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Applications of Nanomaterials on a Food Packaging System—A Review †

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Abstract: In recent years, there has been a significant focus on replacing non-biodegradable materials with eco-friendly biodegradable food packaging materials. The use of biopolymers in packaged foods has been adopted to address environmental issues, given their ability to decompose naturally and being non-hazardous. Despite these benefits, biopolymers present notable drawbacks such as inadequate mechanical strength and restricted ability to withstand water. Over the past two decades, nanotechnology has been increasingly investigated for use in food packaging due to its remarkable qualities. This review article aims to give a summary of the most recent research on the new advancement of nanomaterials for food packaging.

Keywords: nanomaterials; food; packaging; shelf life; nanoparticles; nanotechnology; films

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1. Introduction

Over the past decade, the global trade has led to an increase in the risk of food contamination by disease-causing agents, such as fungi, viruses, and bacteria. This has become a significant concern for food safety worldwide. According to the World Health Organization (WHO), in 2020 alone, foodborne illnesses affected an estimated 600 million people and caused 420,000 deaths [1]. Therefore, it is crucial to explore new techniques to minimize the risk of foodborne diseases. Using food packaging is among the most successful strategies for achieving this goal. In order to improve usability, elasticity, storage stability, aesthetics, sensory attributes' feature, and prevention from chemical as well as microbiological pollutants, food packaging is used throughout the food supply chain. Physical and chemical alterations in water content, colour, taste, mass, bioavailability, and texture were also reduced.

The manufacture, characterization, modelling, and use of nanoparticles (NPs), which seem to be composite innovations with such a size category as around 1 to 100 nanometres, are all elements of the topic of nanoscale study. Many NPs have radically distinct characteristics compared to quantitative substances when the particle dimension falls along with the predefined threshold. Nanostructures also have different physical, chemical, and optical properties. Casein micelles and pectin nanostructures, two examples of naturally occurring nanomaterials, may be found in both plants and animals. Nonetheless, the food business has created synthetic nanoparticles for a variety of applications. As an example, the development of nanometre salt grains was aimed at reducing salt intake by increasing the surface area, thereby providing the same savoury taste with a smaller amount of salt to humans [2]. Nanomaterials are also employed to encapsulate vitamins or minerals, acting as carriers to enable the transmission of vitamins through the bloodstream via nanocapsules [3,4]. By possessing strong mechanical, heat resistance, and barrier properties, nanomaterials help maintain food quality during transport, prolong the freshness of fruits and vegetables during storage, and safeguard meat and poultry against harmful pathogens [5]. Figure 1 shows the benefits of nanomaterials on food packaging applications.

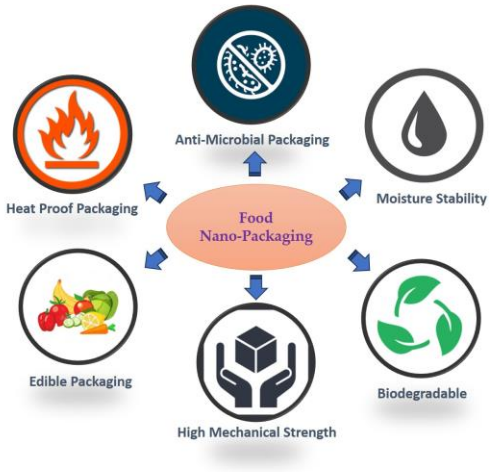

Figure 1. Schematic representation of nanomaterials for food packaging application.

The article provides an extensive scope by exploring the many ways that nanoparticles are used in food processing. It explores issues including improving barrier qualities, antimicrobial capabilities, and intelligent packaging capabilities made possible with nanotechnology [6]. Additionally, the essay discusses environmental effects, regulatory issues, and gives case examples to demonstrate practical uses. The importance of nanoparticles in expanding the range of options for bettering the packaging of food in terms of protection, preservation, and long-term viability is emphasized as it draws to a close [7]. Therefore, nanomaterials represent a promising solution for additives to improve the polymeric properties of food packaging materials.

2. Applications of Nanoparticles in Food Packaging Systems

2.1. Nanoclay

Nanocomposites were the first nanostructure to become an option for polymeric composites, which continue to be more frequently the substance for use in food products [8,9]. Because of its affordability, relatively inexpensive cost, and processing simplicity, in addition to its excellent stability and non-toxicity, which considerably improve the characteristics of the final composite, nanoclay is commonly used in the development of nanomaterials with polymers. The clay nanomaterial montmorillonite (MMT), which is generated from volcanic or rock ash, is frequently utilised in nanocomposites for food packaging. The silicon dioxide tetrahedral layers form in montmorillonite clay particles being sandwiched by an octahedral film of aluminium or magnesium hydroxide [10,11]. Since MMT is made from volcanic debris and rocks, it is a product that is both readily available and reasonably priced [12]. In order to attain a large surface area (more than 750 m^2/g), nanoclay is made of a cluster of granules with a reduced exposed surface that may be uniformly distributed and sandwiched into the polymerization. Composites that include nanoclay are resistant to the penetration of gases and other contaminants [13,14].

The overall proportion and volumetric percent of the clay filler, in addition to their level of alignment and dispersal, all affect how well nanomaterials function in regards to resistance. Exfoliated nanoparticles are more useful as barriers in packing than traditional food packaging [15,16]. According to experiments, adding nanoclay to beer cans can extend beer storage from 77 to 210 days [17]. By using nanoclays in nylons and plastic bottles, packing is thickened, gas penetration is decreased, and the expiry date of goods that are susceptible to oxygen exposure is increased [18,19]. Recently, it was proposed to use a nanocomposite material for walnut packing that contains 3% nanoclay, which significantly improves the resilience to methane intrusion [20].

Nanoclay has emerged as a promising material for food processing due to its ability to improve the physical and mechanical properties of food products [21]. The incorporation of nanoclay into food processing has shown potential for enhancing food quality, extending shelf life, and reducing spoilage [22]. The use of nanoclay in food processing has the potential to improve food safety and reduce the risk of foodborne illnesses by inhibiting the growth of microorganisms. Nanoclay-based materials can also be used to develop sustainable and eco-friendly food packaging and processing solutions, reducing the environmental impact of food production and consumption.

2.2. Silver Nanoparticles

The food industry has been paying close attention to the development of antimicrobial composite packaging films due to the rising demand for safe and high-quality food products [23,24]. Silver, which is a transition metal with high thermal and electrical conductivity, has been recognized for its antimicrobial properties and has been used in medicine to treat infections. Antibacterial food packaging is designed to release biocidal chemicals that enhance food quality, prevent spoilage, and extend shelf life [11]. Among various inorganic nanomaterials, AgNPs are widely used in food packaging technology to provide antibacterial properties for products such as fresh fruits, fresh meats, and consumer goods. Due to its ability to inhibit a wide range of microorganisms, nano-silver is extensively used as a disinfectant solution and detergent in dry-cleaning. It exhibits a potent antimicrobial effect against multiple strains of bacteria, including drug-resistant ones. Silver nanoparticles possess a broad spectrum of antibacterial properties and can be lethal to various microorganisms, such as bacteria, algae, fungi, and potentially some viruses.

The author of [25] demonstrated that silver nanoparticles can hinder the growth of microorganisms, and they also have the ability to increase the shelf life of meat. The effectiveness of the silver nanoparticles in eliminating microorganisms is heavily reliant on their particle size. The most effective antibacterial action is observed in silver nanoparticles that are not clumped together and are evenly distributed, with a size ranging from 1 to 10 nm and a large surface area that can release ionic Ag. Silver nanoparticles, which are typically used for sterilization, have antimicrobial, anti-yeast, anti-fungal, and antiviral properties because they have a larger surface area per unit mass than bulk silver particles or micro-scale silver content. Recent studies indicate that the integration of AgNPs and ZnO-NPs into low-density polyethylene (LDPE) can effectively prolong the shelf life of orange juice [26]. The resulting active nanocomposite, when combined with heat treatment, has demonstrated exceptional antimicrobial properties.

2.3. Zinc Oxide

The food industry is making extensive use of zno nanoparticles (zinc oxide) as just a supply of zinc, a necessary element that is necessary for development as well as growth. The Food and Drug Administration has designated it as a generally recognised as safe (GRAS) substance. ZnO nanoparticles are an illustration of an inorganic metal oxide, which is produced in a manufacturing environment using physical vapour or thermomechanical techniques. Several synthesis methods have been employed to produce ZnO nanoparticles, including chemical reactions using various precursors, as well as thermal decomposition, precipitation, and hydrothermal techniques. Due to its antimicrobial properties, UV blocking capabilities, and lower cost compared to Ag nanoparticles, the use of ZnO nanoparticles in safe food packaging has increased significantly. Research suggests that ZnO nanostructures exhibit superior antimicrobial activity against *E. coli*, Bacillus atrophaeus, and Salmonella aureus when compared to other metal oxides [27]. ZnO-NPs are a particularly appealing option for use in packaging applications when compared to AgNPs due to their lower toxicity to humans and animals and lower cost. ZnO nanoparticles possess a high surface-to-volume ratio, electrical conductivity, optical transparency, and direct contact with the bacterial cell wall, allowing for the superior destruction of bacterial cells compared to their micro- or macro-scale counterparts [28].

2.4. Titanium NPs

According to their physiochemical properties and barrier properties, titanium dioxide nanoparticles (TiO_2-NPs) are a thoroughly researched and valued metal oxide nanomaterial. Moreover, TiO_2-NPs can alter the characteristics of renewable materials and have a number of benefits, such as cost, non-toxicity, and photostability. In several energy-related and environmental domains, such as air and water purification, control applications, self-cleaning interfaces, and water electrolysis, these nanoparticles have been employed more and more as a stronger photocatalytic material. TiO_2-NPs have attracted a lot of interest in the food packaging market because of strong antibacterial properties.

Being exposed to ultraviolet (UV) rays, TiO_2-NPs exhibit antibacterial capabilities and produce reactive oxygen compounds, which can kill germs [29]. TiO_2 can also boost the mechanical qualities of polymer nanocomposites when used as nano-additives. In order to create three main sheets for packing bread, synthesised nanocomposites of TiO_2, Ag-TiO_2, and Ag-TiO_2-zeolite are used. A variety of nutritional indicators, including amino acids, fat oxidation, and carbs, along with acidity and increases in moulds and yeasts, were studied in order to determine the usefulness of nanocomposites in the stabilization of bread [30].

2.5. Copper and Copper Oxide

Many studies have been conducted on the antibacterial characteristics of copper-based nanoparticles, including copper nanoparticles (CuNPs) and copper oxide nanoparticles (CuO-NPs). CuO-NPs have received a lot of attention from researchers and are widely recognised for their capacity to stop a variety of bacteria from growing. This is because their broad surface energy enables more contact with bacteria's cell membranes. CuO-NPs have been used in a variety of industries, including biological devices, renewable energy, and food engineering. Copper-based nanoparticles have been used in a variety of fields in addition to their antibacterial capabilities, including sensing applications, enzymes, environmental cleaning agents, packaging for food, electronics, magnetized storage media, and photovoltaic panels.

CuO-NPs can also increase the mechanical and barrier qualities of packing materials, according to research. CuO-NPs can enhance the tensile strength, elongation at break, and water vapour barrier qualities of packaging films [31]. In addition, it has been suggested that CuO-NPs have antioxidant capabilities that might aid in stopping lipid oxidation and increase the shelf life of food goods [32]. It is crucial to remember that CuO-NPs' toxicity remains an area of risk, particularly with regard to prolonged exposure. CuO-NPs should indeed only be used in situations where appropriate safety precautions and laws are in place.

2.6. Nano-Silica

Nano-silica is widely used in waterproof coverings, particularly for self-cleaning technologies. It can make food within bottles or containers available whenever placed in a non-adhesive covering. In a study by one of the authors, a great aquaphobic posterboard was developed by coating Aerosil® (Evonik, Wesseling, Germany) silica nanoparticles. The nanosized silica created a lotus-like surface, which showed a remarkable capability of water resistance. Rice husk, an agricultural byproduct containing silica and carbon, has also been used to synthesize hybrid nanomaterials. The size of the silica nanoparticles has an impact on the properties of composites, with smaller nanoparticles leading to better results. Additionally, it was found that a small concentration of SiO_2 produces better outcomes than a larger concentration.

In addition to hydrophobic coatings, nano-silica has also been used as a reinforcement agent in polymer composites due to its high surface area and ability to improve mechanical properties [26]. The addition of nano-silica can improve the tensile strength, elongation at break, and thermal stability of the composite material. Furthermore, nano-silica has been investigated for its potential as an antimicrobial agent in food packaging. Studies have shown that nano-silica can inhibit the growth of bacteria such as *E. coli* and *S. aureus*, and can also improve the barrier properties of packaging material, leading to the better preservation of food products [33]. Overall, the versatility and multifunctional properties of nano-silica make it a promising material for various applications in the field of food packaging and beyond.

2.7. Nano-Starch

Medicine and food packages, in addition to the fabrication of papers, elastomers, and resins, all employ starch as a common ingredient. Its popularity is due to several factors, including its low cost, non-toxicity to humans and animals, environmental friendliness, and abundance. Starch can exist in two forms, linear amylose and branched amylopectin, as identified. The crystalline structure of starch must be extracted using mixtures of amorphous as well as crystalline starch in order to produce nano-starch. Investigators utilized a number of methods to separate amylose from starches, including mechanical micro-fluidizer treatment, acid hydrolysis, precipitation, and enzyme hydrolysis.

Starch nano-crystals have advantages over manufactured emulsion latex that come naturally to them. Some modifiers can be applied to starch films to lessen brittleness, although the barrier as well as mechanical qualities of these films are influenced by water contents [34]. Acid hydrolysis is the process of soaking starch at a temperature less than its gelation threshold in a weak acid. The crystal areas of the starches are degraded relatively slowly compared to just the amorphous portions, making them the targets of the weak acid. In the end, a virtually pure crystalline residue is obtained and applied to nanoscale platelets' implantation. Despite their substantial vulnerability to dehydration, starch nano-crystals have already shown promise as useful fillers for flexible food containers because they are able to enhance both mechanical and barrier qualities [35]. As natural and inexpensive binders, starch nano-crystals are appealing as a potential replacement for synthetic emulsion latex. The starch-based nano-biopolymer binder may indeed be made by using cationic starch, which is frequently used in surface coatings to various synthetic dry toughness polymers. A summary of various nanoparticle applications in food packaging materials is shown in Table 1.

Table 1. Summary of various nanoparticle applications in food packaging materials.

Nanoparticles	Applications	Results	References
Nanoclay	Beer cans	Extended the beer's storage period	[35]
	Walnut	Increased the shelf life of walnut kernel	[20]
Silver	Broiler meat	Maintains quality and shelf life	[36]
	Orange juice	Integration of AgNPs in LDPE prolongs the shelf life	[26]
Zinc	Antimicrobial	Antimicrobial activity against *E. coli* and *B. atrophaeus*	[27]
	Antibacterial	Destruction of food bacterial cells	[28]
Titanium	Active films	Ethylene scavenging activity to the active film	[29]
	Bread packing	Increased rye bread shelf life	[30]
Copper Oxide	Edible coating	Achieved excellent barrier properties	[37]
	Antioxidant	Improved the quality of guava	[32]
Nano-silica	Grapes	Reduced the decay percentage	[38]
	Clove oil	Inhibits *E. coli* and *S. aureus*	[33]
Nano-starch	Antioxidant	Decreased the oxidative reaction	[18]
	Composite film	Improved the film properties	[34]

3. Future Research

Future study on the work might include investigation into customer perception, safety compliance, sustainability evaluation, and nanocomposite improvement. It is also crucial to investigate advancements in characterisation, effective packaging, commercial uptake, and international legislation. The advancement of nanomaterials in food containers will depend heavily on longevity studies and multidisciplinary research to ensure effectiveness, security, and future viability in decades ahead.

4. Conclusions

In conclusion, an innovation regarding the way scientists approach the conservation of food, preservation, transportation, and consumption has been developed through the incorporation of nanotechnology in food technology. Significant insights from this unique area include the following:

Enhanced Food Safety: Nanomaterials' antibacterial qualities provide efficient ways to prevent the replication of microbes in food items. Food deterioration is greatly reduced owing to this invention, which also improves overall safety for food.

Reduced Food Waste: Food wastage has been decreased as a result of the use of nanoparticles in food manufacturing. This goal is in line with a business's objective of reducing food waste by extending the shelf life and tastes of products.

Sustainability: Sustainable packaging alternatives have been offered through the development of nanotechnologies, which offers materials that are disposable and favourable to the environment. These developments guarantee the effective distribution and storage of food, addressing important challenges like food insecurity and contamination in the environment.

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