discrete patches or printed elements within the packaging rather than being uniformly dispersed throughout the film. This approach minimizes interference with mechanical properties while allowing targeted sensing functionality (Yam *et al*., 2005) [19]. In biodegradable packaging systems, the challenge lies in achieving adequate sensitivity and selectivity while maintaining compatibility with biodegradable materials and ensuring food- contact safety.

Time temperature indicators (TTIs) are intelligent devices designed to provide information on cumulative thermal exposure, which is a critical factor influencing food spoilage. Although TTIs are not always biodegradable, recent research has explored the development of biodegradable or bio-based TTIs compatible with sustainable packaging concepts (Kerry *et al*., 2006) [9]. TTIs are particularly valuable for cold-chain monitoring, as temperature abuse during storage and transportation can significantly accelerate microbial growth and spoilage even if initial packaging conditions are optimal. The integration of intelligent packaging systems with digital technologies has further expanded their potential applications. Smartphone-assisted colorimetric analysis allows semi-quantitative assessment of indicator responses through RGB or color difference measurements, reducing subjectivity in visual interpretation (Kuswandi *et al*., 2011) [10]. These digital approaches can enhance traceability, enable data collection across the supply chain, and support more informed decision- making by retailers and consumers. However, standardization of image acquisition conditions, calibration protocols, and data interpretation remains a challenge for widespread adoption. The combination of active and intelligent functions within a single biodegradable nanocomposite packaging system offers synergistic benefits.

Active components slow spoilage processes, while intelligent indicators provide real-time feedback on food quality, enabling dynamic shelf-life management rather than reliance on fixed expiration dates. This integrated approach has the potential to significantly reduce food waste by preventing premature disposal of safe food and improving consumer confidence (Realini & Marcos, 2014) [13]. Nevertheless, the integration of multiple functions within a single packaging material introduces challenges related to material compatibility, stability, and performance optimization. Interactions between active agents and indicator compounds may lead to interference, such as antimicrobial agents affecting indicator sensitivity or antioxidants altering colorimetric responses.

To address these challenges, multilayer and compartmentalized packaging designs have been increasingly explored. In such systems, active and intelligent components are spatially separated, for example by placing indicators on an inner label or coating layer while active agents are incorporated into the structural film. Nanocomposite design plays a critical role in enabling these architectures by providing mechanical reinforcement and barrier performance while accommodating functional layers (Rhim *et al*., 2013) [14]. The selection of biodegradable materials, nanofillers, and processing techniques must therefore be carefully optimized to balance functionality, safety, and sustainability. Overall, active and intelligent packaging functions represent key enabling technologies for next-generation biodegradable food packaging systems. Advances in biodegradable nanocomposites have made it possible to incorporate antimicrobial, antioxidant, and sensing functionalities within environmentally friendly materials. Despite significant progress, challenges related to stability, safety, scalability, and standardization remain and must be addressed to facilitate industrial implementation. Continued interdisciplinary research integrating materials science, food chemistry, microbiology, and packaging engineering will be essential to fully realize the potential of active and intelligent biodegradable packaging in reducing food waste and improving food safety.

4. Performance Evaluation and Characterization

The successful development and implementation of biodegradable nanocomposite packaging films with active and intelligent functions require comprehensive performance evaluation using standardized and food-relevant characterization methods. Performance assessment serves multiple purposes: validating improvements over conventional biodegradable films, establishing structure–property–function relationships, ensuring food safety and regulatory compliance, and demonstrating practical applicability in real food systems. For active and intelligent packaging, characterization extends beyond conventional mechanical and barrier testing to include antimicrobial and antioxidant efficacy, sensor responsiveness, migration behavior, biodegradability, and shelf-life validation. The integration of these diverse performance metrics is essential to justify the potential of multifunctional packaging systems for food quality monitoring and waste reduction (Rhim *et al*., 2013; Duncan, 2011) [3,14].

4.1. Mechanical and Physical Properties

Mechanical performance is a fundamental requirement for food packaging films, as materials must withstand handling, processing, transportation, and storage without failure. Tensile strength, elastic modulus, and elongation at break are the most commonly reported parameters, typically measured according to ASTM D882 or equivalent standards. Pure biodegradable polymers such as starch, chitosan, and protein-based films often exhibit inadequate mechanical strength and brittleness, limiting their practical use. The incorporation of nanofillers has been consistently shown to improve mechanical performance due to effective stress transfer at the polymer– nanofiller interface and restriction of polymer chain mobility (Sorrentino *et al*., 2007).

Nanocellulose-reinforced films generally exhibit significant increases in tensile strength and modulus, even at low filler loadings (1–5 wt%), while maintaining acceptable flexibility. Clay- based nanocomposites also show mechanical reinforcement, although excessive filler content or poor dispersion can lead to embrittlement and reduced elongation. The mechanical performance of nanocomposite films is therefore strongly dependent on filler type, loading level, dispersion quality, and interfacial compatibility (Azeredo *et al*., 2017).

Table 1 summarizes representative mechanical property ranges reported for biodegradable packaging films before and after nanocomposite reinforcement.

Table 1: Representative mechanical properties of biodegradable and nanocomposite packaging films

Material system	Tensile strength (MPa)	Elongation at break (%)	Key observations
Starch-based film	5-15	10-60	Brittle, moisture-sensitive
Chitosan film	20-50	5-30	Good strength, limited flexibility
PLA film	40-70	2-10	High strength, brittle
Nanocellulose-reinforced biopolymer	50-120	5-40	Significant reinforcement at low loadings
Clay-based nanocomposite	30-90	3-20	Improved strength, risk of embrittlement

Sources: Sorrentino *et al*. (2007); Rhim *et al*. (2013) [14]; Azeredo *et al*. (2017) [1]; Xu *et al*. (2024) [18].

These results demonstrate that nanocomposite design is a key strategy for achieving mechanically robust biodegradable films suitable for real-world packaging applications.

4.2. Barrier Properties (Gas and Moisture Transmission)

Barrier performance against oxygen, carbon dioxide, and water vapor is critical for preserving food quality, as gas and moisture transfer strongly influence microbial growth, oxidation, and texture changes. Water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) are commonly used metrics to evaluate barrier properties. Most biodegradable polymers are inherently hydrophilic, resulting in poor moisture barrier performance compared to conventional plastics. Nanocomposite reinforcement has been shown to significantly improve barrier properties through the creation of tortuous diffusion pathways that slow gas and vapor transport (Duncan, 2011) [3]. Nanocellulose and layered silicate clays are particularly effective in enhancing barrier performance due to their high aspect ratio and planar morphology. Well-dispersed nanofillers increase the effective diffusion path length, reducing permeability without substantially increasing film thickness. However, barrier improvements can be compromised at high humidity levels, especially for polysaccharide-based systems, highlighting the need for careful material selection and multilayer designs (Xu *et al*., 2024) [18].

Table 2: Typical barrier property trends in biodegradable nanocomposite films

Film type	WVTR ($g\ m^{-2}\ day^{-1}$)	OTR ($cm^3\ m^{-2}\ day^{-1}$)	Effect of nanofillers
Starch/chitosan film	High (500-2000)	Moderate	Limited barrier
PLA film	Moderate	High	Poor oxygen barrier
Nanocellulose nanocomposite	Reduced by 30-70%	Reduced by 20-60%	Strong tortuosity effect
Clay-based nanocomposite	Reduced by 40-80%	Reduced by 30-70%	Dispersion-dependent

Sources: Rhim *et al*. (2013) [14]; Duncan (2011) [3]; Xu *et al*. (2024) [18].

Barrier enhancement is particularly important for active packaging systems, as controlled gas permeability can influence the release and effectiveness of antimicrobial and antioxidant agents.

4.3. Evaluation of Active Packaging Performance

The effectiveness of active packaging systems is typically assessed through antimicrobial and antioxidant activity assays. Antimicrobial performance is commonly evaluated using agar diffusion tests, viable cell count reduction, or time–kill studies against representative spoilage and pathogenic microorganisms such as Escherichia coli, Staphylococcus aureus, Listeria monocytogenes, and Pseudomonas spp. (Realini & Marcos, 2014) [13]. Chitosan-based and essential oil–loaded films often demonstrate significant microbial growth inhibition, with nanocomposite structures enabling prolonged activity through controlled release mechanisms.

Antioxidant activity is usually measured using chemical assays such as DPPH or ABTS radical scavenging tests, as well as lipid oxidation indicators (e.g., peroxide value, thiobarbituric acid reactive substances) in food systems. Nanocomposite films incorporating natural antioxidants have been shown to reduce oxidation rates in lipid-rich foods, although release kinetics and antioxidant stability remain critical factors influencing performance (Kerry *et al*., 2006) [9].

4.4. Intelligent Packaging Performance and Sensor Validation

The performance of intelligent packaging systems is evaluated based on sensitivity, selectivity, response time, stability, and correlation with food quality parameters. Colorimetric indicators are typically characterized using spectrophotometric analysis or digital image processing to quantify color changes in response to pH variation or gas concentration. For anthocyanin-based indicators, calibration curves relating color parameters (e.g., RGB values or ΔE) to pH or volatile basic nitrogen concentration are commonly reported (Kuswandi *et al*., 2011) [10]. A critical aspect of intelligent packaging validation is demonstrating correlation between indicator response and established spoilage markers, such as microbial counts (CFU/g), TVB-N values, or sensory evaluation scores. Several studies have shown strong correlations between colorimetric responses and microbial growth in fish and meat products, supporting the practical relevance of intelligent indicators for freshness monitoring (Xu *et al*., 2024). However, indicator stability under light exposure, temperature fluctuations, and long-term storage remains a key challenge.

4.5 .Migration, Safety, and Biodegradability Assessment

Food-contact safety is a critical requirement for packaging materials, particularly those incorporating nanomaterials and active agents. Migration testing into food simulants is typically conducted according to EU or FDA guidelines to assess the potential release of nanoparticles, dyes, or active compounds into food. Studies indicate that well-immobilized nanofillers such as nanocellulose and clays generally exhibit minimal migration, whereas metal-based nanoparticles require careful evaluation due to potential toxicity concerns (Llorens *et al*., 2012) [11]. Biodegradability and compostability are commonly assessed through soil burial tests, enzymatic degradation studies, or standardized composting protocols. The incorporation of nanofillers does not necessarily hinder biodegradation, provided filler loadings remain low and materials are properly designed. However, inorganic nanoparticles may persist in the environment, raising concerns regarding long-term ecological impact (Duncan, 2011) [3].

4.6. Shelf-Life Studies and Waste Reduction Potential

Ultimately, the performance of active and intelligent packaging systems must be validated in real food applications. Shelf-life studies involving meat, fish, dairy products, or fresh produce are commonly conducted under controlled storage conditions to compare conventional packaging with active and intelligent alternatives. These studies typically demonstrate delayed microbial growth, reduced oxidation, and improved sensory quality, accompanied by visible indicator responses that reflect food freshness (Realini & Marcos, 2014) [13]. The integration of performance evaluation data with shelf-life outcomes provides strong evidence for the potential of biodegradable nanocomposite packaging to reduce food waste. By extending shelf life and enabling informed decision-making, active and intelligent packaging systems can reduce premature food disposal and improve supply chain efficiency. However, standardized testing protocols and quantitative waste- reduction metrics are still needed to enable meaningful comparison across studies.

4.7. Discussion

The performance evaluation and characterization of biodegradable nanocomposite packaging films with active and intelligent functions reveal both substantial progress and persistent challenges that influence their practical applicability. Mechanical, barrier, active, and intelligent performance metrics collectively demonstrate that nanocomposite design is an effective strategy for overcoming many of the intrinsic limitations associated with biodegradable polymers.

However, the wide variability in reported results across studies highlights the strong dependence of performance on material selection, nanofiller type and loading, dispersion quality, and processing conditions. From a mechanical perspective, the incorporation of nanofillers such as nanocellulose and layered clays consistently enhances tensile strength and stiffness, enabling biodegradable films to approach or, in some cases, surpass the performance of conventional plastic packaging. Nevertheless, improvements in strength are often accompanied by reductions in elongation at break, particularly at higher filler loadings or in poorly dispersed systems. This trade- off between strength and flexibility remains a critical design consideration, as excessive brittleness can limit film processability and handling performance. The discussion of mechanical data across studies suggests that optimal nanofiller concentrations are typically low, emphasizing the importance of dispersion and interfacial compatibility rather than filler quantity alone.

Barrier performance improvements represent one of the most significant advantages of nanocomposite packaging systems. The tortuous path mechanism introduced by high-aspect-ratio nanofillers effectively reduces gas and moisture permeability, which is essential for controlling oxidation and microbial growth in packaged foods. However, barrier enhancements are often diminished under high-humidity conditions, particularly in polysaccharide-based systems, due to moisture-induced swelling and plasticization. This limitation underscores the need for hybrid strategies, such as multilayer structures or surface coatings, to maintain barrier performance under realistic storage conditions.

The evaluation of active packaging performance demonstrates that antimicrobial and antioxidant functionalities can be successfully incorporated into biodegradable nanocomposites, leading to measurable reductions in microbial growth and oxidative degradation. However, the effectiveness of these functions is highly dependent on controlled release behavior. Rapid release of active agents may provide strong initial protection but short-lived effectiveness, whereas overly restricted release can limit antimicrobial or antioxidant activity. Nanocomposite structures offer a promising means of tuning release kinetics, yet standardized methods for comparing release behavior across studies are lacking. As a result, reported antimicrobial and antioxidant performance is often difficult to directly compare, highlighting the need for harmonized testing protocols. Intelligent packaging evaluation further illustrates the potential and limitations of current systems. Colorimetric indicators, particularly anthocyanin-based pH sensors, have demonstrated strong correlations with spoilage markers such as microbial counts and volatile basic nitrogen levels in several food models. These findings support their practical relevance for freshness monitoring. However, indicator stability remains a major challenge, as sensitivity to light, temperature, and oxygen can lead to signal drift or fading over time. Additionally, many intelligent indicators lack selectivity, responding to multiple environmental stimuli rather than specific spoilage compounds. This can complicate interpretation and reduce reliability in complex food systems.

Migration, safety, and biodegradability assessments highlight an important tension between functionality and sustainability. While bio-based nanofillers such as nanocellulose and clays generally exhibit low migration potential and good environmental compatibility, metal-based nanoparticles raise unresolved concerns regarding long-term safety and environmental persistence. The discussion of migration data suggests that immobilization strategies and low filler loadings are essential, yet comprehensive toxicological evaluations remain limited in the literature. Furthermore, while most studies report biodegradability of the polymer matrix, fewer address the fate of nanofillers after degradation, representing a critical knowledge gap for life-cycle assessment. Perhaps most importantly, shelf-life studies reveal that performance improvements measured under laboratory conditions do not always translate directly to real-world waste reduction. Although many active and intelligent packaging systems demonstrate extended shelf life and improved quality retention, few studies quantify the extent to which these improvements reduce actual food waste at the consumer or retail level. The lack of standardized metrics for waste reduction and the limited inclusion of consumer behavior considerations restrict the ability to assess the true impact of these technologies.

The discussion of performance evaluation data indicates that biodegradable nanocomposite packaging films with active and intelligent functions hold strong potential for sustainable food packaging applications. However, achieving consistent, reliable, and scalable performance requires a more integrated approach that combines material optimization, standardized characterization methods, safety assessment, and real-world validation. Future research should prioritize comparative studies using standardized protocols, long-term stability testing under realistic storage conditions, and quantitative evaluation of waste-reduction outcomes to bridge the gap between laboratory innovation and commercial implementation.

5. Challenges, Research Gaps, and Future Perspectives

Despite significant advances in biodegradable nanocomposite packaging films with active and intelligent functions, several scientific, technological, and practical challenges continue to limit their large-scale adoption. Addressing these challenges requires not only material innovation but also standardization, interdisciplinary integration, and closer alignment between laboratory research and real-world packaging systems. A critical examination of current research reveals key gaps that must be resolved to fully realize the potential of these multifunctional packaging technologies for food quality monitoring and waste reduction. One of the most persistent challenges lies in balancing multifunctionality with material performance. While the incorporation of nanofillers, active agents, and intelligent indicators can impart valuable properties, it also increases system complexity. Interactions between polymer matrices, nanofillers, antimicrobial or antioxidant agents, and sensing components can negatively affect mechanical strength, barrier performance, or functional stability. For example, antimicrobial agents may interfere with colorimetric indicators, or nanofillers may alter the optical properties required for accurate visual sensing. Achieving compatibility among multiple functional components within a single biodegradable system remains a major materials design challenge, particularly when long-term stability under varying storage conditions is required.

Another critical challenge relates to the stability and reliability of intelligent packaging components. Natural dyebased indicators, especially anthocyanins, are attractive due to their biodegradability and consumer acceptance, but they are highly sensitive to light, temperature, oxygen, and humidity. This sensitivity can lead to premature color changes, fading, or irreversible degradation, reducing the reliability of freshness indicators. Although encapsulation and nanocomposite-based stabilization strategies have shown promise, there is currently no consensus on optimal stabilization approaches, and long-term performance data under realistic storage and distribution conditions remain limited. From a performance evaluation standpoint, the lack of standardized testing protocols represents a major research gap. Mechanical, barrier, antimicrobial, antioxidant, and sensing performance are often evaluated using different methods, conditions, and metrics across studies, making direct comparison difficult. In particular, antimicrobial efficacy is frequently reported using qualitative or short-term assays that may not reflect real food storage scenarios. Similarly, intelligent indicator performance is often validated under simplified laboratory conditions rather than in complex food matrices. The absence of harmonized protocols hinders objective assessment of progress and slows the translation of research findings into industrial practice.

Safety and regulatory considerations constitute another major barrier to commercialization. While biodegradable polymers and bio-based nanofillers such as nanocellulose are generally regarded as safe, the inclusion of metal or metal-oxide nanoparticles raises concerns regarding migration, toxicity, and environmental persistence. Comprehensive toxicological data, particularly regarding chronic exposure and post-degradation behavior of nanofillers, remain scarce. Furthermore, regulatory frameworks for nanomaterials in food packaging are still evolving, creating uncertainty for manufacturers and limiting industrial investment. Future research must prioritize safety-by- design approaches, emphasizing inherently safe materials, immobilization strategies, and transparent risk assessment.

The environmental sustainability of active and intelligent packaging systems also requires more rigorous evaluation. Although biodegradable materials are often assumed to be environmentally benign, the incorporation of nanomaterials and functional additives can complicate end-of-life behavior. Many studies focus primarily on biodegradation of the polymer matrix, with limited attention to the fate of nanofillers and active compounds after degradation. Comprehensive life cycle assessments that consider raw material sourcing, manufacturing, use-phase benefits, and end-of-life impacts are still lacking. Without such assessments, it is difficult to quantify the true environmental advantage of multifunctional biodegradable packaging over conventional alternatives. A significant research gap exists in the quantification of food waste reduction. While many studies demonstrate shelf-life extension and improved quality retention, few explicitly link these outcomes to measurable reductions in food waste at the retail or consumer level. Behavioral factors, such as consumer trust in intelligent indicators and willingness to rely on freshness signals rather than expiration dates, are rarely addressed. Future research should integrate material science with consumer studies and supply chain analysis to evaluate how active and intelligent packaging influences decision-making and waste generation in practice.

Scalability and economic feasibility represent additional challenges that must be addressed before widespread commercialization can occur. Many biodegradable nanocomposite films are produced using laboratory-scale techniques such as solution casting, which may not be compatible with industrial manufacturing processes. The thermal sensitivity of active agents and intelligent indicators further complicates scale-up using conventional extrusion or thermoforming methods. Research into scalable fabrication techniques, such as multilayer structures, coatings, and printing technologies, is essential to bridge the gap between laboratory prototypes and industrial products.

Looking ahead, several promising directions can guide future research and development. The design of multilayer and compartmentalized packaging systems offers a practical approach to integrating active and intelligent functions while minimizing material incompatibilities. Advances in bio-based nanofillers and green chemistry can further enhance safety and sustainability. The integration of digital technologies, including smartphone-assisted sensing and data analytics, presents opportunities for more objective and user-friendly intelligent packaging systems. Additionally, the development of standardized performance metrics and testing protocols will be critical for benchmarking progress and facilitating regulatory approval.

biodegradable nanocomposite packaging films with active and intelligent functions represent a powerful strategy for addressing food quality, safety, and waste reduction challenges. However, their successful implementation depends on overcoming material compatibility issues, improving functional stability, ensuring safety and regulatory compliance, and demonstrating tangible environmental and economic benefits. Addressing these challenges through coordinated, interdisciplinary research will be essential for translating promising laboratory innovations into commercially viable and socially impactful packaging solutions.

6. Conclusion

Biodegradable nanocomposite packaging films integrating active and intelligent functions offer a promising strategy for improving food quality monitoring and reducing food waste. Biodegradable polymers derived from renewable resources provide environmental advantages over conventional plastics, but their inherent limitations in mechanical strength and barrier performance necessitate advanced material design. The incorporation of nanofillers has been shown to effectively enhance structural and barrier properties while enabling the integration of antimicrobial, antioxidant, and sensing functionalities. Active packaging systems can delay microbial growth and oxidative degradation, whereas intelligent indicators provide real-time information on food freshness, supporting informed decision-making across the supply chain. Despite these advances, challenges related to functional stability, material compatibility, safety, scalability, and regulatory acceptance remain significant. In particular, the lack of standardized characterization methods and quantitative metrics for assessing food waste reduction limits direct comparison between studies and real-world implementation. Future research should focus on safe-by-design materials, multilayer packaging architectures, standardized performance evaluation, and digital integration to improve reliability and user acceptance. With continued interdisciplinary efforts, biodegradable active and intelligent nanocomposite packaging systems have strong potential to contribute to more sustainable and efficient food packaging solutions.

7. References

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