Journal of Food Quality and Hazards Control 11 (2024) 149-156

Application of Nanomaterials in Food Packaging: A Review Study

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HIGHLIGHTS

- Nanotechnology is widely used in all stages of producing, processing, storing, bundling, and transporting of agrarian items.
- Nanomaterials have provided promising solutions to solve some of the practical barriers to biopolymers.
- The most influential factor regarding future and development of nanotechnology is population and its growth, and people's lifestyles.

Article type
Review article

Keywords
Nanotechnology
Food Packaging
Nanocomposites
Nanomaterials

Article history
Received: 02 May 2024
Revised: 28 Jun 2024
Accept: 03 Aug 2024

ABSTRACT

Nanotechnology is one of the unused innovations which has opened its way to different businesses, and is broadly utilized in several areas. One of these industries which play a crucial role in wellbeing of the community is bundling industry. This is a review study conducted on nanotechnology in food packaging. Data collection was based on study features, nanotechnology, nano-composites, and food packaging. The results of research studies have revealed that nanotechnology-based packaging was able to repair packages and prevent food spoilage. Advantages of nanotechnology in food industry, including the ability to enrich as well as encapsulate and preserve useful compounds for their controlled delivery to the target cell, the ability to cover undesirable flavors, the utilization of dynamic, and shrewdly packaging and its application in food quality and security diagnostics have encouraged using this technology. Using these packages will protect food against exchange of oxygen and moisture from the external. Furthermore, nano-materials can be used to protect food from spoilage. Natural polymers such as sugars and proteins are able to form green nano-composites in combination with nano-materials and biomaterials such as cellulose nanofibers, which are non-toxic, biodegradable, and biocompatible, and are transformed into the environment by decomposing organisms. Knowing the capabilities of nanotechnology, it is hoped that the current food packaging systems can be modified and products can be introduced to the community in accordance with the culture of proper nutrition.

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To cite: Sadeghizadeh-Yazdi J., Nayik G.A., Hajimirzadeh M.S., Akramzade N. (2024). Application of nanomaterials in food packaging: a review study. *Journal of Food Quality and Hazards Control*. 11: 149-156.

DOI: 10.18502/jfqhc.11.3.16586 Journal website: http://jfqhc.ssu.ac.ir

Introduction

Nowadays, packaging industry has become a powerful technology to minimize the activity of bacteria and food spoilage through scientific packaging (Baltic et al., 2013; Farhoodi, 2016; Sing et al., 2017). The most critical innovation in food packaging industry has been nanopackaging. Nanotechnology means using structures with sizes from 1 to 100 nm (Onyeaka et al., 2022). It is used in food industry in many ways. These applications include the use of nanotechnology in packaging materials, agriculture, food production processes, and self-catering (Sing et al., 2017). Nanotechnology in food packaging is crucial for enhancing gas barrier properties and improving moisture and thermal stability of various packaging materials (He and Hwang, 2016). Nanotechnology is widely used in all stages of producing, processing, storing, bundling, and transporting of agrarian items (Onyeaka et al., 2022). The presentation of nanotechnology in rural and nourishment businesses ensures expanded generation and quality, as well as securing the environment and the planet's assets (Jain et al., 2018).

Today, many food and agricultural products in the country are losing their favorable market due to inadequate storage and packaging, which can lead to many economic losses (Inbaraj and Chen, 2016). Nanotechnology, as a powerful tool in this field, can help improve the country's economy. One industry that has been slow to adopt technology is food industry, and nanotechnology is a topic that is little known. Generally, the public eagerness to utilize normal nourishment items has anticipated the use of nourishment innovations, and nanotechnology is no exception. Researchers and industry proprietors have distinguished the potential employments of nanotechnology in nearly all segments of the nourishment industry. Two of the most prominent examples are food processing and food packaging, with nanotechnology being more widely used in food packaging, most likely because the nanoparticles that are directly related to food are not added, and the natural structure of the food is preserved (Ozturk et al., 2015). Food packaging is done by diverse materials. Over the past two decades, plastics, with yearly development of 5%, have been the most broadly utilized materials for food packaging, paper, and paperboard. Oil-based plastic materials such as polyethylene, polypropylene, polyamide, in spite of the environmental problems, are utilized broadly in food industry due to greatly resistance. On the other hand, the use of biopolymers natural such as starch in food packaging has problems. Its films of are high hydrophilicity and relatively weak mechanical properties (Jiang et al., 2016).

Conventional food packaging systems passively protect food by creating a barrier between food and its environment. Active packaging is one of the new concepts in food packaging developed in response to consumer demands and market trends. These packages are defined by protecting the nutrient through a favorable connection with food, for example by releasing the desired constituents such as antioxidants and antimicrobials, and eliminating certain harmful factors such as oxygen and water vapor. Communication usually improves food stability. Active packaging is used for a variety of food such as bread, pastries, cakes, pizza, fresh dough, cheese, meat, and a variety of its products and fruits (Biji et al., 2015). Packaging in food industry extends the shelf-life of the material by preventing the growth of microorganisms, undesirable changes, and reducing quality due to the exchange of gases, aromas, moisture, and improved product appearance (Pereira De Abreu, 2012).

Among the nanoparticles mainly used in food packaging industry are silicon oxide and silver (Ag) oxide nanoparticles, which in addition to their oxygen, carbon dioxide inhibition properties and increase in mechanical feature of the packaging, have antibacterial activity (Fakhouri et al., 2014). Concerns have been raised regarding the migration of nanoparticles from packaging to food; however, the results related to migration and risk assessment of nanoparticles are not very clear (Primožič et al., 2021). In other words, the use of nano-materials in food industry, taking into account their advantages and disadvantages, can pose a potential risk to human health (Onyeaka et al., 2022).

Due to environmental problems, studies have focused on biodegradable polymers to create food packaging materials. On the other hand, the utilization of agrarian by-products and the food industry's creation of biodegradable materials to supplant petroleum-based polymers have led to developing intrigued in bundling applications. The introduction of nanotechnology into the field of biodegradable polymers and the generation of biodegradable nano-composites does not overcome the inalienable deficiencies of biopolymers, but it diminishes unclear meaning utilized as closed coatings. Food packaging is possible while minimizing environmental pollution caused by plastic waste (Mihindukulasuriya and Lim, 2014). This paper reviews differences of nano-materials in food packaging, including clay polymer nano-composites as impermeable materials, Ag, and copper nanoparticles as powerful antimicrobial ingredients, and nanosensor-centered methods for quality realization and identifying substances such as gases and pathogens is incorporated into food packaging.

Nanotechnology

Nanotechnology is the review of events and functions at the atomic, molecular, and nanomolecular level. This practice is applicable in many fields, and food industry is one of them which drew consideration lot of attention. The first area in food industry where nanotechnology is affected is food packaging (Rim et al., 2013). In general, the goal of food packaging is to increase storage time and to completely protect food from the risk of internal, external, and microbial spoilage (Laaninen, 2015). Nanotechnology allows designers to modify the structure of materials at the molecular level to make materials more desirable. With different nanostructures, plastics are permeable to various gases/water vapors, which are suitable for storing fruits, vegetables, drinks, and other food. Using nanoparticles, lightweight glass and packages are produced which are resistant to high temperatures (Sadeghizadeh-Yazdi et al., 2019).

Use of nanotechnology in food packaging

Packaging is one of the key issues in the field of food safety. Using nanoscience can increase the quality and efficiency of packaging materials, and thus ensure food security. The nature of nanoscale provides a new foundation for innovation and technology integration (Bratovcic et al., 2015). Some research attempts to address the use of nanotechnology with emphasis on food production and processing (Wesley et al., 2014). Nanotechnology refers to designing, describing, producing, and applying the structure and utility of nanoscale systems. Bio-nanotechnology has emerged as an integration between technology and nanotechnology for the development of biosynthetic and environmental technology regarding the synthesis of nanomaterial (Maksimović et al., 2015). The science of nanotechnology is new and new methods are being considered to bring about the transformation of packaging industry. Nanotechnology powers providers to revise the framework of packaging elements on a molecular scale and give it desirable features (Sekhon, 2014). The goal of using nanoscience is to increase the quality and efficiency of packaging materials, inform consumers of tears and small holes, and repair them according to an environmental situation like changes in temperature and humidity, and thus to ensure food security (Pereda et al., 2019).

A research study done by Tahmouzi et al. (2024) discussed about using of nano-materials in food packaging. They found that Bacterial Cellulose Nano-Fiber (BCNF) and Zinc Oxide Nano-Particles (ZnO NPCs) improves microbiological and physical properties of chitosan film.

A summary of review articles performed on the use of nanotechnology and nano-composites in food packaging it is shown in Table 1.

Table 1: A summary of review articles performed on the use of nanotechnology and nano-composites in food packaging

Authors	Objectives	Methods
(Sujithra and Manikkandan, 2019)	Comprehensive presentation to nanobundling in nourishments, nanomaterials, and different methods utilized in nanobundlings, such as chemical discharge nano bundling, nanosensors, and track bundling, nano antimicrobial bundling, nano biodegradable bundling, and their applications and potential application in food.	Nanotechnology, nanosensors
(Dimitrijevic et al., 2015)	Evaluation of exposure to nanoparticles and potential risk on human health and the environment as well should be considered.	Nanotechnology nanoparticles
(Huang et al., 2018)	Giving modern openings and challenges for the advancement of nanomaterials within the food industry.	Nanotechnology
(Berekaa, 2015)	Center on the huge benefits of nanotechnology in food industry in terms of nourishment handling, bundling, security, and quality control.	Nanotechnology, nanosensors
(Sharma et al., 2017)	Approaches and rule regarding nanoparticles incorporation in food packaging are being reviewed.	Nanotechnology
(Singh et al., 2017)	The potential of nanoparticle uses in various fields of food science enhance food security, extending storage life, and other functional properties.	Nanotechnology, nanoparticles
(Mandal et al., 2009)	Application of nanotechnology in food packaging.	Nanotechnology, nanosensors, and nanoparticles
(Omanović-Mikličanin et al., 2016)	The main focus appears to be on food packaging and health food products.	Nanotechnologyand nanoparticles
(Ashfaq et al., 2022)	This review explores the most commonly used nanoparticles in food packaging, the significant changes they cause in the properties of packaging material, and the commercially available nano-based packaging materials	Nanotechnology
(Primožič et al., 2021)	The main focus is on advances in food nanopackaging, including bio-based, improved, active, and smart packaging.	(Bio)nanotechnology, noanoparticles and nonocomposites
(James et al., 2024)	The present work is a comprehensive study to analyze biomedical and other applications of carrageenan along with underlying mechanism or mode of action along with synergetic application of nanotechnology.	Nanotechnology

Nanocomposite

Today, most of the materials used for packaging are almost depleted, indicating a serious environmental and global problem. Using edible polymers and biodegradation due to difficulties in implementation, processing, and cost, the application of nanotechnology with these polymers can offer new opportunities to improve not only their properties but also their cost-efficiency. Some composites are added to polymers to increase the strength, thermal, and mechanical stability (Bajpai et al., 2018). For example, nano-reinforcing materials such as nanotubes, nanometer-sized black carbon, silica, calcium carbonate, oxides, and carbon fiber are used as additives in polymer mixtures. Nanoclay-based composites are used as heat-resisting and gas-insulating layers in food and beverage packaging (Maisanaba et al., 2014).

Application of polymeric nanocomposites can include the production of wear-resistant and corrosion-resistant coatings, gas-and-steam-resistant packaging, conductive plastics, durable fibers for textile industry tools, and household appliances (Othman, 2014). Food packaging with nanocomposite films produces properties such as mechanical strength, oxygen, and moisture retention, and antimicrobial properties. In addition to transferring these nanoparticles to food, which are a separate issue, their effect on human wellbeing and the environment is so important that prior to commercialization of this emerging technology, relevant safety regulations, and standards must be formulated and applied (Pradhan et al., 2015).

Nano-coating

Nano-coatings have been in use for decades, and are now widely used. Nano-coatings are layers as wide as a few nanoseconds. In fact, nano-coating is a waxy coating which is widely used as a coating for food products such as cheese and apples. Edible nano-coatings have nanometer-sized nanomaterials that are not visible to the naked eye, and at the nanoscale, they have provided many features in food packaging industry (Momin et al., 2013). The essential part of nano-coatings is to secure nourishment and improve the surface of the package. Nano-coatings have been utilized in an assortment of nourishments such as meat, vegetables, natural products, cheese, sweets, chocolate, fries, and pastry kitchen items (Athinarayanan et al., 2014). In general, nano-coatings are mostly used to prevent the passage of moisture and fat gases. Nano-coatings are antibacterial coatings that lack chemical germicides and resistant to chemicals, alkalis, and heat (Kalia and Parshad, 2015).

Nanosensors

Biosensor technology is an important choice in agribusiness and food industry. The technology ensures quality and food safety in a cost-effective and rapid manner, controls products, and processes, and detects gases in packaged foods to integrate packaging materials (Sing et al., 2017). Nanosensors are used in order to quickly identify and diagnose pathogens, allergenic proteins, and prepare smart packages to analyze food for the presence of toxins (Primožič et al., 2021). In making biosensors, different types of nanomaterials are used, one of which is gold nanoparticles. The purpose of using these materials in food packaging systems is to identify nanoparticles released in packaged food over a short period of time. Among other applications, such nanomaterials can improve the sensitivity and capability of chemical compounds, bacteria, viruses, and toxic substances (Dasgupta et al., 2015). They can monitor the quality and freshness of food during storage and hygiene. Nanosensors respond to environmental factors such as temperature, humidity, oxygen content, microbial factors, and pathogens, providing useful information to manufacturers and consumers about storage conditions of materials in terms of temperature, expiration date, and so on (Bajpai et al., 2018).

Antimicrobial properties of nanoparticles and the detection of food-borne pathogens

The major application of nanotechnology in food packaging is its antimicrobial properties. Therefore, nanobiotechnology is a very important technique in increasing antimicrobial properties of food packaging (Primožič et al., 2021). The use of nanotechnology has given tall trusts for accomplishing tall security nourishment items, expanding rack life, and eventually, making more efficient nourishment. Generally, the rationale for food packaging is to avoid microbial deterioration and misfortune of supplements, and subsequently, expanding the rack life of nourishment (Bajpai et al., 2018). One of the pernicious impacts of nourishment is the irresistible maladies caused by contact with nourishments whose essential source is a drain. Subsequently, the end of microbes in food packaging is one of the most imperative issues within the preparation of generating, handling, transporting, and nourishment capacity; utilizing nanomaterials due to their antimicrobial properties increases the shelf-life (Shafiq et al., 2020). Some examples of antimicrobial nanomaterials are titanium dioxide (TiO_2), Ag, iron (II, III) oxide (Fe_3O_4), ZnO, and copper (II) oxide (CuO) (Chadha et al., 2022). In addition to having antimicrobial properties, metal nanoparticles affect the physico-chemical properties of packaging films. So that, studies have shown that incorporating Ag nanoparticles into gelatin and sodium alginate films significantly affected their tensile properties, transparency, structure, and barrier properties positively (Tahmouzi et al., 2024). In recent years, nanomaterials have been used to detect food-borne pathogens. Ag nanocolloids, plasmonic gold, magnetic pellet, Ag nanoparticles, graphene oxide, and carbon nanotubes are commonly used to detect pathogenic bacteria. Moreover, synthetic molecular DNA marked with colored probes is used to identify food pathogens. In the same direction, *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes* have been identified using protein G-liposomal nano-vesicles in pure and mixed cultures (Bajpai et al., 2018).

Environmental impacts of food packaging

With the ongoing growth of the global population, consumption of packaged food has risen substantially (5% annual growth rate). Food packaging is an urgent global issue and their disposal can remarkably affect the environment. Unfortunately, the convenience of food packaging industry consumes the highest volumes harmful material with single use or non-biodegradable nature, they pose huge threat to the environment. Plastic is a widely used material for food packaging and it dumped almost everywhere causing an adverse effect to the ecosystem. Food packaging materials make up almost half of all municipal solid waste, since they remain in and around it for a long time, destroying soil components. It also pollutes air while its manufacture often degrades the environment, as greenhouse gases are emitted into the air. Life Cycle Assessment (LCA) serves as an effective method for analysis of the environmental impacts of food packaging systems comprehensively.

Nanomaterials

Nanomaterials have provided promising solutions to solve some of the practical barriers to biopolymers, which aimed at packaging food and beverages. Improved capabilities and new packaging concepts are made possible with advances in nanomaterials research and technologies. The high performance of nanoparticles and nanotubes has enabled the application of biodegradable polymers in food packaging industry. Nanotechnology empowers originators to alter the structure of bundling components on an atomic scale (Cushen et al., 2014). The most common type of nanomaterial in food industry is titanium oxide, an antimicrobial, and Ultra-Violet (UV) radiation protective agent in packaging, which is used in food containers and ingredients. Ag, an antimicrobial specialist in nourishment bundling, is commonly utilized in nourishment holders and supplements. Nano clay is used in food packaging. Zinc (Zn) and ZnO, a food additive, are used as antimicrobial agents in food packaging. Silicon dioxide (SiO_2) is a food additive used in food packaging as well (Echegoyen and Nerín, 2013). TiO_2 particles are one of the most widely used semiconductor nanoparticles with properties such as hydrophilic, photocatalytic, UV, and antibacterial to repress the development of different microorganisms such as Gram-negative and Gram-positive microbes and parasites. Antimicrobial additives are used for food and storage containers in the structure of polymeric nanocomposites used in packaging (Singh et al., 2017). One of the nanomaterials utilized for its antimicrobial properties within the nourishment industry is Ag nanocomposite. Ag is broadly used as an antimicrobial element within nourishment and refreshment businesses (Pinto et al., 2013). Nanoparticles of different metal oxides such as ZnO, magnesium oxide (MgO), and Ag are utilized within the packaging industry. ZnO is one of the most common utilized metal oxides. Certainly, clay nanoparticles used in food packaging are the most important composites (Thiruvengadam et al., 2018).

In general, the types of nanomaterials used in food packaging can be divided into polymeric nanomaterials (cellulose, chitosan, zein, starch), non-polymeric nanoparticles (clay, graphite), metal-based nanoparticles (Ag, Zno, Tio_2, Cu), and nanosensor (Sadeghi et al., 2021).

A review of previous research shows that nanotechnology is an effective tool in food packaging industry and can play a crucial part in maintaining food quality (Bratovčić et al., 2015). One of the types of polymeric nanocomposites is clay polymeric nanocomposites which are very popular among users due to their properties such as cheaper and lower weight. These clay nanocomposites are also impermeable and contribute to a longer shelf-life (Chowdhury et al., 2017). Ag and Cu nanocomposites have high antimicrobial activity, protect food from germs such as viruses, fungi, and bacteria, and play an important role in increasing the shelf-life of food. Nanosensors used in smart packaging are able to recognize the presence of gases, odors, chemical contamination and pathogens inside food packaging in a non-destructive manner (Bumbudsanpharoke and Ko, 2015). In general, the addition of inorganic nanoparticles to biodegradable polymer materials increases functional properties of packaging films, including mechanical, thermal, chemical resistance, gas, and water barrier properties. However, the safety of nanoparticles in food should be evaluated according to their nature and characteristics in food matrix in which they are distributed (Onyeaka et al., 2022). Research results have shown that adding natural antioxidant compounds to packaging films cannot provide proper functional properties, and only after the addition of nanofillers, this is achieved in order to strengthen the nanometer surface force, which is mainly related to low solubility and compatibility of the compounds in the matrix of hydrophobic polymers (Vieira et al., 2022). The use of nanomaterials in food packaging enables the modification of ready-made food and additives to fine-tune and manipulate the physical contents of food. Food is considered nano food when nanoparticles or nanomaterials are utilized in one of the stages of planting, processing, or packaging. In addition to packaging, nanotechnology is also used in the preparation of nutritional supplements. The production of nutritional supplements also shows the use of nanotechnology in food industry. Nanoceuticals and nutrition-be-nanotech are brand names for nutritional supplements prepared through nanotechnology. These powder materials are used to increase the absorption of nutrients. Nanocochleates are a suitable tool for carrying nutrients to body cells without affecting the color and taste of food. In food industry, the encapsulation technique is used to prepare capsules with a nano structure to carry Cu, Fe, and probiotics. Food supplements prepared with nanotechnology are much more effective, compared to common supplements, since they are more effective on body cells due to their size (Chellaram et al., 2014). Although it is very difficult to assess the risk of diseases caused by chemicals in food packaging, following the regulations of the Environmental Protection Agency (EPA), LCA instructions, recycling, preparation of edible wrappers, packaging prepared from milk proteins, and biodegradable packaging materials, can minimize the negative effects of food waste on the environment and humans.

One of the limitations of this study was missing some articles because of the search strategy and keywords.

Conclusion

Nanotechnology can increase the performance of food packaging. The most influential factor regarding future and development of nanotechnology is population and its growth, and people's lifestyles. Nanotechnology in food packaging emphasizes provision of healthy food to customers through production of sensors capable of rapidly detecting and detecting toxins in pathogenic compounds and microorganisms in food samples and expanding antimicrobial levels for machines used in food production. Experts are working, expanding the production of cheaper coatings, and ultimately, producing healthier food. By increasing the impact of nanotechnology on food packaging and the entry of this kind of packaging into the consumer market, the health of food is becoming more important. This need will strengthen the acceptance of nanotechnology in sensory applications, and in this way, nutritional health can be realized. For example, technology can warn buyers and sellers of the expiry date of food. New antimicrobial coatings and contaminant plastic bags have made significant progress in ensuring health and safety of packaged food. Although much attention has been paid to the application of nanotechnology in food packaging and products available on the market, there are still many unexploited capabilities.

Author contributions

J.S.-Y. and G.A.N. designed the study; M.S.H. and N.A. collected the data; J.S.-Y., G.A.N., M.S.H., and N.A. analyzed the data and wrote the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

The authors declared no conflict of interest.

Acknowledgements

Thanks are owed to Research Center for Food Hygiene and Safety, Shahid Sadoughi University of Medical Sciences, Yazd, Iran.

Funding

This research did not receive any specific grant from funding agencies.

Ethical consideration

All study protocols were reviewed and ethically approved by the Ethics Committee of Shahid Sadoughi University of Medical Sciences, Yazd, Iran (Approval ID: IR.SSU.SPH. REC.1403.097).

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