Zinc-Based Biodegradable Films for Food Packaging: A Comprehensive Review Article.

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Abstract—**The escalating global crisis of plastic pollution, combined with increasing consumer demand for sustainable and safe food products, has accelerated interest in biodegradable food packaging materials. Zinc oxide nanoparticles (ZnO NPs) have emerged as one of the most promising functional additives in this domain, owing to their remarkable antimicrobial activity, ultraviolet (UV) light-blocking capacity, enhanced mechanical and barrier performance, and status as a Generally Recognized as Safe (GRAS) substance by the U.S. Food and Drug Administration (FDA). This comprehensive review critically examines the current state of research on zinc-based biodegradable films for food packaging applications. It systematically addresses: (1) the environmental imperative driving the shift from conventional petroleum-derived plastics to biopolymer-based systems; (2) the synthesis routes and physicochemical characteristics of ZnO NPs, including green synthesis methods; (3) the key biopolymeric matrices employed including chitosan, starch, polylactic acid (PLA), polybutylene adipate-co-terephthalate (PBAT), gelatin, and alginate and the functional properties conferred by ZnO incorporation; (4) the molecular mechanisms of antimicrobial action, particularly reactive oxygen species (ROS) generation and zinc ion release; (5) documented applications in preserving fresh fruits, vegetables, meat, seafood, and dairy products; (6) food safety considerations including nanoparticle migration and regulatory frameworks (EFSA, FDA, EU Regulation No. 10/2011); and (7) prevailing challenges and future research directions. The review synthesizes evidence from over 60 peer-reviewed publications spanning 2016–2025, concluding that zinc-based biodegradable nanocomposite films represent a viable, multifunctional, and commercially scalable solution to address the twin imperatives of food safety and environmental sustainability.**

Index Terms—**zinc oxide nanoparticles; biodegradable packaging; food packaging; biopolymer nanocomposite; antimicrobial films; active packaging; ZnO NPs; sustainable packaging; chitosan; PLA; PBAT; shelf life**

I. INTRODUCTION

Food packaging serves as the fundamental interface between food products and the external environment, providing protection against physical damage, microbial contamination, moisture loss, and oxidative deterioration throughout the supply chain. For decades, conventional synthetic plastics primarily polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS) have dominated food packaging due to their low cost, excellent mechanical strength, and versatile barrier properties. However, these materials pose severe environmental challenges. As of 2023, global plastic production has surpassed 450 million tonnes annually, with food packaging accounting for the single largest segment of plastic consumption (Our World in Data, 2023). The recycling rate for plastic containers and packaging remains critically low at approximately 13.6% in the United States alone (EPA, 2018).

The environmental consequences of plastic waste are well documented. Food and drink packaging constitutes approximately 88% of coastline litter worldwide, and an estimated 1–2 million tonnes of plastic enter the world's oceans annually (FoodFacts.org, 2024). Microplastic contamination has been detected not only in marine ecosystems but also in agricultural soils, drinking water, and human biological samples, raising significant public health concerns. Plastic production currently utilizes approximately 12% of the world's petroleum, and projections suggest this could double or triple by 2050 (Environment.co, 2024). Scientists project that cumulative plastic production could emit up to 56 gigatons of CO_2 equivalents between now and 2050, underscoring the climate urgency of transitioning to sustainable packaging materials.

Against this backdrop, biodegradable packaging materials derived from renewable biopolymers have attracted substantial research and industrial interest. The global biodegradable packaging market was valued at approximately USD 5.70 billion in 2025 and is projected to reach USD 9.15 billion by 2034, at a compound annual growth rate (CAGR) of 6.05% (Business Research Insights, 2025). Regulatory frameworks worldwide are accelerating this transition: the European Union's Single-Use Plastics Directive (EU 2019/904), India's Plastic Waste Management (Amendment) Rules 2022, and similar legislation in Canada, Australia, and several U.S. states collectively mandate the phasing out of non-compostable plastic materials.

While biopolymers such as chitosan, starch, polylactic acid (PLA), polybutylene adipate-co-terephthalate (PBAT), gelatin, and alginate offer favourable biodegradability and renewability, their intrinsic functional properties particularly mechanical strength, gas and moisture barrier performance, and antimicrobial capacity often fall short of those exhibited by conventional petroleum-derived films. This performance gap has driven extensive research into nanocomposite approaches; wherein inorganic nanoparticles are incorporated into biopolymer matrices to enhance their physicochemical and functional properties.

Among the various inorganic nanofillers investigated, zinc oxide nanoparticles (ZnO NPs) have emerged as particularly promising candidates. ZnO NPs offer a unique combination of potent, broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria as well as fungi; effective UV light absorption due to their wide bandgap (~3.37 eV); improved mechanical reinforcement; and enhanced barrier properties. Critically, ZnO is classified as a GRAS (Generally Recognized as Safe) material by the U.S. FDA (21 CFR 182.8991) and has received a positive safety evaluation from the European Food Safety Authority (EFSA) for packaging applications (Optimizing Antimicrobial Efficacy, PMC, 2024). Furthermore, the availability of eco-friendly green synthesis routes using plant extracts aligns ZnO NP production with the broader sustainability goals of biodegradable packaging.

This review comprehensively synthesizes the current scientific literature on zinc-based biodegradable films for food packaging. It critically evaluates synthesis methodologies for ZnO NPs, the properties of key biopolymer matrices, the functional enhancements achieved through ZnO incorporation, mechanisms of antimicrobial action, food preservation applications, safety and regulatory considerations, and future research directions. By providing this synthesis, the review aims to guide researchers, food technologists, and packaging engineers toward the rational design of next-generation sustainable food packaging systems.

II. THE ENVIRONMENTAL IMPERATIVE FOR BIODEGRADABLE FOOD PACKAGING

2.1 The Global Plastic Crisis

The pervasive use of synthetic plastics in food packaging has created an environmental crisis of unprecedented scale. An estimated 5 billion tonnes of plastic waste are dispersed globally in terrestrial and aquatic environments, with residence times ranging from hundreds to thousands of years (Frontiers in Food Science and Technology, 2025). The non-biodegradable nature of conventional plastics means that even material discarded decades ago continues to fragment into microplastics and nanoplastics, which penetrate food chains and human tissues. A 2024 study estimated that even if all new plastic production ceased immediately, the degradation of existing waste would still double plastic pollution by 2040 (FoodFacts.org, 2024). The food and beverage sector is a disproportionately large contributor to this problem, particularly through single-use packaging for beverages, fresh meats, produce, and dairy products.

2.2 Biopolymers as Sustainable Alternatives

Biopolymers offer a compelling sustainable alternative to petroleum-derived plastics by virtue of their derivation from renewable biological sources and their capacity for natural biodegradation mediated by microorganisms. Key biopolymers of interest in food packaging include polysaccharides (starch, chitosan, cellulose, alginate, pectin, pullulan), proteins (gelatin, whey protein, soy protein, zein), and synthetic biodegradable polyesters including PLA (derived from fermentation of agricultural feedstocks), PBAT, and polybutylene succinate (PBS). These materials exhibit favorable biodegradability, biocompatibility, and, in many cases, inherent biological activities such as antioxidant or antimicrobial properties (Dhalsamant et al., 2025; Dirpan et al., 2023).

However, the commercial adoption of biopolymer-based packaging is constrained by significant functional limitations. Compared to conventional plastics, biopolymer films typically exhibit lower tensile strength and elongation at break, higher water vapor permeability (WVP) due to their hydrophilic nature, insufficient oxygen barrier properties, and limited resistance to extreme temperature and humidity conditions. These deficiencies translate to shorter food shelf lives under practical storage conditions, limiting their direct substitution for plastic films in high-performance applications. The incorporation of functional nanofillers, particularly ZnO NPs, represents a principal strategy for overcoming these limitations without compromising the biodegradability of the base polymer matrix.

III. ZINC OXIDE NANOPARTICLES: PROPERTIES, SYNTHESIS, AND CHARACTERIZATION

3.1 Physicochemical Properties of ZnO NPs

Zinc oxide (ZnO) is an n-type semiconductor with a hexagonal wurtzite crystal structure, a wide direct bandgap of approximately 3.37 eV, and a large exciton binding energy of 60 meV at room temperature. These fundamental properties confer several technologically valuable characteristics. The wide bandgap enables strong absorption of ultraviolet (UV) radiation in the range of 200–400 nm while remaining largely transparent in the visible spectrum, making ZnO NPs highly effective UV shields for food packaging applications (Optimizing Antimicrobial Efficacy, PMC, 2024). ZnO NPs are commercially available in particle sizes ranging from 10 to 800 nm and in various morphologies including spherical, rod-like, flower-shaped, and sheet-like forms, each with distinct surface area-to-volume ratios and consequently different functional properties. The high surface area of ZnO NPs which increases dramatically as particle size decreases is a critical determinant of both antimicrobial potency and film reinforcement efficacy.

The synthesis of ZnO NPs can be accomplished through chemical, physical, and biological routes. Chemical synthesis methods include sol-gel processing, hydrothermal synthesis, co-precipitation, solvothermal methods, and chemical vapor deposition. Physical methods encompass ball milling and vapor phase deposition. While these conventional approaches afford precise control over particle size, morphology, and crystallinity, they typically involve hazardous chemicals, high energy input, and generation of toxic by-products, raising concerns about process sustainability and the environmental footprint of the resulting materials.

3.2 Green Synthesis of ZnO NPs

Green synthesis methods, employing plant extracts, microbial biomass, or agricultural by-products as reducing and capping agents, have gained substantial traction as eco-friendly alternatives to conventional chemical synthesis (Hamed et al., 2023; Nanotechnology Reviews). These biogenic approaches eliminate dependence on hazardous chemicals, generate biodegradable by-products, and are inherently cost-effective and scalable. The phytochemicals present in plant extracts including phenolic acids, flavonoids, alkaloids, and terpenoids serve simultaneously as reducing agents (converting Zn^{2+} to ZnO) and as stabilizing/capping agents, preventing nanoparticle agglomeration and modulating particle size and morphology.

Numerous plant species have been successfully employed for ZnO NP green synthesis. Notable examples include: Justicia adhatoda leaf extract, which has been reported to yield ZnO NPs with a remarkably small crystallite size of approximately 5.2 nm (RSC Advances, 2025); Elettaria cardamomum extracts yielding particles suitable for antibacterial applications (RSC Advances, 2025); banana peel and date seed extracts (Hussien, 2023); pomegranate peel extract (Meshkatalsadat et al., 2023); and Ocimum lamifolium leaf extract (Tilahun et al., 2023). Green-synthesized ZnO NPs have been reported to exhibit superior biocompatibility and enhanced antimicrobial activity relative to chemically synthesized counterparts, attributed to synergistic interactions between the inorganic ZnO core and residual phytochemical capping agents.

The incorporation of ZnO NPs into biodegradable polymer matrices has been achieved through diverse processing techniques, each with advantages and limitations with respect to nanoparticle dispersion and resulting film properties. Solvent casting (solution casting) is the most widely employed method in laboratory-scale research, offering facile preparation and good control over composition. Extrusion-based methods — including twin-screw extrusion, cast extrusion, and extrusion blow molding are preferred for scalable, industry-compatible production. Melt compounding and electrospinning are also employed, particularly for the production of nanofiber-reinforced composites. A critical challenge across all processing methods is achieving uniform nanoparticle dispersion within the polymer matrix; agglomeration of ZnO NPs at higher loading concentrations leads to non-homogeneity, phase separation, and deterioration of both mechanical and antimicrobial properties (Phothisarattana & Harnkarnsujarit, 2023).

IV. KEY BIOPOLYMER MATRICES FOR ZINC-BASED PACKAGING FILMS

4.1 Chitosan-Based Films

Chitosan, a linear polysaccharide derived by deacetylation of chitin obtained from crustacean shells and fungal cell walls, is among the most extensively studied biopolymers for food packaging. Its inherent antimicrobial activity, arising from electrostatic interactions between its positively charged amino groups and negatively charged bacterial cell membranes, film-forming ability, biocompatibility, and biodegradability make it an ideal base material. However, pure chitosan films are characterized by high moisture sensitivity, poor water barrier properties, and relatively low mechanical strength that limit their practical utility in humid food environments. The incorporation of ZnO NPs synergistically addresses these limitations while amplifying the antimicrobial efficacy of the base polymer.

Souza et al. (2021) demonstrated that chitosan films incorporated with ZnO NPs synthesized from food industry by-products exhibited significantly enhanced antimicrobial activity against common food spoilage organisms. Amjadi et al. (2019) formulated active packaging from chitosan nanofibers combined with ZnO NPs and demonstrated marked reduction in bacterial growth in cheese, used as a food model. A recent study on chitosan/starch/modified ZnO cross-linked composite films (CS-c-ST-c-mZnO) reported that surface modification of ZnO NPs with KH-550 (3-aminopropyl triethoxysilane) substantially improved nanoparticle dispersion within the polymer matrix, achieving a tensile strength of 16.50 ± 0.23 MPa, elongation at break of 181.65%, water vapor transmission rate of 7.3 $g/m^2/24h$, and oxygen transmission rate of 36.9 $cm^3/m^2/24h \cdot atm$ at 3 wt% ZnO (ACS Applied Nano Materials, 2025).

The development of multifunctional ZnO-tannic acid (ZnO@TA) nanoparticles embedded in polyvinyl alcohol/chitosan (PVA/CH) blend films represents a notable recent advance (Fabrication of Multifunctional ZnO@TA, PMC, 2024). ZnO@TA(50)@PVA/CH films exhibited the highest tensile strength (48.72 ± 0.23 MPa) and Young's modulus (2163.46 ± 61.4 MPa) among the studied formulations, along with substantial inhibition zones against S. aureus (11 ± 1.0 mm), A. flavus (12.3 ± 0.57 mm), and C. albicans (13.6 ± 0.57 mm). The tannic acid moiety contributed antioxidant functionality, conferring dual active packaging capability.

4.2 Starch-Based Films

Starch is among the most abundant, low-cost, and widely available biopolymers globally, derived from agricultural sources including maize, potato, cassava, rice, and wheat. Its biodegradability, non-toxicity, and film-forming ability make it attractive for packaging applications. However, starch films are inherently brittle, highly hydrophilic, and exhibit poor barrier and mechanical properties that severely limit their practical utility. Thermoplastic starch (TPS), produced by plasticization with water and/or polyols such as glycerol, exhibits improved processing characteristics but remains moisture-sensitive.

ZnO NP incorporation into starch-based films has been shown to substantially improve their functional properties. Research on sago-based films embedded with micro- and nano-ZnO at concentrations of 1%, 3%, and 5% demonstrated significant improvements in thickness, water vapor permeability, optical properties, and thermal stability at 5% loading (Biodegradable Films with Nano- and Micro-ZnO, PMC, 2023). Studies on starch-based ZnO nanocomposite films for grape preservation showed that biopolymer films with embedded ZnO-neem NPs extended the shelf life of wrapped black grapes by up to 9 days, with the film biodegrading 30–50% within 28 days of soil burial demonstrating that enhanced functional performance need not compromise intrinsic biodegradability (Starch-Based Antibacterial Food Packaging, PMC, 2024).

PBAT/thermoplastic starch (TPS) blends incorporated with ZnO NPs at 3–5% concentrations have been developed as fully biodegradable active packaging films (Phothisarattana & Harnkarnsujarit, 2024). The PBAT component provides the requisite flexibility and processability, while TPS contributes biodegradability and reduced cost. ZnO incorporation improved mechanical properties, water barrier performance, and conferred antimicrobial activity that effectively extended the shelf life of packaged food models, including banana and tomato fruits.

4.3 Polylactic Acid (PLA)-Based Films

Polylactic acid (PLA) is a commercially significant bio-based thermoplastic polyester produced by ring-opening polymerization of lactide derived from the fermentation of agricultural feedstocks such as corn starch, sugarcane, and cassava. PLA is classified as GRAS by the FDA and exhibits mechanical properties comparable to commodity plastics such as PET. Its transparency, high stiffness, and excellent printability make it particularly suitable for food packaging. However, PLA suffers from brittleness, poor elongation at break, inadequate gas and moisture barrier properties at high humidity, and relatively low thermal stability (heat deflection temperature ~55°C), which constrain its applicability in hot-fill and retort packaging.

The incorporation of ZnO NPs into PLA matrices has been demonstrated to improve barrier and mechanical properties while imparting antimicrobial functionality. Rhim et al. (2016) reported PLA/ZnO NP composite films with enhanced UV-light barrier properties and antimicrobial activity against foodborne pathogens (ScienceDirect). More recent work on ZnO-modified PLA/PBAT composites demonstrates that ZnO NPs can enhance mechanical strength by 30–70% depending on concentration, dispersion efficiency, and polymer compatibility (R Discovery, 2024). PBAT, characterized by high elongation at break (up to ~700%) and excellent flexibility, is frequently blended with PLA to overcome PLA's brittleness; ZnO NPs further optimize the mechanical profile of such blends while simultaneously providing active packaging functionality.

4.4 Gelatin and Protein-Based Films

Animal-derived proteins, particularly gelatin (from collagen hydrolysis of bovine, porcine, or fish sources), whey protein, and soy protein, are another important class of biodegradable film-forming materials. Gelatin films exhibit good film-forming ability, transparency, oxygen barrier properties, and edibility, but suffer from poor water resistance and mechanical weakness in humid conditions. ZnO NP incorporation into gelatin matrices has been reported to improve rheological properties, thermal stability, and sorption isotherm characteristics (Mohammadi Nafchi et al., 2014).

A 2024 study on antimicrobial gelatin-based films incorporating cinnamaldehyde and ZnO NPs reported significantly enhanced antimicrobial performance against food spoilage bacteria, with synergistic interactions between the natural essential oil constituent (cinnamaldehyde) and ZnO NPs substantially expanding the spectrum and potency of antimicrobial action (Scientific Reports, 2024). Similarly, multifunctional betanin nanoliposomes incorporated into gelatin/chitosan nanofiber/ZnO nanocomposite films demonstrated enhanced fresh beef preservation, retarding microbial growth and lipid oxidation in refrigerated storage (Meat Science, 2020). Studies on rice starch–gelatin composite films with ZnO NP incorporation reported simultaneous improvements in UV-light barrier properties, thermal stability, tensile strength, and antimicrobial properties (Homthawornchoo et al., 2022; Polymers).

4.5 PBAT and PBS-Based Films

Polybutylene adipate-co-terephthalate (PBAT) and polybutylene succinate (PBS) represent the principal class of petrochemical-derived biodegradable polyesters used in food packaging. Despite their petroleum origin, both polymers are certified biodegradable under industrial composting conditions (EN 13432). PBAT exhibits excellent flexibility, toughness, and processability by conventional plastic processing equipment, making it highly relevant to industry transition scenarios. PBS offers a balanced profile of mechanical properties and biodegradation rate.

Phothisarattana and Harnkarnsujarit (2023) investigated PBAT/PBS/ZnO nanocomposite films produced by twin-screw extrusion followed by cast extrusion, with ZnO loadings up to 4.5 wt%. The resulting films demonstrated antimicrobial activity against both E. coli and B. cereus, improved water barrier properties, and at ZnO concentrations above 2.7%, significantly delayed discoloration of packaged minced pork a key indicator of lipid oxidation and microbial deterioration. However, the study also documented that ZnO loadings above 2.7% caused surface topography non-homogeneity and void formation, indicating that particle agglomeration at higher concentrations remains a significant technical challenge. A subsequent study on PBAT/ZnO films (ScienceDirect, 2025) demonstrated that nano-ZnO could inhibit bacterial growth on packaged banana and tomato surfaces, with the bacteriostatic property of nano-ZnO maintaining fruit quality parameters including firmness, color, and weight loss rate.

V. MECHANISMS OF ANTIMICROBIAL ACTION

5.1 Reactive Oxygen Species Generation

The antimicrobial activity of ZnO NPs against both Gram-positive bacteria (e.g., S. aureus, B. cereus, L. monocytogenes), Gram-negative bacteria (e.g., E. coli, Salmonella spp., P. aeruginosa), and fungi (e.g., Aspergillus spp., Candida albicans) is primarily attributed to three interconnected mechanisms, with reactive oxygen species (ROS) generation being the most critical (Kim et al., 2022; Food Reviews International).

Under ambient conditions, and particularly upon UV or visible light exposure, ZnO NPs generate a spectrum of highly reactive oxygen species including hydrogen peroxide (H_2O_2), hydroxyl radicals (·OH), and superoxide anion radicals ($\cdot O_2^-$) through photocatalytic excitation of electrons across the ZnO bandgap (Review on ZnO Antibacterial Activity, Academia.edu, 2025; Functional Properties and Safety, PMC, 2024). ROS mediate microbial killing through multiple pathways: oxidative damage to cell membrane lipids (lipid peroxidation), protein denaturation and enzyme inactivation, damage to nucleic acids including DNA strand breakage and base oxidation, disruption of the proton motive force across the bacterial membrane, and induction of oxidative stress gene expression leading to programmed cell death.

A fundamental structure-activity relationship governs ROS generation: as ZnO particle size decreases, the surface area-to-volume ratio increases, exposing a greater number of surface-active sites for photocatalytic reactions. H_2O_2 generation is directly proportional to the available ZnO surface area, which explains the well-documented finding that smaller ZnO NPs exhibit enhanced antibacterial activity against both S. aureus and E. coli compared to their larger counterparts (ZnO Nanostructures in Active Antibacterial Food Packaging, Food Reviews International, 2022). Surface defects and abrasive surface texture of ZnO NPs also contribute to antimicrobial potency through enhanced reactive site density.

5.2 Zinc Ion Release

A complementary mechanism of antimicrobial action involves the dissolution of ZnO NPs and consequent release of soluble zinc ions (Zn^{2+}) (ZnO NPs: Synthesis, Antimicrobial Activity, Academia.edu). Zn^{2+} ions are toxic to microorganisms at elevated intracellular concentrations through multiple pathways including disruption of enzyme active sites (many of which require precise metal coordination), competitive displacement of essential metal cofactors (Fe^{2+}, Mg^{2+}), inhibition of DNA synthesis, and disruption of the electron transport chain. The zinc ion release rate is influenced by the pH of the food matrix, temperature, humidity, and the nature of the biopolymer matrix with more acidic conditions accelerating dissolution and increasing antimicrobial potency, though also raising concerns about migration into food.

5.3 Direct Physical Interaction

ZnO NPs can also exert antimicrobial effects through direct physical interaction with microbial cell surfaces. The positive surface charge of ZnO NPs under physiological pH conditions promotes electrostatic attraction to the negatively charged cell membranes of bacteria. Upon contact, ZnO NPs may physically disrupt the membrane bilayer through abrasive mechanical interaction, facilitate their internalization via endocytosis, or directly adsorb onto the bacterial surface, blocking nutrient uptake and gas exchange (Comprehensive Evaluation, SSRN, 2023). Internalized ZnO NPs generate intracellular ROS, further amplifying oxidative stress and compromising mitochondrial function, ultimately leading to cell death. The relative contribution of each mechanism varies with ZnO NP size, morphology, concentration, medium pH, and the specific target microorganism.

VI. FUNCTIONAL PROPERTIES OF ZINC-BASED BIODEGRADABLE COMPOSITE FILMS

The incorporation of ZnO NPs into biodegradable polymer matrices modifies multiple physicochemical and functional properties of the resulting films. Table 1 summarizes representative studies on ZnO NP-incorporated biopolymer films for food packaging, and Table 2 provides a systematic overview of the property changes associated with ZnO NP incorporation.

Table 1. Summary of Representative Studies on ZnO NP-Incorporated Biodegradable Food Packaging Films

Biopolymer Matrix	ZnO Conc. (wt%)	Key Improvement	Target Pathogen	Reference
Chitosan	1–3%	↑TS, ↓WVP, antimicrobial	S. aureus, E. coli	Souza et al. (2021)

Biopolymer Matrix	ZnO Conc. (wt%)	Key Improvement	Target Pathogen	Reference
Chitosan/Starch	3%	↑TS (16.5 MPa), ↑thermal stability, ↓OTR	E. coli, S. aureus	Chitosan-c-ST-c-mZnO (2025)
PLA	1–5%	↑mechanical, ↑UV-barrier, antimicrobial	Foodborne pathogens	Rhim et al. (2016)
PBAT/PBS	2.7–4.5%	↑WVP, ↓discoloration of pork	B. cereus, E. coli	Phothisarattana et al. (2023)
Gelatin/Chitosan	0.5–2%	↑shelf life by 4–8 days, antifungal	Aspergillus spp., Candida	Jovanović et al. (2021)
Rice Starch/Gelatin	1–5%	↑TS, ↑UV-barrier, ↑thermal stability	General pathogens	Homthawornchoo et al. (2022)
PVA/Chitosan + ZnO@TA	1–5%	↑TS (48.7 MPa), ↑antifungal activity	S. aureus, A. flavus, Candida	ZnO@TA (2024)
PBAT/TPS	3–5%	↑barrier, ↑mechanical, antimicrobial active packaging	Gram-positive/negative	Phothisarattana & Harnkarnsujarit (2024)

TS = Tensile Strength; WVP = Water Vapor Permeability; OTR = Oxygen Transmission Rate; VLT = Visible Light Transmittance

Table 2. Effect of ZnO Nanoparticle Incorporation on Key Functional Properties of Biodegradable Films

Property	Effect of ZnO	Typical Range	Mechanism
Tensile Strength	↑ 30–70%	16–50 MPa (at 1–5% ZnO)	Filler reinforcement; crosslinking

Property	Effect of ZnO	Typical Range	Mechanism
Water Vapor Permeability	↓ 20–50%	Tortuous path effect	ZnO creates nano-barriers in matrix
UV Barrier	↑↑ (significant)	Blocks 200–400 nm UV	ZnO bandgap absorption (3.37 eV)
Antimicrobial Activity	Strong, broad-spectrum	MIC: 0.5–5 mg/mL	ROS generation + Zn^{2+} ion release
Thermal Stability	↑ 5–15°C Td	Td increase: ~8–15°C	ZnO–polymer hydrogen bonding
Transparency/Optical	Slight decrease	>70% VLT at ≤3%	Light scattering by nanoparticles
Biodegradability	Variable (matrix-dependent)	30–80% in 28 days	ZnO may slightly delay degradation

6.1 Mechanical Properties

Tensile strength (TS) and elongation at break (EAB) are the primary mechanical parameters characterizing packaging film performance. ZnO NPs function as nanofillers in biodegradable matrices, providing reinforcement through physical filler-matrix interactions and, in some formulations, through chemical crosslinking. At optimal concentrations (typically 1–3 wt%), ZnO NP incorporation has been reported to increase tensile strength by 30–70% across various biopolymer matrices (R Discovery, 2024). The mechanical reinforcement mechanism involves restriction of polymer chain mobility by well-dispersed ZnO particles, formation of a percolating nanoparticle network, and hydrogen bonding between ZnO surface hydroxyl groups and biopolymer functional groups (Bio)polymer/ZnO Nanocomposites, PMC, 2019).

The effect on elongation at break is more variable and matrix-dependent. In brittle matrices such as pure chitosan and starch, low ZnO NP concentrations may improve EAB through plasticization effects, while higher concentrations typically reduce elongation due to increased crosslink density. In inherently flexible matrices such as PBAT, ZnO incorporation can reduce EAB while substantially improving stiffness and tensile strength, creating a more balanced mechanical profile.

6.2 Barrier Properties

Gas and moisture barrier performance is critical to food shelf life, as oxygen transmission drives lipid oxidation and aerobic microbial growth, while moisture transfer promotes microbial proliferation and quality deterioration. ZnO NPs improve barrier properties by creating a tortuous path effect — well-dispersed ZnO particles within the polymer matrix force diffusing gas and water vapor molecules to navigate a longer, more circuitous path through the film, effectively reducing permeability (Bio)polymer/ZnO Nanocomposites, PMC, 2019). Reductions in WVP of

20–50% and significant decreases in oxygen permeability have been documented at ZnO loadings of 1–5% in various biopolymer matrices. A multilayer PLA/PBAT film with ZnO NP-loaded sodium alginate coating demonstrated a water vapor transmission decrease from 5.77×10^{-14} to 3.41×10^{-14} $g \cdot cm \cdot cm^{-2} \cdot Pa^{-1} \cdot s^{-1}$ (Yutong et al., 2024; Journal of Food Safety).

6.3 UV Barrier and Optical Properties

Light-induced oxidation of unsaturated lipids and photodegradation of vitamins represent significant drivers of food quality loss in transparent packaging. ZnO NPs are highly effective UV absorbers due to the electronic transitions across their 3.37 eV bandgap, providing strong absorption across the entire UV range (200–400 nm) while maintaining transparency in the visible spectrum. This enables the development of films that simultaneously provide excellent light barrier protection against photo-oxidation while allowing consumers to visually inspect packaged products a significant advantage over opaque UV-blocking alternatives. The UV-blocking efficacy of ZnO NPs has been documented across chitosan, starch, gelatin, and PLA matrices (Homthawornchoo et al., 2022; ZnO NPs and Nanocomposites as Smart Coating, ScienceDirect, 2025).

6.4 Thermal Stability

Thermal stability, assessed by thermogravimetric analysis (TGA), determines the processing window and high-temperature performance of packaging materials. ZnO NP incorporation consistently improves the thermal degradation temperature (Td) of biopolymer matrices by 5–15°C at optimal loadings, attributed to physical crosslinking between ZnO surface hydroxyl groups and polymer chains, which restricts chain mobility and delays thermal depolymerization. For chitosan-starch-mZnO cross-linked films, a thermal degradation temperature increase of 8°C (DTG peak at 343°C) was reported at 3% ZnO loading (CS-c-ST-c-mZnO, ACS Applied Nano Materials, 2025).

VII. APPLICATIONS IN FOOD PRESERVATION

7.1 Fruits and Vegetables

Fresh produce constitutes one of the most challenging categories for packaging due to their continued metabolic activity post-harvest, including respiration, ethylene production, transpiration, and susceptibility to both microbial spoilage and physiological deterioration. Elevated respiration rate, ethylene synthesis, oxidative reactions, and enzymatic browning are key factors reducing shelf life of perishable produce (Leng et al., 2022).

Chitosan-cellulose acetate phthalate films containing ZnO NPs extended the shelf life of black grapes by up to 9 days compared to unwrapped controls (Starch-based Antibacterial Packaging, PMC, 2024). ZnO NP-based nanocomposite films synthesized via a green approach using Mimusops elengi demonstrated efficacy in preventing deterioration of green grapes for 14–21 days (Kumar et al., 2019). Carboxymethylcellulose-based composite coatings incorporating cinnamaldehyde and ZnO NPs improved postharvest quality of cherry tomatoes in terms of firmness retention, reduced weight loss, and maintained color parameters (Guo et al., 2020). Chitosan-based nanocomposite films containing nettle-leaf extract-derived CuO and ZnO NPs demonstrated extension of guava fruit shelf life through combined antioxidant and antimicrobial activity, with CuO NPs > ZnO NPs in antioxidant efficacy (Nettle-Leaf ZnO/CuO Films, PMC, 2021).

In novel active packaging for minimally processed pomegranates, edible coatings and films combining ZnO NPs with pomegranate peel phenolic compounds demonstrated synergistic enhancement of shelf life, combining the antimicrobial action of ZnO with the antioxidant capacity of polyphenols (Anean et al., 2023; Materials).

7.2 Meat and Seafood

Meat and seafood products are highly susceptible to spoilage due to their rich nutrient composition, high water activity ($a_w > 0.95$), and the diverse microbial communities present on their surfaces. Bacteriological spoilage, lipid oxidation, myoglobin oxidation (discoloration), and off-odor development collectively determine the shelf life of these products. Multifunctional betanin nanoliposome/gelatin/chitosan nanofiber/ZnO nanocomposite films demonstrated capacity to retard both microbial growth and lipid oxidation in fresh beef stored under refrigeration (Meat Science, 2020). PBAT/PBS films with ZnO NPs above 2.7% loading effectively delayed the discoloration of packaged minced pork by inhibiting microbial growth and blocking UV radiation-induced pigment oxidation (Phothisarattana et al., 2023).

7.3 Dairy and Bakery Products

In dairy applications, Amjadi et al. (2019) demonstrated that chitosan nanofiber/ZnO NP active packaging dramatically reduced the growth of inoculated bacteria in fresh cheese, with antimicrobial efficiency exceeding 95% within 3 hours of contact for the 0.8Ag/0.2ZnO composite film (extrusion blow molding; Zhai et al., 2022). Novel active packaging based on carboxymethyl cellulose-chitosan-ZnO NP nanocomposites has been demonstrated to increase the shelf life of bread by inhibiting mold growth, a major economic loss factor in bakery industries globally (Noshirvani et al., cited in Scientific Reports, 2024).

VIII.FOOD SAFETY, NANOPARTICLE MIGRATION, AND REGULATORY FRAMEWORK

8.1 Zinc Ion Migration and Safety Thresholds

The primary food safety concern associated with ZnO NP-incorporated food packaging films is the potential migration of zinc species — both in nanoparticulate form and as dissolved ionic zinc (Zn^{2+}) — from the packaging material into the food matrix. Extensive migration studies have established that zinc migration from food packaging occurs predominantly in the ionic form (Zn^{2+}) rather than as intact nanoparticles, and that the mass transfer of ZnO in nanoparticulate form from polymer matrices is generally negligible (EFSA, 2015; ScienceDirect migration study, 2024).

The EFSA's Scientific Committee on Food established a No Observed Adverse Effect Level (NOAEL) of 50 mg zinc/person/day and recommended an upper tolerable intake limit of 25 mg zinc/person/day (EFSA, 2015; PackagingLaw.com). The daily dietary intake of zinc from all food sources in developed countries typically ranges from 9–14 mg/day. The critical regulatory question, therefore, is whether the additional zinc exposure from migration of ionic zinc from packaging could collectively push total dietary zinc intake above the established tolerable upper limit, particularly when considering cumulative exposure from multiple zinc-containing food contact materials. EFSA's CEF Panel has noted that while available migration data for ionic zinc from ZnO NP packaging applications are generally within current specific migration limits (SML), the upper tolerable limit could theoretically be exceeded when dietary exposure from all sources is considered (EFSA Issues Scientific Opinion, PackagingLaw.com).

8.2 Regulatory Framework

At the international regulatory level, ZnO is classified as GRAS (Generally Recognized as Safe) by the U.S. FDA (21 CFR 182.8991), permitting its use in food contact applications. The European Union has included ZnO in Annex I of Regulation (EU) No. 10/2011 on plastic food contact materials and articles as an authorized substance, subject to migration limits. EFSA has issued a positive safety evaluation for ZnO NPs specifically for use as UV absorbers in polyolefin packaging, based on the absence of significant migration in particulate form (Optimizing Antimicrobial Efficacy, PMC, 2024). The EUON (European Union Observatory for Nanomaterials) report published in October 2024 confirmed that included studies on food contact materials assessed nanoparticle release according to regulatory standards, including EU Regulation No. 10/2011 (Food Packaging Forum, 2024).

Regulatory risk assessment for nanomaterials in food packaging is conducted on a case-by-case basis, as nanomaterials may exhibit biological and physiological properties distinct from their bulk material counterparts. EFSA updated its guidance on nanomaterials in the food chain in 2021, providing frameworks for assessing technical requirements and risk assessment methodologies specifically addressing small particles and nanoforms (EFSA Journal, 2021). Key guidance provisions cover migration testing of nanoparticles from food contact materials, characterization requirements for nanoforms, and tiered risk assessment approaches based on nanomaterial physicochemical properties, exposure levels, and toxicological data.

8.3 Factors Influencing Migration

Multiple factors govern the rate and extent of zinc migration from ZnO NP-incorporated packaging films into food matrices: (1) ZnO NP concentration higher nanofiller percentage in nanocomposites correlates with increased migration potential, more so than particle size, contact time, or temperature (FDA/EFSA Safety Concerns, FCI); (2) food matrix pH acidic foods promote ZnO dissolution and ionic zinc release, with migration rates substantially higher in low-pH simulants (acetic acid) versus neutral or fatty food simulants; (3) polymer matrix type and crystallinity matrices with lower crystallinity permit faster diffusion of zinc species; (4) processing conditions surface area, exposure to UV light, and temperature all influence zinc species mobility; and (5) nanoparticle surface modification surface-coated or functionalized ZnO NPs exhibit reduced dissolution rates and migration compared to uncoated particles.

IX. CURRENT CHALLENGES AND LIMITATIONS

9.1 Nanoparticle Agglomeration

One of the most persistent technical challenges in ZnO NP-incorporated food packaging films is achieving homogeneous nanoparticle dispersion within the polymer matrix. ZnO NPs have a strong tendency to agglomerate due to their high surface energy and van der Waals interactions, particularly at concentrations above 3 wt% (Phothisarattana & Harnkarnsujarit, 2023). Agglomeration leads to non-uniform distribution of active sites, formation of voids and defects in the film matrix, deterioration of mechanical and barrier properties, reduction of photocatalytic and antimicrobial efficacy, and compromised optical properties including haze and transparency. Surface modification strategies including silane functionalization (KH-550 treatment), surface grafting, and preparation of ZnO-surfactant complexes show promise in improving dispersion, but add processing complexity and cost.

9.2 Scalability and Industrial Processing

A fundamental gap exists between laboratory-scale development (typically employing solvent casting on a bench scale) and industrial-scale production by continuous processing methods such as blown film extrusion, cast extrusion, and injection molding. Biopolymer processing is inherently more challenging than thermoplastic processing due to narrow thermal processing windows, thermal sensitivity of bioactive components, moisture-induced degradation during melt processing, and incompatibility with high-speed manufacturing lines (Next-Generation Food Packaging, PMC, 2025). The incorporation of ZnO NPs introduces additional considerations including equipment wear from abrasive nanoparticles, health and safety requirements for handling nanopowders, and quality control challenges in ensuring batch-to-batch consistency. Significant investment in process optimization and scale-up studies is required to translate laboratory findings into commercial reality.

9.3 Cost Competitiveness

The cost of ZnO NP-incorporated biodegradable films currently remains higher than both conventional plastic films and unmodified biopolymer films. Cost drivers include the synthesis and surface modification of ZnO NPs, higher raw material costs of biopolymer matrices relative to bulk commodity plastics, more complex processing requirements, and quality control measures for nanocomposite materials. While advances in green synthesis using agricultural waste and by-products reduce NP synthesis costs, the overall cost differential remains a significant barrier to market adoption. The evolution of regulatory frameworks mandating biodegradable packaging and the growing consumer premium for sustainability may partially offset these cost disadvantages over time.

9.4 Biodegradation Dynamics

The effect of ZnO NP incorporation on the biodegradation behavior of biopolymer matrices presents a complex and sometimes contradictory picture. While the base biopolymer matrices are inherently biodegradable, ZnO NPs may interfere with biodegradation processes by acting as antimicrobial agents that inhibit the very microorganisms responsible for polymer degradation in compost or soil environments. Studies on PBAT antimicrobial films note that the incorporation of antimicrobial agents including ZnO can delay the biodegradation process (ZnO Enhancing PBAT Properties, ScienceDirect, 2025). Comprehensive biodegradation studies under standardized composting and soil burial conditions are needed for specific formulations to establish their true environmental end-of-life profile and compliance with biodegradability standards (EN 13432, ASTM D6400).

9.5 Toxicological Gaps

Notwithstanding the GRAS status of bulk ZnO and EFSA's positive evaluation of ZnO NPs for specific packaging uses, significant knowledge gaps remain regarding the long-term biological effects of dietary exposure to ZnO NPs and their transformation products. Nanoparticles exhibit distinct biological behavior compared to bulk materials, and their small size enhances potential for bioaccumulation in organ tissues (FDA/EFSA Safety Concerns, FCI). The detection of nanomaterials in complex food matrices remains analytically challenging, complicating accurate dietary exposure assessment. Comprehensive chronic toxicology studies specifically addressing ZnO NP dietary exposure through packaging migration are urgently needed to build the evidence base for informed regulatory decision-making.

X. FUTURE RESEARCH DIRECTIONS AND PROSPECTS

The field of zinc-based biodegradable food packaging is rapidly evolving, and several research directions offer substantial promise for addressing current limitations and expanding applications: (1) Smart and Intelligent Packaging Integration: ZnO-based packaging systems can be functionalized with chromogenic pH-sensitive dyes, oxygen indicators, or freshness sensors to create intelligent packaging capable of monitoring food quality in real time. A biodegradable conductive film based on PLA modified with polyaniline and ZnO/CuO has been demonstrated to estimate product shelf life through electrochemical sensing (Biodegradable Packaging Industry Trends, 2024). Such smart packaging systems represent a convergence of sustainability and digital food safety monitoring.

(2) Multifunctional Nanocomposites: Combining ZnO NPs with complementary functional additives — such as essential oils (cinnamaldehyde, eugenol, thymol), plant extracts, antioxidant

molecules (curcumin, resveratrol), or other nanoparticles (titanium dioxide, silver) — can create synergistic active packaging systems with expanded antimicrobial spectra, dual antioxidant-antimicrobial functionality, and reduced ZnO loading requirements, thereby mitigating migration concerns while maintaining efficacy (Gelatin/Cinnamaldehyde/ZnO Films, Scientific Reports, 2024).

(3) Advanced Surface Modification and Encapsulation: Nanoencapsulation of ZnO NPs within biodegradable polymer shells (e.g., PLA, chitosan, alginate) or surface functionalization with biopolymer coatings can control zinc ion release kinetics, reduce agglomeration, improve biocompatibility, and enable stimuli-responsive release of antimicrobial ions triggered by packaging environment conditions (humidity, pH, temperature). Such controlled release systems can optimize the antimicrobial effect while minimizing migration of zinc species into food.

(4) Circular Economy Alignment: Future research should explicitly address the full life cycle of ZnO NP-incorporated biodegradable films, from raw material sourcing and processing energy through end-of-life biodegradation, composting behavior, and potential environmental fate of released ZnO NPs. Life cycle assessment (LCA) studies specifically comparing ZnO-incorporated biodegradable films against conventional plastic alternatives and unmodified biopolymer films are critically needed to quantify net environmental benefits.

(5) Machine Learning and Predictive Design: The growing volume of experimental data on ZnO NP-biopolymer nanocomposite properties creates opportunities for machine learning approaches to predictive film design. Artificial neural networks and genetic algorithms have already been applied to optimize film properties from formulation parameters (Modeling and Optimization of PLA/PBAT Films, ScienceDirect, 2025), offering a promising route to accelerate the development of optimized zinc-based packaging systems.

(6) Standardization and Regulatory Harmonization: Developing internationally harmonized test methods for characterizing ZnO NP migration from food packaging, standardizing biodegradation testing protocols, and establishing clear regulatory thresholds for nanoforms of zinc in food contact materials will be essential prerequisites for broad commercial adoption of zinc-based biodegradable packaging. Collaboration between regulatory bodies (EFSA, FDA, FSSAI, FSANZ), standards organizations (ISO, ASTM), and industry is necessary to create the enabling regulatory environment.

XI. CONCLUSION

Zinc-based biodegradable films for food packaging represent one of the most scientifically well-developed and practically promising approaches in the rapidly advancing field of sustainable active food packaging. The integration of zinc oxide nanoparticles into biodegradable biopolymer matrices including chitosan, starch, PLA, PBAT, gelatin, and their blends and composites confers a multifunctional profile encompassing potent broad-spectrum antimicrobial activity, enhanced mechanical strength, improved gas and moisture barrier performance, effective UV-light shielding, and improved thermal stability. These properties collectively translate to meaningful extensions in the shelf life of diverse food products including fresh produce, meat, seafood, dairy, and bakery products, as documented across an extensive body of peer-reviewed research.

The antimicrobial potency of ZnO NPs is primarily mediated through reactive oxygen species generation, zinc ion release, and direct physical disruption of microbial membranes, with smaller particle sizes and higher surface areas conferring superior antimicrobial activity. Green synthesis methods using plant extracts align ZnO NP production with sustainability principles, offering cost-effective, eco-friendly, and potentially biocompatibility-enhanced alternatives to conventional chemical synthesis.

From a safety perspective, ZnO is classified GRAS by the U.S. FDA and has received a positive EFSA evaluation for specific packaging applications. Migration studies confirm that zinc transfer from nanocomposite packaging occurs primarily as ionic Zn^{2+} and that migration at properly designed loading levels is generally within established regulatory limits. However, ongoing research is needed to address the potential for cumulative dietary zinc exposure from multiple packaging sources and to close toxicological knowledge gaps specific to nanoform exposures.

Key challenges including nanoparticle agglomeration at higher loadings, the need for industrial-scale process development, cost competitiveness relative to conventional materials, and the complex interplay between ZnO incorporation and biodegradation dynamics must be systematically addressed through targeted research. Future opportunities in smart packaging integration, stimuli-responsive controlled release systems, multifunctional nanocomposite design, and machine learning-assisted formulation optimization offer compelling paths forward.

As regulatory frameworks globally converge toward mandating biodegradable, compostable, and recyclable packaging, and as consumer demand for sustainable, safe food products continues to intensify, zinc-based biodegradable nanocomposite packaging films are positioned to play a pivotal role in the global transition to a sustainable circular bioeconomy for food packaging. Interdisciplinary collaboration between materials scientists, food technologists, toxicologists, regulatory scientists, and industry partners will be essential to fully realize this transformative potential.

XII. DECLARATIONS

Author Contributions

All authors contributed equally to the conception, literature review, drafting, and critical revision of the manuscript. All authors have read and approved the final submitted version.

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Data Availability Statement
All data discussed in this review are available from the primary sources cited within the reference list.

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