Chapter 13

Prospective Nanomaterials for Food Packaging and Safety

Mohammad Harun-Ur-Rashid¹, Israt Jahan², Abu Bin Imran³, and Md. Abu Bin Hasan Susan⁴*

¹Department of Chemistry, International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh

²Department of Cell Physiology, Graduate School of Medicine, Nagoya University, Nagoya 464-0813, Japan

³Department of Chemistry, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

⁴Department of Chemistry, University of Dhaka, Dhaka 1000, Bangladesh

*susan@du.ac.bd

Abstract

Nanotechnology is being explored widely to improve food packaging. The development of innovative packaging materials using nanotechnology has had remarkable growth in the last few years. For the last two decades, substantial scientific efforts have been placed into replacing bulk and conventional materials with eco-friendly and biodegradable nanotechnology products or, more specifically, nanostructured materials in the food packaging industry. The advantages of nanotechnology and applications of nanostructured materials in food packaging are overviewed in this chapter. The common, profitable, and marketable acceptance of nanomaterial based food packaging systems and future perspectives are discussed by providing a broad and improved understanding of implementing nanotechnology products in food packaging.

Keywords

Nanotechnology, Nanomaterials, Active Packaging, Intelligent Packaging, ZnO Nanoparticles, Carbon-Based Nanomaterials, Green Polymer Nanocomposites
1. **Introduction**

With the invention of canning in the nineteenth century, modern food packaging has made significant advances due to universal trends, technological and scientific improvements, and buyer preferences. Food casing or packaging has always been a part of constant development and the manufacturing company is constantly under pressure to supply more. Recent food science and technology have broadened, expanded, and refined conventional food casing methods and added new ones. The materials used in food packaging acts as a barrier to external elements and allow reaching food to the customer in a healthy and safe way. In addition to the move toward globalization, safety, protection and longer shelf life are necessary, along with monitoring safety and quality based on global standards. Gradually, the conventional materials have been replaced by smart nanomaterials such as nanocomposite gels [1-3], polymer nanocomposite [4-6], structural colored nanomaterials [7-9], molecular machines [10], nanomaterial based biosensors [11], and so on.

The advent of nanotechnology has had a most important impact on food packaging applications due to unique physicochemical and biological properties of nanomaterials. It has become one of the most up-and-coming technologies to refashion conventional food science applications. The implementation of nanotechnology in the processing, packaging, and safety of food has proved its competence in food industries, illustrated in Fig. 1 [12]. Various preparation techniques could produce nanomaterials with desirable chemical and physical properties, which might be utilized in food trade.
Implementation of nanotechnology by utilizing various nanomaterials such as nanoparticles (NPs), nanocomposites, nanoemulsions, and nanoengineered materials in food trading sectors has proven to be the best solution for addressing many issues and limitations, especially in food packaging and preservations [13, 14]. In this regard, with the help of nanoscale reaction engineering, nanobiotechnology, heat and mass transfer, and molecular synthesis, different nanostructured materials have been synthesized for manufacturing nanotracers and nanosensors for food packaging, preservation, delivery, and development. Biodegradable materials are preferred for the improvement and manufacturing of food packaging and preservation to control environmental pollution [15]. For the last few years, the coating of biodegradable and natural polymers on the surface of food has attracted tremendous attention and has proven prospective impacts in preserving food items [16, 17]. It is noteworthy that the stakeholders of food industries, working in the area of food packaging, are concerned about the introduction of antimicrobial packaging and detection of contamination during the packaging of food material. Modern and advanced food packaging systems may offer superior, easy, less expensive, and cost-effective methods to preserve foods than conventionally practiced techniques such as drying, freezing, canning, and dehydration. Nanotechnology has a wide variety of applications in food trading, as shown in Fig. 2.
The key importance of packaging is to save the different types of food items from biological, chemical, and physical damage. The food products such as vegetables, fruits, milk and milk based products, dry fruits, raw and dried meat, bakery products, raw and dried fish, sauces, and so on require more attention on the nutrition quality and shelf life [18]. In this connection, diverse techniques of packaging and materials are determined by the types of products packed. The food packaging operations is carried out to encounter several objectives such as physical and chemical protection, handling and transportation, stocking and marketing, information transmission, antitampering, and anticounterfeiting (Fig. 3).
Nanomaterials are more beneficial than conventional materials in providing improved preservation and quality maintenance of food products. NPs can alter the physical and mechanical properties of packaging polymers by improving their strength, durability, flexibility, barrier, and reusing properties. Many new food items have been introduced into the market with the requirements of consumers to monitor quality during and before the consumption. Moreover, it is required to minimize and control the food adulterant throughout the preservation period. All these requirements have led to the development of advanced packaging systems, for example, active packaging (AP) and intelligent packaging (IP), illustrated in Fig. 4. The detection of defects and the monitoring of food quality from the manufacturing to consumption stage are the basic functions of IP system by applying different indicators and sensors like gas indicators, time-temperature indicators, and humidity, calorimetric, optical, and electrochemical sensors and biosensors. Active packaging technology helps to maximize the shelf-life of food products by diffusing and absorbing $O_2$, $CO_2$, and ethanol [19].
2. Prospective nanomaterials in food packaging

At present, nanostructured materials have found multidimensional applications in the food industry. Fig. 5 shows a variety of nanomaterials utilized in food trade. Food-borne illness is a global public health concern. The severity of food-borne diseases affects the economy, global health, trade, and commerce badly by lowering productivity and increasing medical expenses. Consequently, the clamor for new techniques to control food-borne pathogens has increased remarkably in recent years. So food packaging plays an essential role in maintaining food quality, ensuring food safety, and minimizing food-borne diseases. Food packaging having novel functionalities called active packaging can provide food safety by maintaining quality by extending food shelf life, increasing cost-benefit ratio, and eventually improving overall convenience. Functional materials present in active food packaging systems come in contact with food content and alter the environment or change the food composition inside the pack. For instance, antimicrobial packaging is one of the active packaging systems where food surface interacts with the antimicrobial functional materials and inhibits or reduces the growth of microorganisms that spoil the food items, illustrated in Fig. 6.
Figure 5. Different types of nanostructured materials utilized in food industries for numerous purposes. The figure has been reproduced with the permission from [20].

Figure 6. Different concepts and clarifications of antimicrobial activities demonstrated by various nanomaterials. The figure has been reproduced with the permission from [21].
2.1 ZnO nanoparticles

Antimicrobial actions of ZnO NPs either in the form of suspensions (nanofluids) or in the form of intrinsic NPs. ZnO NPs are effective against gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis* [22-24]. Some gram-negative bacteria, for example *Escherichia coli*, *Campylobacter jejuni*, and *Pseudomonas aeruginosa* are sensitive to ZnO NPs [25-29]. Compared to *S. Aureus*, *E. coli* exhibits more sensitivity to ZnO NPs [30, 31]. Fig. 7 and Fig. 8 illustrate the structural characteristics of the membranes of gram-positive and gram-negative bacteria and the antimicrobial actions of ZnO NPs by multiple mechanisms towards microorganisms respectively [32].

![Figure 7. Structural characteristics of the membranes of gram-positive and gram-negative bacteria. The figure has been reproduced with the permission from [32].](image-url)
Figure 8. ZnO NPs capable of exhibiting antimicrobial actions through multiple mechanisms. The figure has been reproduced with the permission from [32].

2.2 Carbon-based nanomaterials in food packaging

The learning of carbon-based nanomaterials (CBNs) for food packaging applications has attracted attention due to their exceptional chemical and physical properties, including thermal, mechanical, electrical, optical, and structural diversity. CBNs are a novel class of materials that are widely used in food industry. CBNs, viz., carbon dots (CDs), graphene, activated carbon-based nanocomposites, carbon nanotubes, etc., are environmentally benign and better materials for food packaging. With antibacterial efficiency, they support food preservation and other applications [33]. Applications of CBNs in food trading have been depicted in Fig. 9. CBNs are better resources over the other materials in the ground of nanoscience and material science. They have attracted considerable interest from scientists since their discovery. They can be roughly divided according to their spatial dimensions, into fullerenes (zero-dimensional), carbon nanotubes (one-dimensional), graphene (two-dimensional), graphene coil (multidimensional), etc. They are found to be superior food-packaging materials compared to conventional ones.
CDs also known as fluorescent carbon are a new class of fluorescent small-carbon nanomaterials with particle sizes of less than 10 nm. CDs have various sorts of potential applications in food packaging. They have been used as antioxidant, antimicrobial, photoluminescent, and UV-light blocker additives in food packaging materials to reduce chemical deterioration and inhibit the growth of pathogenic and spoilage microorganisms in foods with the capacity to sense the freshness of food. They can be manufactured from environmentally friendly sources at a low price, such as microorganisms, food by-products, and waste streams, or they may be generated in foods during normal processing operations, such as cooking. CDs/polyvinyl alcohol (PVA) films can be used as active food packaging materials [34]. The incorporation of CDs in the PVA film enhances the water resistance properties, antimicrobial and antioxidant properties, mechanical properties, thermal stability, and UV blocking properties, illustrated in Fig. 10. The application of CDs/PVA film as active packaging is capable of notably increasing the shelf life of various foods such as jujube, banana, and fried meatballs.
Flexible, transparent, and photoluminescent CDs reinforced PVA based nanocomposite films show UV-blocking, mild antioxidant, and good antimicrobial activity against both gram-positive and gram-negative bacteria [35]. This CDs/PVA films significantly extend the shelf-life of strawberries as a model for perishable food products (Fig. 11). Fresh strawberries, dip coated with CDs/PVA, exhibit strong resistance towards fungal growth, spoilage, and weight and moisture loss. The CDs/PVA nanocomposite films are non-cytotoxic, UV light blocker, and antimicrobial. As a result, these nanocomposite films can be used as additives for producing edible coatings and food packaging.
Carbon nanotubes are available as either single wall nanotube (SWNT) or multiwalled nanotubes (MWNT). They are commonly used as low-resistance conductors and catalytic reaction vessels. Globular milk proteins can self-assemble into similarly structured nanotubes in some appropriate environmental conditions. Carbon nanotubes are used to improve the mechanical and antimicrobial properties of the polymer used in packaging. They are also used to form oxygen sensors to monitor their concentration in modified atmospheric packaging. Carbon nanotubes are incorporated into a synthetic polymer matrix used for food packaging to provide antimicrobial properties and intelligent sensors that can detect food spoilage.

Carbon nanotubes reinforced polymer nanocomposite films of PVA modified with ZnO NPs are important candidates as food packaging materials [36]. The synthesis and application of CNT-PVA-ZnO NP polymer nanocomposite films have been illustrated in
Fig. 12. These films have greater thermal stability, hydrophobicity, water vapor transmission rate, and antibacterial activity than PVA films. The packaging system made from CNT-PVA-ZnO NPs polymer nanocomposite films restrict the water loss in vegetables for up to 4 days at room temperature. This packaging material can extend the shelf life of chicken meat, since CNT-PVA-ZnO NP polymer nanocomposite films restrict the growth of natural microorganisms in raw chicken. The experimental results show that CNT-PVA-ZnO NP polymer nanocomposite films having good transparency are suitable for food packaging applications.

Graphene-based nanocomposites have been used to get better UV resistance as a blockade against gases and still have good thermal, mechanical, and electrical properties compared to their polymeric matrices. Furthermore, graphene-based nanomaterials shared through biodegradable polymers suggest high potentials to be used as antimicrobial and antioxidant in dynamic packaging technology resulting in more excellence, safety, extended shelf-life, and added value [37]. Graphene derivatives in biopolymer-based composites for food packaging applications have been shown in Fig. 13. They have many extraordinary and outstanding properties, which make them ideally effective for use in biosensors to monitor and track the quality of food. These properties include high conductivity, mechanical flexibility, amenability for versatile surface functionalization, ultrahigh surface area, biocompatibility, and so on. [38].

Figure 12. Carbon nanotubes reinforced polymer nanocomposite films of PVA modified with ZnO NPs as food packaging materials. The figure has been reproduced with the permission form [36].
Polyhydroxybutyrate (PHB), a natural polymer of microbial origin, is an excellent alternative to petroleum-based food packaging materials. The inferior thermal, mechanical, and barrier properties of PHB have restricted the versatile application for commercial food packaging. Such limitations can be overcome by incorporating graphene Gr-NPs and can be used in food packaging [39]. The Gr-NPs-PHB nanocomposites have been investigated and found with superior thermal, mechanical, cytotoxicity, barrier, and biodegradable properties, which are considered as key factors for selecting any material for food packaging applications (Fig. 14). They can increase the shelf life four times more for oxygen and moisture sensitive food items such as milk produces and potato chips. PVA/graphene-based nanocomposites are just one example of polymeric nanocomposites with considerable potential in the food packaging industry. They have exceptional gas and moisture barrier properties and high-quality thermal resistance. In smart packaging, graphene can be used as a sensor for biochemical or microbial changes in the product.
packed to detect specific food-borne pathogens or gases. Thus, this type of packaging can serve as oxygen and spoilage indicators for food safety and quality monitoring [40].

![Graphene reinforced highly biodegradable PHB based polymer nanocomposites with antimicrobial activity for food packaging applications. The figure has been reproduced with the permission from [39].](image)

**Figure 14.** Graphene reinforced highly biodegradable PHB based polymer nanocomposites with antimicrobial activity for food packaging applications. The figure has been reproduced with the permission from [39].

### 2.3 Bio-based nanomaterials for food packaging

Bio-based nanomaterials are eco-friendly and sustainable packaging materials. These are chosen to make an obstacle for insects and microorganisms that cause degradation of food and spread diseases among the consumers. As a consequence, spoilage of foods and diseases of consumers are completely controlled and minimized [41, 42]. Natural and bio-polymers have found their prospective applications in safe and sustainable food packaging and preservation because of their outstanding, attractive, and unique features, such as
biodegradability, chemical stability, and biocompatibility, which make them an essential source of viable materials for commercial production [43]. Generally, protein-based nanomaterials, carbohydrate (polysaccharide)-based nanomaterials, lipid-based nanomaterials, antibacterial agents, and bio-based nanocomposites are used in antimicrobial food packing system, illustrated in Fig. 15.

Figure 15. Different types of bio-based nanostructured materials utilized for antimicrobial food packaging applications. The figure has been reproduced with the permission from [42].

Starch, chitosan, and cellulose are common non-toxic and biodegradable polysaccharides to serve as an important source of nanosized reinforcements in antimicrobial food packaging [44]. Chitosan is one of the most popular and effective biopolymers in food coating and packaging since it has excellent film forming, antimicrobial, and biodegradable characteristics [45-47]. Chitosan and its derivatives have been employed as an alternative of natural antioxidant and antibacterial agents in powder form, as coating, casted film, and NPs.

Starch, produced from rice, corn, maize, barley, wheat, vegetables, potato, and soya, is extensively utilized as naturally renewable carbohydrate polymeric nanomaterials for making polymer films to be used in food packaging. Starch-based polymer films are cheap, biodegradable, non-toxic, and naturally abundant. They show excellent oxygen barrier
properties but incapable of showing moisture barrier characteristics; however, the inclusion of chitosan in starch can overcome that limitation and improve the mechanical and barrier properties [48]. Starch and its derivatives are very much potential for manufacturing bio-nanocomposite, which could be utilized as suitable materials for cost-effective food spoilage detection and food packaging applications [49]. Nano-starch (NS) is a unique type of starch material with outstanding physiochemical properties. Because of its nano-scale size, NS shows a tendency to agglomeration, a natural process. In addition, due to the presence of a single hydroxyl (OH-) group, NS is unsuitable for hydrophobic environments. That is why modified-NS (MNS) with enhanced hydrophobicity, dispersion property, and stability is more effective to be utilized in many commercial sectors, especially in food packaging applications, illustrated in Fig. 16 [50].

![Preparation of MNS](image)

**Figure 16.** Preparation of modified nano-starch (MNS) particles and their potential applications in food trading. The figure has been reproduced with the permission from [50].

### 2.4 Green polymer nanocomposites for food packaging

Recent concern on petrochemical-based polymeric materials has created huge interest in green polymer nanocomposites for food packaging industries. Biodegradable green polymer nanocomposites should be effectively sensitive to microbial degradation and decomposed into carbon dioxide, water, and inorganic compounds in the presence of naturally occurring microorganisms like bacteria, fungi, and algae when disposed into soil. Green polymer nanocomposite materials must meet basic requirements such as barrier properties for light, aroma, water vapor and gases, strength, printing properties, optical properties, molding and welding properties, migration resistance, thermal and chemical resistance, disposal requirements, antistatic properties, retaining sensory properties, and above all environmental and health safety. The permeability of polymeric nanocomposites depends on the shape, size, and distribution of nanofillers throughout the polymer matrix. The alignment and dispersion pattern of filler NPs may enhance the tortuosity of the gaseous path and diffusion rate in polymer nanocomposites. The presence of regular dispersion of nanofillers with greater surface area and aspect ratio in the polymer matrix
may improve the barrier properties of polymer nanocomposite packaging materials against water vapor, gases, and liquids.

The application of advanced green polymer nanocomposite based packaging materials offers several advantages, such as the protection of food from the attack of various microorganisms and UV radiation, illustrated in Fig. 17. These nano packaging materials can release antimicrobial agents, retain water vapor, absorb ethylene, and remove oxygen. The chitosan/MgO nanocomposite is an essential candidate in food packaging applications, with 86% improved tensile strength and 38% higher elastic modulus compared to pure chitosan [51].

![Figure 17. The functionality of green polymer nanocomposites-based food packaging, which is eco-friendly and protects food against microorganisms and UV light. The figure has been reproduced with the permission from [52].](image)

The effective implementation of nanotechnology has provided the green polymer nanocomposites excellent performance as packaging materials concerning health and environmental safety, and economical benefits including a reduction in emissions and wastages, easy transport and storage, decrease in the chance of any attack of food components and human health, decrease in energy factors of production, protection from gases and light, and biodegradability. Polymers employed for preparing green polymer nanocomposites are different types of carbohydrates, including starch, cellulose, chitosan, agar, alginate, and carrageenan, naturally occurring proteins (soy protein, collagen, casein, corn zein, wheat gluten, gelatin whey protein), and derived components from biodegradable polymers such as poly(L-lactide), poly(glycolic acid), poly(butylene...
succinate), PVA, poly(ε-caprolactone), and microbial polyesters such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate), poly(hydroxyalkanoates), and poly(β-hydroxybutyrate). Green polymer nanocomposite thin films made from starch, kefiran, and ZnO NPs can be used as food packaging material [53]. Such polymer nanocomposite has excellent packaging features such as greater mechanical strength, moisture and oxygen barrier, flexibility, rigidity, thermal and chemical stability, and resistance against the attack of food constituents and microorganisms (Fig. 18).

Green polymer nanocomposites, composed of starch and nanoclay fillers, are suitable for biodegradable packaging materials, as shown in Fig. 19 [54]. Remarkable improvements in barrier properties and mechanical strength might be achieved through the inclusion of nanomaterials as fillers. Extensive research has been conducted to produce environmentally benign green polymer nanocomposites as environmental and health safety are a great concern in the present age.

Soybean polysaccharide based nanocomposites composed of TiO₂ NPs exhibit excellent performance as food packaging materials that extend the food shelf-life up to 6 months. Biodegradable aliphatic polyester polylactide, produced from renewable resources, finds prospective applications in food packaging. Polylactide has been blended with nanofillers like protein, inorganic fillers, starch, and natural fiber flax to prepare a green polymer nanocomposite that represents an effective alternative to conventional polymer composite.

Figure 18. Schematic representation of UV irradiation technique and the activities of ZnO NPs under UV radiation (left side) and the distribution and arrangement of ZnO NPs between the starch and kefiran chains. The figure has been reproduced with the permission from [53].
Figure 19. Photographs (a and b) and scanning electron microscopic images (c and d) of the film produced with 4% (mass/mass) arrowroot starch and 17% glycerol (mass/mass of starch). The figure has been reproduced with permission from [54].

3. Concerns, future scopes, and conclusion

Nanotechnology has a great impact on society through applications in food packaging. It can offer items at a lower price and create more effective food delivery systems. In view of offering safe food, good nutrition, and better health to the present and future world population, novel and advanced technologies are undeniable in the food preservation and packaging industries. For the last few decades, extensive research has been conducted to explore the effective and successful utilization of nanomaterials in different formats by implementing unique and excellent physiochemical characteristics. Nanomaterials have found their modern and advanced applications in the development of novel techniques for food packaging, analysis, preservation, transportation, and safety. The application of nanotechnology and its products in food trading has offered less energy consumption and waste production during any associated process. However, any new technology conveys moral accountability regarding sensible application and the acceptance that there are probable precipitous dangers that might accompany great positive potential. In correspondence to the development and application of nanotechnologies, it is pretty standard that there will be new administrative rules and regulations to oblige nanotechnology products.

Although many research works have been conducted to develop the quality of nanomaterials, investigations on toxicity and freshness are still not adequate or more likely at the initial stage. Substantial studies should be accomplished before the potential application of nanomaterials, especially in the food sector, which is associated with public health and environmental concern. Advanced methods must be implemented so that the properties and the fate of nanomaterials can be identified, characterized, and determined to know the biotransformation in food.
Nanomaterials are progressively being utilized in a broad spectrum of applications. According to present food packaging research, the application of nanostructured materials through the practical application of nanotechnology can provide a variety of alternatives for an active and intelligent packaging system for food preservation and transportation. The approach of utilizing nanomaterials in food packaging is well accepted has become increasingly practical in the food industry in the future due to the increasing demand for the varieties of fascinating foods and the resulting arrangement of safer packaging of food items. Nanotechnology, used to fabricate food packaging, offers remarkable improvements in the characteristics of packaging materials, but more research initiative should be taken to interpret the role of nanotechnology products, their advantages, and disadvantages in the food packaging process.

Acknowledgements

A.B. Imran gratefully acknowledges the support from the Committee for Advanced Studies and Research (CASR) in BUET for funding. MABHs also acknowledges supports from Bose Centre for Advanced Research in Natural Sciences and Semiconductor Technology Research Centre of the University of Dhaka, Bangladesh.

References


