International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

Role of Nanomaterials in improvement of food packaging

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International Journal of Science and Research Archive, 2024, 13(02), 048–052

Publication history: Received on 18 September 2024; revised on 27 October 2024; accepted on 31 October 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2073

Abstract

Nanotechnology in food and beverage packaging has garnered significant interest due to its potential benefits, but it also raises safety concerns related to the toxicology of engineered nanoparticles (ENPs). The primary issue is whether ENPs can migrate from food contact polymers into food and under what conditions this occurs. This review has two main objectives: First, it will examine the current advancements in ENP applications for food packaging, focusing on the latest risk assessment strategies and the conflicting findings from cytotoxicity studies. It will also highlight the often-overlooked effects of food matrices on nanoparticle behavior in the gastrointestinal tract, discussing a recently proposed standardized food model for evaluating the toxicity and fate of ingested ENPs. Second, the review will thoroughly analyse current market dynamics and industrial applications of ENPs in food packaging, aiming to offer a comprehensive overview of their impact and trends in the industry.

Keywords: Nanotechnology; Food Packaging; Engineered nanoparticles (ENPs); Bio nanocomposites; Nanosensors

1. Introduction

Nanotechnology has increasingly become a pivotal technology for the food industry, offering innovative solutions for enhancing food quality, safety, and agricultural growth (Figure 1) and encompassing various technological fields, focusing on the nanoscale to create materials with unique properties, such as high surface-to-volume ratios and altered physicochemical characteristics, including solubility, strength, and optical properties. This has led to a new industrial revolution, significantly impacting agriculture, food, and medicine. Bio-nanotechnology combines biological molecules with nanostructures, driven by consumer demand for higher-quality, healthier food. This field is advancing rapidly, with current research focusing on improving processing, packaging, quality control, and developing nutrient-rich delivery systems. The global nanomaterials market, valued at over $69 billion in 2022, is projected to grow to around $248.56 billion by 2030, highlighting the increasing demand for nanoparticle-based materials in the food industry. Nanotechnology has the potential to enhance food packaging by extending shelf life, maintaining freshness, and improving safety. Nanoparticles can be incorporated into films to create nanofilms that improve gas permeability, reduce harmful gases, and act as barriers against microbial spoilage. With traditional plastic polymers posing environmental and health risks due to their non-biodegradable nature, research focuses on developing edible coatings and films from bionanocomposites. These bio-based materials, including antimicrobial nanoparticles, offer solutions for reducing waste and improving food safety and quality. Despite these advancements, the use of biomaterials in food packaging remains limited [1].

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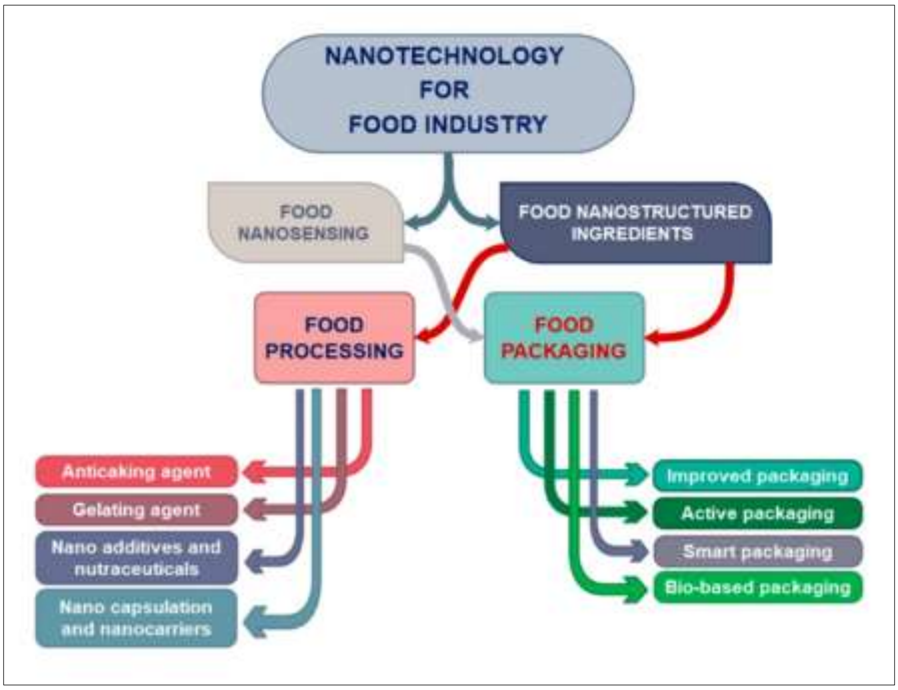

Figure 1 Application of Nanotechnology in the food industry [2].

Aim of review

This review aims to explore the use of nanoparticles in food packaging to enhance the shelf life, quality, and safety of packaged food throughout its journey from industry to distribution, consumption, and storage. Nanotechnology in the food industry can be categorized into two main areas: food nanosensing and nanostructured ingredients. Nanostructured ingredients are used in food processing and packaging to improve nutritional value, prevent caking, enhance texture, and protect flavors and other properties. In food packaging, advancements include improved active, smart, and bio-based packaging solutions. The review will summarize the role of (bio)nanotechnology in these applications, discuss some negative aspects associated with its use, and consider future perspectives and developments in the field.

2. Food packaging

Food packaging is critical for ensuring food safety by preventing spoilage and contamination, maintaining quality, and reducing weight loss. Nanotechnology offers a promising approach to improving food packaging through the use of nanostructured and nanomodified materials. These advancements can enhance packaging properties, such as temperature and moisture stability, barrier functions, and mechanical strength. Nanomaterials can also provide active functions like antimicrobial, antioxidative, and UV protection and enable smart packaging features such as gas detection and product identification [3].

2.1. Improved Food Packaging

Incorporating functional nanomaterials into polymers can significantly enhance packaging by improving gas barrier properties, temperature and humidity resistance, mechanical strength, and flexibility. For instance, adding clay nanoparticles to polymers like ethylene-vinyl alcohol (EVOH) and polystyrene (PS) has been shown to reduce oxygen and water vapor permeability, thus extending the shelf life of packaged foods. Nanocoatings, including both edible and non-edible types, provide additional benefits. Generally used plasticisers are mentioned in (Table 1). Edible nano-coatings, applied directly to food products, offer flavor, color, and antimicrobial properties. Non-edible coatings serve as protective barriers [4][5]. Nanoclays and other nanomaterials improve barrier properties and can be used in both coatings and laminates [6].

Table 1 Generally used plasticisers in food packaging [4][5].

Type	Representative	E number	ADI value
Polyols	Glycerol	E422	Not specified
	Sorbitol	E420	Not specified
	Polyethylene glycerol	E1521	0-10mg/kg body weight
Sugars	Glucose	-	-
	Sucrose	-	-
Lipids	Monoglycerides	E471	Not specified
	Phospholipids	(Lecithin E322)	Not specified
Natural source	Triglycerides from vegetable oil	(sorbitan tris tearate E492)	0-25mg/kg of body weight
	Fatty acid esters	-	-

2.2. Active packaging

Globally, approximately 1.3 billion tons of food are discarded each year, largely due to spoilage, which poses significant environmental and health concerns and leads to economic losses and increased healthcare costs. New technologies and materials are needed to address these issues to reduce food waste and enhance food safety. Active food packaging materials, which extend the shelf life of food, are a promising solution. Unlike traditional non-degradable materials like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), modern active packaging includes scavengers, absorbers, and emitters that can be integrated into both conventional and biodegradable materials. These new materials often feature antimicrobial agents, antioxidants, and preservatives to improve food quality and safety [7].

2.3. Antimicrobial Active Packaging

Antimicrobial packaging aims to preserve food and extend its shelf life by inhibiting microbial growth. This can be achieved by incorporating active agents or coatings within the packaging materials. Metal-based nanoparticles, such as silver (Ag), copper (Cu), and zinc oxide (ZnO), are frequently used for their antimicrobial properties and can be combined with other agents for enhanced effectiveness [8][9]. Nanoencapsulation techniques can stabilize essential oils, improving their antimicrobial and antioxidant properties. Herbs and spices, known for their high antioxidant and antimicrobial polyphenols, are valuable for active packaging. For example, films with silver-copper nanoparticles and cinnamon essential oil have shown prolonged antibacterial action. Similarly, buckwheat starch films with ZnO nanoparticles have demonstrated significant antimicrobial activity against pathogens like Listeria monocytogenes. Other studies have highlighted the effectiveness of titanium dioxide (TiO2) and zinc oxide (ZnO) nanoparticles in reducing bacterial growth when incorporated into low-density polyethylene (LDPE) films [7]. Active packaging technologies offer improved protection against pathogens, extended shelf life, and enhanced resistance to environmental factors. The high surface area-to-volume ratio of nanoparticles compared to conventional materials provides more effective inhibition of foodborne pathogens. Additionally, these technologies enhance packaging materials' thermal, physicochemical, mechanical, and optical properties.

2.4. Smart Food Packaging

Smart food packaging leverages nanoparticles to enhance monitoring capabilities for chemical, biochemical, and microbial changes in food and its environment. Nanoparticles, including metal nanoparticles and photonic nanocrystals, offer superior performance compared to traditional colorimetric indicators due to their unique optical properties and high surface reactivity [10]. Nanosensors embedded in packaging can detect specific pathogens, gases, and spoilage indicators, providing real-time feedback to consumers. This technology helps ensure food quality and safety by alerting users to spoilage through visual changes in the packaging, reducing reliance on shelf-life labels [11].

3. Bio-Based Packaging

Bio-based or biodegradable packaging materials derived from renewable resources offer an eco-friendly alternative to traditional plastics. The production of bioplastics such as bio-poly (ethylene terephthalate), polybutylene succinate, and polylactic acid (PLA) is projected to grow significantly, driven by their environmental benefits. These materials can degrade into CO2, water, and biomass, reducing environmental impact. Biodegradable polymers are categorized into those from biomass (e.g., polysaccharides, proteins), synthesized from bio-monomers (e.g., PLA), or produced by microorganisms (e.g., polyhydroxybutyrate). Despite higher costs than fossil-based polymers, integrating nanotechnology into bio-based materials can enhance their physical and chemical properties and make them more cost-effective [12]. Common bio-nanocomposites used in food packaging include starch derivatives, PLA, polyhydroxybutyrate (PHB), polybutylene succinate (PBS), chitosan, and cellulose.

4. Starch-Based Nanomaterials:

Starch is an abundant, renewable, and biodegradable biopolymer with promise for food packaging applications. Despite its advantages, native starch exhibits limitations such as poor barrier properties, water sensitivity, and brittleness. To address these issues, starch is often combined with other materials. Starch nanoparticles (SNPs), which can be derived through acid or enzymatic hydrolysis, offer improved functionality for biodegradable packaging. For example, pea starch nanocrystals and taro starch nanoparticles have enhanced film properties, such as reducing vapor permeability and increasing opacity [5].

5. Cellulose-Based Nanomaterials:

Cellulose, sourced from lignocellulosic biomass, is an eco-friendly and biodegradable material with significant potential in food packaging. Various forms of nanocellulose—such as cellulose nanofibrils, cellulose nanocrystals, bacterial nanocellulose, and hybrid nanomaterials—are explored for this purpose. Cellulose nanoparticles reinforce polymer composites, improving packaging films' mechanical and barrier properties. For instance, bacterial cellulose films enhanced with lignin and cellulose nanocrystals demonstrated improved tensile strength, reduced water vapor permeability, and added UV-absorbing and antioxidant properties, making them suitable for packaging sensitive food products [12].

6. Chitosan-Based Nanomaterials

Chitosan, derived from chitin and found in abundant renewable sources, is another promising polysaccharide for food packaging. It is known for its antimicrobial properties, inhibiting various pathogenic microorganisms, including bacteria and fungi. Chitosan’s antimicrobial action is attributed to its ability to disrupt bacterial cell walls or act as a chelating agent. However, chitosan’s mechanical, thermal, and barrier properties are often inferior to non-biodegradable polymers. The acid pH required for chitosan film formation can also lead to gelation issues. To overcome these limitations, chitosan is often combined with other molecules to enhance its properties for effective food packaging applications [13][14].

6.1. Safety Concerns of (Bio)Nanotechnology Usage in Food Packaging

Nanotechnology is a rapidly developing field, and nanomaterials are of significant technological and economic interest and have a huge impact on many industries, especially in the food packaging industry. In general, the beneficial effects of nanocomposite materials are well recognized as opposed to the potential (eco)toxicological effects and effects of nanoparticles on human health, where fewer studies were performed. Their interaction with the food system concerns human and animal health. Using nanomaterials in nanosensing or food packaging applications can lead to the migration of nanomaterials into humans through inhalation, skin penetration or ingestion. This can occur due to the leaching of nanocomponents from packaging or sensing elements into the food or by storing packaging nanosensors in landfills with the possibility of release into the environment [15]. A potential concern should be focused on the migration of nanomaterials from the packaging or the sensing element inside the packaging into the food. The most evident contact route of nanomaterials to the human body in food application is upon ingestion. Therefore, the gastrointestinal tract properties such as pH, presence of various surface-active molecules, electrolytes, digestive enzymes, gut microbiota, and mechanical forces influence the absorption of nanomaterials, which may cause changes in the properties and agglomeration state of nanoparticles [16].

7. Conclusion

The use of nanotechnology is known in diverse fields. Nanotechnology is a boon to food packaging as it keeps the food fresh and more nutritious than any other technique. Various options are available in the nanotechnology of food packaging, from biobased to sensor-based. It provides a remarkable improvement in packaging technology, but further research is needed to improve safety standards. With more intense research, non-toxic, environmentally safe food packaging nanomaterials will be developed in the future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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