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# Nanocomposites in Food Packaging: Market, Safety Regulation, Migration

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## ABSTRACT

**Background and aim**: New food packaging methods can extend food shelf life, and rising consumer demand for processed foods has driven rapid sector-wide progress (from electronic machinery to flexible and sterile films, metal containers, aluminum foil, and flexographic printing) advancing the food industry's economy, quality, safety, and spoilage reduction. This review provides an overview of the most common materials comprising nanocomposites employed in food packaging, focusing on those prepared through high technologies in nanotechnology capable of extending the shelf life of packaged materials while preserving food safety and quality. In addition, the capability of materials in development of food packaging as active and intelligent packaging forms via nanocomposite biomaterials will be discussed. Finally, common methods of nanomaterial synthesis and effects of nanomaterials on human health will be reviewed.

**Material and Methods**: This structured narrative review synthesized peer-reviewed literature (2015–2026) from PubMed, ScienceDirect, Wiley, and institutional repositories, supplemented by EU and FDA regulatory texts and industry market reports, using keyword searches covering nanocomposite packaging, nanoparticle migration, and food contact regulation with manual backward citation screening.

**Results and Conclusion:** The reviewed literature indicates that nanocomposite materials—particularly nanoclays, nanosilver, and metal oxide nanoparticles—substantially extend shelf life and preserve food quality through enhanced barrier properties and antimicrobial activity. However, regulatory frameworks remain largely substance-based, and migration studies show that nanoparticle release depends strongly on matrix encapsulation and use conditions, leaving safety assurance under real-world scenarios incompletely resolved. Nanocomposites offer significant commercial and functional promise for active and intelligent food packaging, their sustainable adoption requires harmonized specific regulation and standardized migration testing to confirm consumer safety.

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| ***What is "already known":*** | • Nanoclays, nano-Ag and metal oxides extend shelf life via barrier and antimicrobial effects.<br>• Functional mechanisms of nanocomposite packaging films, along with the toxicity and nanoparticle release behaviour highlight antibacterial performance and mechanical stability of nanoparticle-based coatings. |
| ***What this article adds:*** | • Optimized nanoparticle production techniques and improving food monitoring systems will help alleviate consumer concerns regarding the quality of packaged food.<br>• Migration safety depends on matrix encapsulation and use conditions, not nanoparticle type alone |

## 1. INTRODUCTION

Nanotechnology represents an emerging scientific discipline that has introduced significant innovations in food packaging for consumers. This technology offers solutions to many existing challenges related to food safety, security, and sustainability. [1-4]. Some studies reviewed the development of nanocomposites based on natural and synthetic biopolymers combined with nanosized materials such as layered silicate nanoclays, metal nanoparticles, and metal oxides. Their study also evaluated the antibacterial activities of these nanocomposites, concluding that such materials possess strong potential for use as active antimicrobial food packaging [5-8]. The functional mechanisms of nanocomposite packaging films, along with the toxicity and nanoparticle release behaviour are reported to highlight antibacterial performance and mechanical stability of nanoparticle-based coatings, particularly those containing nanoclay and nanosilver [9].

## 2. Methods

This review was conducted as a structured narrative review synthesizing scientific literature, regulatory documents, and market intelligence reports on nanocomposite food packaging. The literature search targeted publications indexed in PubMed, ScienceDirect, Wiley Online Library, and institutional repositories, supplemented by regulatory texts from the European Union and the United States Food and Drug Administration (FDA). Given the tripartite scope of the review (market landscape, safety regulation, and migration) the search strategy was designed to capture both peer-reviewed research and grey literature from authoritative regulatory and market analysis sources. Studies were included if they addressed at least one of 3 thematic pillars: (1) market trends, commercial applications, or economic projections for nanocomposite food packaging; (2) safety regulations and legislative frameworks governing nanomaterials in food contact articlesor (3) migration testing methodologies, experimental findings on nanoparticle release from polymer matrices, or toxicological risk assessment of migrated species. Peer-reviewed original research, comprehensive reviews, regulatory guidance documents, and industry market reports were eligible. Studies were excluded if they focused exclusively on non-food-contact nanocomposite applications, lacked sufficient methodological detail for migration assessment, or were published in English.

## 3. NANOMATERIAL

Nanomaterials or nanoparticles (NPs), defined by having at least one dimension below 100 nm, display distinctive physical and chemical features such as flexibility, flame retardancy, recyclability, and antimicrobial activity. These characteristics make them promising substitutes in various fields, including electronics, energy systems, information technology, pharmaceuticals, medicine, and the food industry. Reports indicate that the global production of nanomaterials is expanding by approximately 25% annually across different industrial sectors [10, 11].

In recent years, nanomaterials have been recognized for their potential applications in the food industry, serving multiple purposes such as enhancing food packaging, extending the shelf life of products, improving food safety, and maintaining higher overall food quality [12]. In other words, nanomaterials have revolutionized the food packaging industry [13]. Nanomaterials possess significant potential to maintain essential food characteristics such as taste, color, flavor, texture, and nutritional content by enhancing the mechanical strength, barrier capacity, and antimicrobial performance of packaging materials. Antimicrobial nanocomposites can function as active packaging systems, directly interacting with food surfaces to inhibit or reduce the uncontrolled growth of microorganisms [13, 14]. Many nanomaterials including metals and metal oxides have been demonstrated to have antibacterial effects [15, 16]. The antimicrobial efficiency of nanoscale materials primarily arises from their ability to adopt various shapes at the nanometer scale, including spherical, triangular, rod-like, octahedral, sheet, shell, and flower-like forms. This diversity in geometry is particularly beneficial for antimicrobial purposes, as the effectiveness of nanomaterials is closely related to the surface area available for interactions with biological components [16, 17]. Therefore, antimicrobial nanomaterials, often referred to as nanoantibiotics, represent one of the most promising strategies for preventing and controlling microbial growth and infections. Although the exact


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mechanisms behind their antimicrobial activity are not yet fully understood, it is generally proposed that nanomaterials exert their effects primarily through two major mechanisms: (1) damaging microbial cell membranes by disrupting membrane integrity and potential through direct interaction and binding, and (2) inducing intense oxidative stress through the generation of reactive oxygen species, which cause serious DNA damage, mutations, and ultimately cell death [18-20]. For antimicrobial applications, various metal oxides serve as photocatalysts, meaning they can be exposed to ultraviolet light to produce highly reactive oxygen species (ROS). These ROS demonstrate antimicrobial properties and are utilized in food packaging to minimize biological hazards [21, 22]. Nanomaterial applications extend beyond antimicrobial food packaging, as both nanoparticles and nanocomposites are actively applied in the packaging industry to shield products from harsh external factors, including extreme temperature fluctuations and mechanical stress, thereby prolonging shelf life. The integration of nanoparticles into packaging materials helps maintain food quality and extends product longevity [23-25]. Studies have demonstrated that nanomaterials can detect toxins and harmful bacteria in food products. A wide range of research has emphasized the promise of various nanomaterials—such as nanoparticles, nanofibers, and thin films—as nanobiosensors for food packaging. Specific materials like gold, iron oxide, and zinc sulfide have been recognized for their effectiveness in identifying pathogenic bacteria in foods. As a result, food packaging is viewed as a key field for implementing engineered nanoparticles (ENPs) that actively and intelligently transform conventional packaging. Currently, numerous nanoscale materials have been incorporated into the food packaging sector as functional additives, including silver nanoparticles (AgNPs), copper nanoparticles (CuNPs), gold-based nanoparticles (AuNPs), titanium dioxide (TiO2), zinc oxide (ZnO), nanoclay, carbon nanotubes (CNTs), cellulose nano-whiskers, and starch nanocrystals. Each of these nanomaterials contributes distinct structural and functional properties, providing unique advantages to the pack-aging materials they enhance [7, 26-30]. In the next sections, the most applicable nanomaterials in food packaging industry will be discussed.

## 2.1. Silver

Silver nanoparticles (AgNPs) are incorporated into polymer packaging materials such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and nylon to impart antimicrobial properties. Studies have shown that colloidal silver particles exhibit potent antibacterial activity against various bacteria, including *Escherichia coli (E. coli)* and *Staphylococcus aureus* (*S. aureus*). Additionally, AgNPs can be embedded in natural biopolymers like alginate, chitosan, and starch, where they demonstrate significant antimicrobial effects against both Gram+ and Gram- bacterial strains [31, 32]. Studies using cellulose absorbents loaded with silver nanoparticles have demonstrated a notable reduction in total aerobic bacterial counts, with limited impact on lactic acid bacteria and *Pseudomonas* Sps, and a marked decrease in the numbers of Enterobacteriaceae compared to control samples. Furthermore, films made from starch and clay, further enhanced with silver nanoparticles, provide improved mechanical strength and gas barrier capabilities, as well as effective antimicrobial action due to interactions between the nanoparticles and the many hydroxyl groups within the starch matrix [31-33].

## 2.2. Copper

Copper nanoparticles are valuable in a range of applications, including food processing, medical devices, and water treatment systems. Their antibacterial effects are often found to be on par with those of silver nanoparticles, and they can be incorporated into both synthetic and naturally-derived biopolymer matrices such as cellulose, starch, and chitosan. Research involving cellulose materials embedded with copper nanoparticles has demonstrated marked antibacterial activity, particularly against bacteria such as *K. pneumoniae*. In addition, copper-based nanocomposites can also offer antifungal protection. However, copper is generally not favored for use in the food packaging sector due to its potential toxicity, mainly because it can accelerate biochemical spoilage of foods through chemical oxidation [34-38].

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## 2.3. Titanium dioxide

Among metal oxide nanoparticles, $TiO_2$ stands out as a significant photocatalytic semiconductor with notable properties, long-term stability, and established safety for specific applications. $TiO_2$ exhibits self-cleaning and self-disinfecting abilities, effectively inactivating a broad spectrum of microorganisms through the action of hydroxyl radicals and reactive oxygen species that are generated on its surface under light exposure. These reactive species can oxidize the polyunsaturated phospholipids in bacterial membranes, contributing to $TiO_2$'s antimicrobial effectiveness. When incorporated into food packaging materials, $TiO_2$ nanoparticles enhance protection against foodborne pathogens, odors, stains, spoilage, and allergens. However, some practical limitations remain, as $TiO_2$ nanoparticles have low photon utilization efficiency and require ultraviolet radiation for activation [28, 39-41].

## 2.4. Zinc oxide

ZnO nanoparticles can be integrated into various matrices such as low-density polyethylene (LDPE), polypropylene, polyurethane, paper, and chitosan to provide antimicrobial protection. Among metal oxides, ZnO nanoparticles are regarded as one of the safer options for human use. Research has demonstrated that glass decorated with ZnO nanoparticles exhibits antibacterial activity against both E. coli and S. aureus, while ZnO incorporated into polyurethane films is active aganst species like E. coli and B. subtilis. Additionally, ZnO nanorods deposited on glass surfaces have shown antifungal effects against Candida albicans. When added to biopolymers such as chitosan, ZnO nanoparticles, though slightly less potent than their silver counterparts, can inactivate up to 99.92% of viable *E. coli* after 24 hours of exposure. ZnO nanocomposites are also effective against other microbes including *B. subtilis, Enterococcus faecalis, Pseudomonas aeruginosa, S. typhimurium,* and *S. aureus* [42-46].

## 2.5. Magnesium oxide

Magnesium oxide (MgO), also known as magnesia, is employed as a nanofiller to both enhance the antibacterial properties and the overall performance of materials in which it is embedded. Research showed chitosan-MgO bionanocomposites infused with clove oil for food packaging applications, revealing that these composites display potent antibacterial effectiveness against *Staphylococcus aureus*. Studies have consistently shown that MgO nanoparticles can disrupt both Gram+ and Gram- bacteria, and when integrated into biopolymer matrices like chitosan, especially in combination with natural antimicrobials, provide promising active food packaging solutions [47, 48].

## 2.6. Silicon dioxide

Silicon dioxide, or silica nanoparticles ($nSiO_2$), have been shown to enhance the mechanical strength and barrier properties of various polymer matrices. Research has found that adding $nSiO_2$ to polypropylene (PP) increases tensile assets such as strength, modulus, and elongation, while incorporating $nSiO_2$ into starch matrices results in improved water resistance. The inclusion of $nSiO_2$ into isotactic polypropylene (iPP) with a polypropylene-grafted maleic anhydride (PP-g-MA) compatibilizer boosts the storage modulus, material strength, and oxygen barrier capacity of the composite. Additionally, polyvinyl alcohol nanocomposites fabricated with $nSiO_2$ by radical copolymerization techniques demonstrate improved structural properties and performance [49].

## 2.7. Polymers

Over recent decades, polymers have substituted traditional materials like metals, ceramics, and paper in food packaging. The growing use of synthetic polymers in this field is attributed to their advantageous properties, including lightweight, ease of manufacturing, and affordability. These polymers provide all kinds of mechanical, chemical and microbial protection in the packaging process. In addition, these coatings allow the consumer to display the product. The most studied in the packaging system by using nanoparticles have been concentrated on antimicrobial activity, enzymes function, sensation and barrier properties. Additive materials have focused mainly on non-layered mineral solids such as clay and silicate due to their availability and low cost to enhance the polymers function in the packaging industry [50]. Polymers are generally categorized based on their raw material sources and manufacturing methods into two



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groups: A) natural biopolymers and B) synthetic polymers. Natural biopolymers consist of plant-based carbohydrates like starch, cellulose, chitosan, alginate, agar, carrageenan, among others, as well as proteins derived from animal or plant sources such as soy protein, corn zein, wheat gluten, gelatin, collagen, whey protein, and casein. B) Biodegradable synthetic polymers include materials like poly (L-lactide) (PLA), poly (glycolic acid) (PGA), poly (ε-caprolactone) (PCL), poly (butylene succinate) (PBS), and poly (vinyl alcohol) (PVA). Additionally, biopolymers generated through microbial fermentation consist of microbial polyesters, such as poly (hydroxy alkanoates) (PHA) including poly (β-hydroxybutyrate) (PHB) and poly (3-hydroxybutyrate-Co-3-hydroxyolate) (PHBV), as well as microbial polysaccharides like pullulan and curdlan. CNTs, SiO2, Chitin/chitosan nanoparticles and antimicrobial nanocomposites are another sort of nanomaterials in the food packaging industry. The development of new strategies to remove existing barriers and conduct research to understand the relationship between structural properties and barrier removal emphasizes the effect of nanostructures on their permeability properties. Common strategies for reinforcing barrier properties are the use of polymer compounds, the use of laminated films containing impermeable barriers, the coating of high-strength polymers, and the coating with a barrier such as aluminum foil [51]. Aluminum coatings are often applied as films for packaging containers. Various vapor deposition methods work well by inserting a thin layer of high-barrier material within layers or structural polymer coatings and multilayer systems. However, their use is constrained by the adhesion quality between the coating materials and polymers, which act as compatible fillers. Composites take advantage of their impermeability to enhance barrier performance [52].

## 3. COMPOSITES AND NANOCOMPOSITES

Composites typically comprise a polymer matrix serving as the continuous phase and a filler acting as the dispersed phase. For many years, fibers, platelets, and particles have been employed to create polymer composites with enhanced mechanical and thermal characteristics. The rise of nanotechnology has introduced nanocomposites—materials with at least one dimension under 100 nm—that offer increased strength, improved heat resistance, and superior overall performance. These nanocomposites are becoming popular in food packaging due to their excellent barrier properties, mechanical durability, and thermal stability compared to conventional polymers and composites. For instance, nanoclay montmorillonite (MMT) has been successfully applied to boost the mechanical and thermal performance of nylon. Nanocomposites enable food packaging to better endure the stresses encountered during thermal processing, transport, and storage. Additionally, their superior mechanical strength allows for thinner packaging layers, reducing the consumption of raw materials [53-56].

### 3.1. Montmorillonite Nanomaterials

Filler particles such as MMT and kaolinite nanoclays, along with carbon-based materials like CNTs and graphene nanosheets, are widely used today in polymer composites. MMT clays are made of nanometer-thick magnesium aluminum silicate platelets with diameters ranging from 100 to 500 nm, stacking in layered structures that aggregate into droplets about 8 to 10 micrometers in size. The impact of nanoclays on polymer properties mainly depends on their high surface area to volume ratio, as the polymer-filler interactions are governed by interface forces. For optimal composite properties, nanoclay platelets must be well-dispersed individually and uniformly throughout the polymer matrix [57]. When dispersed, these nanoclays create a tortuous maze-like pathway that significantly impedes the permeation of gases by forcing molecules to take longer routes, thus improving the material's barrier performance. Unlike traditional composites that require high filler content (~60% by volume), nanocomposites achieve superior property enhancements with very low filler loadings (<2% volume) [58]. Graphene nanoparticles which are carbon sheets 20 to 60 nm thick and 0.5 to 25 μm wide, dispersed in polymers such as poly(methyl methacrylate), have shown the ability to increase thermal properties like the glass transition tempera-

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ture by up to 30 °C at low loading leels (1–5 wt%). CNTs offer exceptional mechanical strength, but their use in nanocomposites is limited due to challenges in processing, dispersion, and cost. Together, nanoclays and carbon-based nano-fillers present promising technologies for creating advanced polymer nanocomposites with enhanced mechanical, thermal, and barrier properties, relevant to appli-cations including food packaging.

## 3.2. Biopolymers

Biopolymers have gained significant interest as a sustainable alternative to conventional plastic packaging. They include materials derived from plants such as starch, cellulose, and other polysaccharides and proteins, animal-derived proteins and polysaccharides, microbial products like polyhydroxybutyrate, and polymers chemically synthesized from natural monomers. Most studies on biopolymer films focus on their application as edible coatings [59-63].

Despite their promise, biopolymers generally exhibit weaker mechanical strength and barrier properties, particularly in moisture resistance due to their hydrophilic nature, limiting their industrial applications. However, incorporating nanocomposite technology has shown to enhance their mechanical, thermal, and barrier performances. Nature provides examples of nanocomposites such as mussels, which consist mainly of mineral carbonate (aragonite) combined with organic biopolymers, resulting in exceptional strength and durability. Bone tissue is another natural nanocomposite, combining mineral fibrils and hydroxyapatite, serving as a model for developing biomimetic materials [59-63]. Engineered silicate nanocomposites enhance biopolymers with improved gas barrier properties, tensile strength, and thermal stability through incorporation of nanoscale silicate platelets. Selecting appropriate polymers can create effective barriers against water, gases, and grease by forming nanometer-scale tortuous paths that inhibit penetration. Numerous studies have detailed biopolymer nanocomposites, highlighting starch for its biodegradability and availability as a widely researched food packaging material [59-63]. Efforts have focused on improving starch's properties by blending with polymers or nanoclays. Among these, starch-clay nanocomposites are the most common degradable nanocomposites used in food packaging, showing significant improvements in Young's modulus, tensile strength, and impermeability—key factors for packaging applications such as bottles. Research has demonstrated that nanocomposites exhibit lower diffusion rates than starch alone, likely due to the tortuous paths created by exfoliated montmorillonie (MMT) clay layers, which also reduce water uptake in starch films. More recently, sodium starch/ZnO-carboxymethylcellulose nanocomposites have been developed using ZnO nanoparticles stabilized by carboxymethylcellulose, further expanding functional applications [59, 64, 65].

## 3.3. Polyamine Polyacid (PLA)

PLA is a biodegradable, biocompatible polymer known for its stable compatibility, favorable mechanical strength, and optical clarity. It is primarily derived from lactic acid, a monomer readily produced by fermenting carbohydrate sources, making PLA a sustainable alternative to petroleum-based plastics. Compared to conventional oil-based plastics, PLA offers more environmentally friendly disposal options and a lower ecological footprint during production. However, its broader adoption as a packaging material remains limited due to performance and cost challenges relative to other polymers [66]. Nanotechnology has shown promise in enhancing the properties and applications of PLA composites. For example, nanocomposites of amorphous and chemically modified kaolinite with PLA exhibit improved polymer-clay interaction, leading to a significant (~50%) enhancement in oxygen barrier properties, which is beneficial for food packaging. To overcome PLA's inherent brittleness, plasticizers are often added to the system. Additionally, PLA nanocomposites incorporating layered MMT silicate have demonstrated improved barrier performance, indicating their suitability for food packaging applications [67].

## 3.4. Carbon nanotubes (CNTs)

CNTs can be made up of a single atomic layer forming single-walled nanotubes (SWNT) or multiple concentric layers known as multi-walled nanotubes


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(MWNTs). These MWNTs possess extremely high aspect ratios and elastic moduli. According to reports, CNTs exhibit theoretical elasticity modulus and tensile strength values around 1 TPa and 200 GPa, respectively [68]. In a study, CNTs were chemically modified by adding carboxylic acid groups onto their surfaces to improve bonding with the poly(ethylene-2,6-naphthalene) matrix. Even at very low loadings of 0.1% by weight, CNTs significantly enhance both the thermal and tensile stability of the composite material [69]. Research demonstrated that PLA-based nanocomposites containing CNTs can achieve a 200% improvement in water vapor transmission rates compared to pure PLA, alongside increases in modulus and toughness.

## 3.5. Starch nanocrystals

Native starch granules exhibit a slow hydrolysis rate at the low temperatures of gelatinization due to the separation of the more hydrolysis-resistant crystalline lamellae. Studies showed that incorporating starch nanocrystals (SNCs) into pullulan films enhances tensile strength and modulus, although it reduces elongation at break. Furthermore, adding 20% or more of SNCs significantly decreases the water vapor permeability of pullulan films, improving their barrier properties [70]. Another investigation reported that incorporating SNCs into polyvinyl alcohol matrices subtly enhances tensile strength and stiffness up to 10 wt% loading. Comparatively, SNCs demonstrate better dispersion and stronger interfacial interactions with polyvinyl alcohol than native starch granules, thus leading to superior mechanical properties in the composites. These advantageous effects position starch nanocrystals as promising reinforcing agents for biodegradable polymer films in food packaging applications, where improved strength and moisture barrier properties are essential [71].

## 3.6. Chitin/chitosan nanoparticles

A group of researchers produced chitin whiskers through acid hydrolysis of chitin. The whiskers prepared by a researcher measured approximately 500 nm in length and 50 nm in diameter, while those from other study were about 417 nm long and 33 nm in diameter. Another study incorporated these chitin whiskers into isolated soy protein (SPI) thermoplastics and found that the whiskers not only improved the tensile strength of the matrix but also significantly enhanced its water resistance [72]. Chitosan nanoparticles can be synthesized via ionic gelation, where the positively charged amino groups of chitosan interact electrostatically with polyanion crosslinkers such as tripolyphosphate. De Mora et al. developed chitosan-tripolyphosphate (CS-TPP) nanoparticles and embedded them into hydroxypropyl methylcellulose (HPMC) films. The addition of CS-TPP nanoparticles notably enhanced the mechanical properties and barrier performance of the films, with improvements attributed to the dispersed nanoparticles creating discontinuities within the HPMC matrix [73-77].

## 3.7. Protein nanocomposites

The capacity to form films from various proteins has long been exploited in industrial settings. Animal-derived proteins commonly used commercially include casein, whey protein, collagen, egg white, and fish myofibrillar proteins. Plant-derived proteins of interest feature soy protein, zein (corn protein), and wheat gluten. Protein-based films generally offer superior oxygen barrier properties compared to polysaccharide films due to their polarity, linear structure, and lower free volume, which also contribute to reduced water vapor permeability [78]. Nevertheless, significant challenges in food packaging remain, such as proteins' high modulus, substantial water absorption, and elevated gas permeability. Nanocomposite technology has been applied extensively to enhance these properties. Whey protein, in particular, has garnered attention for use as edible films and coatings. Clear whey protein films form effective oxygen barriers. Incorporated $TiO_2$ into whey protein nanocomposites, introducing antimicrobial properties and highlighting potential for food-grade, biodegradable packaging materials. Similar studies explored ZnO-whey protein nanocomposites and their interactions [79]. Soy protein has been researched due to its thermoplastic nature and potential for biodegradable plastics, though its sensitivity to moisture and high strength limits its practical degradability. Combining soy protein with starch and

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plasticizers improves brittleness but often reduces barrier properties. Nevertheless, soy protein nanocomposite films have shown reduced water vapor permeability and improved modulus and tensile strength compared to films without fillers. Din and Yu observed tensile strength increases of 23% without and 47% with ultrasonic treatment in soy protein nanocomposites. Studies by Chen and colleagues indicate that the interaction between positively charged soy protein and negatively charged MMT layers involves hydrogen bonding between –NH groups and Si–O, strengthening the nanocomposite's mechanical properties [80]. Corn zein is a relatively hydrophobic protein naturally forming films in corn kernels. It is employed in the food industry as a coating and biodegradable material. Despite being less sensitive to moisture than other biopolymers, corn zein still exhibits high water vapor permeability and lower tensile strength relative to conventional polymers. Nanocomposites of corn zein using kaolin nanoclays as barrier coatings impart beneficial properties when applied to paper and cardboard and are considered promising alternatives to fluorocarbon barrier coatings in extruded polymers [81, 82].

## 4. ANTIMICROBIAL PROPERTIES OF BIO-NANOCOMPOSITES

Antimicrobial nanomaterials play a central role in active packaging because their high surface-to-volume ratio and increased surface reactivity enhance their ability to combat microbes. Typically, antimicrobial nanocomposites include metal ions such as silver, copper, gold, and platinum, alongside metal oxides like $TiO_2$, ZnO, and MgO. Organically modified nanoclays can also be added to improve both the antimicrobial activity and barrier performance of packaging materials [83, 84]. These nanomaterials can be integrated within the polymer matrix, grafted onto the packaging surface, or applied as coatings. Their controlled release and surface interactions enable prolonged antimicrobial activity, thereby extending the shelf life of food products. The strong antimicrobial performance arises from mechanisms including generation of reactive oxygen species, membrane disruption, and sustained release of antimicrobial agents. Combinations of natural antimicrobials with nanomaterials, such as chitosan and poly-ε-lysine, can synergistically improve efficacy and reduce preservative doses. Furthermore, nanostructured materials like electrospun nanofibers offer large surface areas for incorporating bioactive compounds, creating high-performance antimicrobial packaging films. Current commercialized nano food packaging in the world market [83, 84].

## 5. MIGRATION OF NANOPARTICLES IN FOODS AND IMPACT ON HUMAN HEALTH

Consumer exposure to NPs from food packaging mainly results from the possible migration of these particles into food and beverages. Although various NP-containing food packaging products are commercially available in some regions, there is limited experimental evidence on the extent of NP migration. Dispersed functionalized layered MMT nanoparticles in different thermoplastic starch matrices, including pure potato starch and blends of potato starch with biodegradable polyester, using polymer melt processing has been reported. To comply with European regulations on biodegradable materials, migration tests were carried out. Small pieces of vegetables, such as lettuce and spinach, were packed in bags and subjected to contact tests. These sealed bags were heated at 40°C for 10 days in an electric oven and then cooled gradually to room temperature for analysis [85-88]. The vegetable samples underwent digestion by heating at 105°C until weight stabilization, followed by carbonization at 550°C in a muffle furnace for several hours. After cooling, the ashes were dissolved in hydrochloric acid, heated, filtered, and the filtrates were analyzed by atomic absorption spectroscopy to measure Si, Fe, and Mg release. The test results showed negligible changes in Fe and Mg but a consistent rise in Si, the primary element in MMT nanoparticles, indicating NP migration. Despite this, migration studies in food contact materials remain limited due to the challenges in characterizing NPs within composites and the lack of reliable qualitative and quantitative methods [89, 90]. Public concern over NP migration has grown alongside toxicity studies using animal oral exposure and in vitro cellular models. Two mechanisms explain NP toxicity in humans: one is NP-


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independent toxicity driven by the production of reactive oxygen species (ROS) inside cells; the other is NP-dependent toxicity, influenced by the nanoparticle's chemical makeup. For instance, metal or metal oxide NPs can modify protein secondary or tertiary structures via crystallization processes. Additionally, metal alloys and CNTs (single-wall and multi-wall) can induce direct or indirect genotoxic effects [89, 90]. The toxic impact also varies with NP chemical composition. Insoluble nanoparticles like $TiO_2$, ZnO, and $SiO_2$ may impair gastrointestinal functions and potentially worsen conditions such as irritable bowel syndrome and Crohn's disease, though their role in disease initiation remains unclear. These nanoparticles can adsorb calcium ions and lipopolysaccharides post-absorption in the GI tract, forming conjugates that activate usually resistant immune cells, including peripheral blood mononuclear cells and intestinal phagocytes. Certain metal or metal oxide NPs (Fe/Pt alloy, Co/Cr alloy, ZnO, $SiO_2$, $TiO_2$) as well as CNTs display both direct and indirect genotoxicity. Studies have shown that smaller $TiO_2$ and Carbon Black particles (~20 nm) cause DNA damage, while larger particles (~200 nm) do not, emphasizing particle size as a key factor in toxicity.

## 6. ENVIRONMENTAL FRIENDLY FOOD NANO PACKAGING

Currently, most food packaging materials are essentially non-biodegradable, posing a significant environmental challenge worldwide. Edible and biodegradable films have been developed as a key solution to extend food shelf life and improve quality while minimizing packaging waste. Nonetheless, the use of edible and biodegradable polymers is limited by issues such as brittleness, poor gas and moisture barrier properties, processing difficulties like low heat distortion resistance, and higher costs. For instance, starch has drawn significant interest as a biodegradable material, but thermoplastic starch-based polymers perform poorly because of water sensitivity and weak mechanical strength, with brittleness linked to irregular amylose crystallization [92]. Advantages and disadvantages of Ag, Cu, and clay in packaging vary. Silver nano-packaging offers strong antimicrobial properties, enhancing food safety and shelf life, though it increases costs. Copper provides antimicrobial effects at a lower cost but may have stability issues. Clay improves mechanical strength and barrier functions affordably but lacks inherent antimicrobial activity. Silver nanoparticle packaging benefits include effective microbial control, extended shelf life, and improved product bioavailability. Although more expensive, these advantages can justify higher marketing prices by enhancing consumer appeal and product durability [93]. Table 1 shows antimicrobial application of bio-nanocomposites in food packaging.

In Table 2 migration and antimicrobial properties of nanosilver, nanocopper, and nanoclay particles in food packaging, have been listed [94-111].

Nanoliposomes are also another category of nanomaterials with wide application in food sectors [112-116]. These carriers have emerged as versatile encapsulation systems for bioactive compounds in food matrices, with demonstrated applications in cheese technology including ripening acceleration, fortification, and shelf-life extension. Foundational work on liposome-derived nanocarriers and nano-liposome encapsulation methods has established the technological basis for these food applications. Scaling nanoliposome production under food-grade conditions while ensuring physical stability in complex dairy matrices and navigating regulatory frameworks for nanomaterial-enabled foods will be critical for translating these laboratory advances into commercial cheese manufacturing.

## 7. CONCLUSION

To effectively implement nanotechnology in the food packaging sector, it is essential to understand the various materials involved and their specific properties. Additionally, understanding how these materials enhance packaging by improving transfer processes and minimizing risk factors during long-term food storage is important. Employing optimized nanoparticle production techniques and improving food monitoring systems will help alleviate consumer concerns regarding the quality of packaged food.

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Table 1. Different types of antimicrobial bio-nanocomposites in food packaging (source with modification: R. Sharma, et al. (2020)

| Type of bio-nanocomposite | Food product | Antimicrobial Results |
|---|---|---|
| PLA/ZnO:Cu/Ag | Food simulant: (distilled water) – simulant A, ethanol 10% (v/v) in aqueous solution – simulant B and acetic acid 3% (w/v) in aqueous solution – simulant C | Good mechanical, thermal and barrier properties to ultraviolet light, water vapor, oxygen and $CO_2$; Antibacterial activity and low migration of nanoparticles into food simulants. |
| Starch/halloysite/nisin | Soft cheese | Improved mechanical properties with halloysite addition; Antimicrobial activity against *L. monocytogenes*, *Clostridium perfringens*, and *S. aureus* |
| Low-density polyethylene (LDPE)/Ag, ZnO | Orange juice | A significant decrease of the yeast and mold counts without disrupting juice relevant quality attributes; Significant reduction in growth rate of *Lactobacillus plantarum* |
| PE/Ag, TiO2, kaolin | Chinese jujube | Firmer, heavier, less decay, less browning, slower ripening, decrease in senescence and climacteric evolution |
| Cellulose absorber/Cu | Melon and pineapple juices | Excellent antifungal activity, reducing spoilage-related yeasts and molds |
| Absorbent pad/Ag | Poultry meat | Confirmed antimicrobial effect against *E. coli* and *S. aureus* |
| Allyl isothiocyanate, nisin/ZnO | Liquid egg albumen | Effective inactivation of *Salmonella* |
| Absorber/Ag | Kiwi and melon juices | Reduced counts of total viable microorganisms, yeasts and molds |
| PE/Ag | Apple juice | High bactericide capacity against *Alicyclobacillus acidoterrestris* |
| Pectin/nanohybrid-layered double-hydroxide salicylate | Fresh apricot | Improved elongation at break point for pectin; Improved water vapor barrier properties; Extended shelf life |
| Corn starch/talc NPs | Tomato | Reduction in water vapor and oxygen permeability |
| Gelatin/ethanolic extract from coconut husk/Cloisite Na + nanoclay | Meat powder | Lower lipid oxidation products; Increased moisture barrier properties; Extended shelf life |
| Nano-ZnO–neem oil –chitosan | Carrot | Good inhibition effect as antibacterial activity against *E. coli* |
| Poly(glycidyl methacrylate covinyl ferrocene)/ graphene oxide/iron oxide NPs, and poly(glycidyl methacrylate-covinylferrocene)/MWCNT | Fish | Fish meat freshness control |
| Alginate/nano-Ag | Shiitake mushroom | Spoilage reduction, improvement of sensory attributes, lower weight loss |
| Sodium alginate solution containing Ag NPs | Carrot and pear | Antibacterial film effective against the test strains, *E. coli* ATCC 8739 and *S. aureus* ATCC 6538; Shelf life increase of carrots and pears |
| Calcium alginate film loaded with ZnO NPs | Ready-to-eat poultry meat | Reduction of microbial load of *Salmonella typhimurium* and *E. coli* |
| Nanoemulsion coating of chitosan and mandarin essential oil | Green beans | Reduction in the population of *L. monocytogenes* |
| Chitosan/poly(vinyl alcohol)/Ti NPs | Soft white cheese | Antibacterial activity against Gram+ (*S. aureus*), Gram- (*Pseudomonas aeruginosa*, *E. coli*) bacteria and fungi (*Candidia albicans*); Extension in shelf life |
| Whey protein isolate (WPI)/MMT | Food models (water, 3% acetic acid, 15% ethanol, olive oil) | Increased tensile strength of the WPI film and swelling of the WPI film |

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| | | |
|---|---|---|
| Silver NPs-based cellulose absorbent pads | Beef meat | Reduction in the population of total aerobic bacteria, *Pseudomonas spp.* and *Enterobacteriaceae* |
| Soy protein isolate– MMT | Fresh fruits and vegetables | Improvement in mechanical properties, thermal stability, and water vapor permeability with the addition of MMT |
| Silver NPs-based cellulose absorbent pads | Fresh-cut melons | Retarding the senescence rate of the fresh-cut melons; Reduction in antibacterial activity |
| Edible coating of Polyvinyl pyrrolidone (PVP) containing Ag NPs | Asparagus | Inhibiting the growth of psychrotrophic microorganisms; Lowering weight loss, greener color, and tender textures |
| Nano-ZnO coated poly(vinyl chloride) | Fresh-cut‘ Fuji ’ apples | Preservation of quality indicators such as ascorbic acid and polyphenol content; Lower counts of typical altering microorganisms |
| Thyme essential oil (TEO) and MMT based sweet potato starch films | Baby spinach leaves | Incorporation of TEO in the film reduced the population of *E. coli* and *S. Typhi* on fresh baby spinach leaves |
| LDPE/Ag, TiO2, kaolin | Strawberry | Decelerated decay rate |
| LDPE/Ag2O | Apple slice | Decreased microbial spoilage, delayed browning and weight loss |

Table 2. Literature review of application of nanosilver, nanocopper, and nanoclay particles in food packaging, focusing on their migration and antimicrobial properties.

| Antimicrobial activity results | Antimicrobial activity assay | Migration results | Migration test conditions | Analytical techniques | Preparation method | Nanoparticle size | Nanomaterial | Ref. |
|---|---|---|---|---|---|---|---|---|
| Increase in inhibition of QS in *Chrobacterium violaceum* Inhibition of biofilm formation by ATNPs at 20 µg/ml | Disc diffusion assay for measuring Anti-quorom sensing activity of ATNPs (100-500 µg/ml) | _____ | _____ | SEM | low-temperature-based one-pot sol-gel method | 6-7 nm | AgCl- TiO2 NPs (ATNPs) | [94] |
| Ag and ZnO: high antibacterial activity against *S. aureus* and *E.coli* CuO: antibacterial activity against *E. coli* | Agar diffusion method | _____ | _____ | SEM, EDXA, WVP, UV–Vis, and tensile tests | Solution casting method | ZnO: 20-30 nm CuO: 35 nm Ag: <50 nm | carboxymethyl cellulose (CMC) nanobiocomposites containing metal nanoparticles (ZnO, CuO, and Ag | [95] |
| _____ | _____ | Ag migration in 3% acetic acid: 1.70, 3.0 & 5.6 % at 20, 40 and 70 °C. , Ag migration in 95% aqueous ethanol: 0.24, 0.23 & 0.22 % at 20, 40 & 70 °C | 20 °C 40 °C 70 °C All for 1, 2, 3, 4, 5, 6, 7, 8 and 9 h. | ICP-MS | nanosilver–polyethylene composite food packaging film was purchased from Anson Nanotechnology Co., Ltd (Zhuhai, China) | 7 nm | Nanosilver-polyethylene composite | [96] |
| Intense antimicrobial properties against *E.coli* and *S. aureus* by polyethylene nano- | Japanese Industrial Standard (JIS) method | _____ | _____ | SEM, XRD, TGA, FTIR, DSC | Extrusion method | Not mentioned by the authors | Low-density polyethylene (LDPE) film containing AgNPs | [97] |

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|---|---|---|---|---|---|---|---|---|
| composites containing AgNPs Maximum inhibition of *E.coli* at 0.5g AgNPs with 12 wt% NC. Maximum inhibition of *S. aureus* at 0.3 g Ag NPs for 16 wt% NC. Highest anti-bacterial activity for *E. coli* | Disc diffusion method | ——— | ——— | SEM, EDX, FTIR, TGA, XRD, MRC, WVTR | Solution casting method | Not mentioned by the authors | PVA nanocomposite films containing nanocellulose (NC) and AgNPs | [98] |
| Strong antimicrobial activity against the *E. coli* and *S. aureus* | Agar disk diffusion method | ——— | ——— | SEM, XRD, FTIR, WVTR | Green synthesis method from the *Digitalis purpurea* plant | Not mentioned by the authors | Carrageenan/ AgNPs/Laponite nanocomposite | [99] |
| Bags containing AgNPs had no effect on levels of the three types of spoilage bacteria including TMC, Enterobacteriaceae and Pseudomonas spp. | Total microbial count (CFU) | No silver migration into chicken meat | EU regulation 10/2011 | SEM, ICP-MS, AAS, EDS | FreshLonger™ Plastic Storage bags contained AgNPs, and produced by Sharper Image Corporation (San Francisco, CA, USA) were purchased | 20 nm | AgNPs | [100] |
| The cell load of *Pseudomonas aeruginosa* in CuNPs- C-PLA sample was lower (6.0 Log CFU/m l) than blank PLA sample (7.4 Log CFU/ml) | JIS method | The release kinetics of Cu from CuNPs-C-PLA nano-composite was described according to 1st order kinetic profile | Copper release from the nanocomposites into an aqueous contact solution was carried out by atomic absorption analyses 24h after putting coating in saline solution | TEM, UV–Vis, XPS, ETAAS | Pulsed laser ablation | Not mentioned by the authors | Copper nanoparticles (CuNPs) embedded in PLA (CuNPs-PLA) | [101] |
| The CNW (0.5%)-SA (3%)-CuO NPs (5 mM) films showed the higher zone of inhibition against *S. aureus*, *E. coli*, *Salmonella spp.*, *C. albicans* and *Trichoderma spp* | Disc diffusion method | ——— | ——— | SEM, FTIR, EDS, XRD | The antibacterial polymeric film (APF) were prepared by using the three types of the components such as CuONPs, SA and CNW at different ratios | Not mentioned by the authors | Biopolymeric films (SA-CNW-CuNPs) containing cellulose, sodium alginate and copper oxide nanoparticles | [102] |

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|---|---|---|---|---|---|---|---|---|
| The nanocomposite films with CuONPs exhibited strong antibacterial activity against food-borne pathogenic bacteria, *L. monocytogenes,* and *E. coli*. | Total microbial count (CFU) | ——— | ——— | SEM, FTIR, XRD, UV-Vis, WVP | Solvent casting method | Not mentioned by the authors | Carbohydrate-based composite films incorporated with CuONPs | [103] |
| The CuNPs in HPMC suspension had high antibacterial activity against Gram+, but not against G-bacteria | Disk diffusion method | ——— | ——— | SEM, XRD, WVP | Chemical reduction method | 30 nm | Cu/HPMC bionanocomposites (hydroxypropyl methylcellulose (HPMC) matrix incorporated with CuNPs)) | [104] |
| ——— | ——— | The presence of the nanoclay produced a decrease in the HT release from films | Evaluation of the release rate of HT from the film for samples immersed in methanol. The extracts were analyzed by UV-Vis spectroscopy | DSC, TGA, SEM, TEM, XRD | Melt blending | Not mentioned by the authors | Poly (ε-caprolactone)-based nanocomposites containing Hydroxytyrosol (HT) and cloisite30B (nanoclay) | [55] |
| ——— | ——— | Organoclay and ZnONPs could hinder the release of styrene monomers from nanocomposites to food simulants | 5 °C for 10 days, 40 °C for 24h, 100 °C for 30 min | AFM, GC-FID | Melt mixing | 20 nm | Polystyrene nanocomposites containing organoclay and ZnONPs | [105] |
| ——— | ——— | Presence of nano-clay accelerated in degradation of the LDPE and enhanced the release of clay particles | Ultraviolet (UV) irradiation and low concentration of ozone at 40 °C | XRD, TGA, CL, FTIR, AFM, SEM, TEM, ICP-OES | Spherilene technology | 2-8 nm | Nano-clay-loaded low-density polyethylene (LDPE) composite | [106] |
| ——— | ——— | Migration value of nanoclay from LDPE into acetic acid 3% for 10 days at 40 °C was higher than ethanol 10% | EU regulation 10/2011 40 °C for 10 days and 70 °C for 2h | ICP-MS, SEM-EDX | Debbie Meyer BreadBags and Aisaika Everfresh Bag as two models of Nanoclay food containers were studied | Variable | LDPE nanocomposite | [107] |
| The silver-based nanoclay showed strong antimicrobial activity | Total microbial count (CFU) | Migration of Ag found within the specific migration | The norm UNE-ENV 13130-1 | WAXS, TEM, DSC, WVP | Solution-casting method | 20 nm | PLA biocomposites containing silver-based nanoclay | [108] |

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| against Gram-*Salmonella spp*. | | levels referenced by EFSA† | | | | | | |
| _____ | _____ | Lactic acid migration in 50% ethanol <former generic specific migration limit of 60 mg/kg food (10 mg/dm2) of the Reg. EU 10/2011 | EU regulation 10/2011 | TEM, DSC, XRD, WVTR, SEM | Blown film co-extrusion | Not mentioned by the authors | PLA/clay nanocomposite | [109] |
| _____ | _____ | The migration of PP-Clay was 0.0±0.4 and 2.0±0.4 mg/dm², with no differences to controls. Migration rate <established by the EU regulation | European Standard UNE-EN 1186 | TGA, FTIR, WAXD, ICP-MS | Extrusion method | Not mentioned by the authors | Nanocomposites of polypropylene (PP) + Clay | [110] |
| The cassava starch films incorporated with Na-bentonite and cinnamon oil: significant Antibacterial potential against *E. coli*, *S. typhimurium and S. aureus*. | MIC | _____ | _____ | Film thickness, WVP, TS | Solution-casting method | Not mentioned by the authors | Cassava starch films incorporated with cinnamon essential oil and sodium bentonite clay nanoparticles | [111] |

†European Food Safety Agency

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## 8. DECLARATION STATEMENTS

### 8.1. Funding

None.

### 8.2. Ethics and Consent to Participate

Not applicable. This article is a review of previously published literature and involved no human participants, animals, or identifiable personal data.

### 8.3. Data Availability

datasets were generated or analysed. The literature sources supporting this review are cited in the reference list.

### 8.4. Competing Interest

The authors declare that they have no competing interests.

### 8.5. Authors' Contribution

All authors have made substantial contributions to the conception and design of the study, data collection, analysis, interpretation of results, and manuscript preparation. All authors have read and approved the final manuscript and agree to be accountable for the integrity and originality of the work.

### 8.6. Declaration of Generative AI

Artificial Intelligence (AI) chatbots were used solely to improve the language, grammar, spelling, and clarity of the manuscript. The authors reviewed, edited, and verified all AI-assisted text and take full responsibility for the accuracy, originality, and final content of the manuscript.

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