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Nanotechnology in active packaging system for quality and safety of foods

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Review Article

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Abstract

The meat and food products are perishable and highly nutritious that promote the growth of spoilage microorganisms as well as pathogenic microorganisms such as Salmonella spp., *Listeria monocytogenes, E. coli, Clostridium perfringens*, *C. botulinum*, *Staphylococcus aureus* and many others which causing food safety risk quality deterioration. The traditional packaging methods are unable to meet the demands of modern consumers which needs for introduction of smart packaging techniques. Food packaging may play a crucial role to provide consumers with safe and high-quality food products. One of the most innovative food preservation solutions is active packaging. Its functionality is determined by the inherent qualities of the polymer or the particular qualities of the additives used in the packaging systems. Food packaging which expected to be safer, healthier, and provide higher-quality foods with longer shelf life can be enhanced by nanotechnology without compromising the physical or sensory qualities of food items. Nanotechnology is an achievable technology to develop an innovative approach associated with food processing, food safety, and food packaging. Among them, using of nanotechnology in the food packaging has attracted attention because it can improve the safety and quality of the food products. Consequently, this review aim is to provide a summary of the various ways that nanotechnology is being applied in food packaging while emphasizing its main benefits.

Keywords: *Active packaging, nanotechnology, antimicrobial packaging, Antioxidant*

Introduction

The food industry has faced a burden, particularly regarding with regard to food preservation and safety during manufacturing, distribution, storage and handling. Consumers have been looking for effective ways to package and preserve food for extension the shelf life and protect the food products quality. Active materials have emerged as a result of the evolution of the food packaging industry from basic containment to complex systems that actively interact with the packaged food **Jiang *et al.* (2023).** Food packaging is an important to maintain quality and safety of the food products and maintaining their shelf life. Organic active packaging systems perform several functions such as maintaining freshness, quality, and safety in addition to their main purpose of prolonging the shelf life and promoting the food value. Specific organic active packaging materials are engineered to reduce respiration rate, inhibit microbiological growth, or mitigate moisture transfer **Atta *et al.* (2022).**

Organic nanotechnology plays an important role in food preservation, which provides novel approaches to food monitoring and makes it possible to design packaging with special functional characteristics. Organic nanomaterials utilized in the food packaging to enhance the food safety through repair packaging damage, and preservatives can even be released to improve the shelf life of the food products **de Sousa *et al.* (2023).** Using materials at the nanoscale, Packaging can become more stronger, with better gas and moisture barrier qualities, and with antibacterial properties. Organic active packaging broadly divided into non-migratory active packaging and active releasing packaging. Typically, non-migratory active packaging uses scavengers that are designed to remove undesirable elements from the packaging environment without migration. Non-migratory active packaging technologies in food products are commonly used to scavenge oxygen, absorb moisture, and absorb ethylene. On the other hand, Active releasing packaging mainly consists of emitters that help the desired compounds to migrate into the packaging environment in a controlled manner, which benefits the food product **Ahmed *et al.* (2022).** However, food quality can be enhanced and shelf life increased by using of active nanotechnology packaging.

However, safety of using of nanotechnology in the packaging is complicated due to the migration of nanomaterials into the food. Nanostructures may be hazardous to environment and human. Legislation related to nanotechnology packaging differ from each country **Singh *et al.* (2023) Ganeson *et al.* (2023).** In the United States, the Food and Drug Administration (FDA) regulates packaging containing nanotechnology that comes into contact with food. Although US regulations are more flexible than those of the European Union (EU) Which in fact appear more stringent than those of US **Mitrano & Wohlleben, (2020).** The aim of this review article is to cover the knowledge about the application of nanotechnology in the food packaging and its role in food preservation through active packaging technology.

Classification of Active Packaging

Active packaging is commonly found in two types of systems: sachets and pads inside of packages, and substances that are directly incorporated into packaging materials. Due to its intentional alteration and manipulation of the inside environment, active packaging is regarded as an advanced packaging method. Active packaging, which is categorized in Fig. 1, is a broad and varied group with respect to the solutions employed and their function. Using of appropriate active packing extends the product shelf life **Deshmukh *et al.* (2023).**

Figure (1). Graphical representation of several active packaging technology types for using in food packaging **Deshmukh *et al.* (2023).**

Antimicrobial Compounds

Higher water activity foods are more likely to spoil when they are processed, stored, and distributed in an environment that is exposed to the surroundings. Pathogenic bacteria can multiply quickly in the presence of moisture, nutrients, and oxygen concentration, lowering the quality of the food and become inedible. Therefore, using of antimicrobial active packaging can help to protect the food products under these conditions. Using a variety of approaches, antimicrobial compounds can be added to the packaging matrix against pathogenic microorganisms that contaminate food products, a process known as antimicrobial packaging **Deshmukh & Gaikwad (2024).** Antimicrobial packaging could be developed with both natural and synthetic antimicrobial agents. However, due to cost-effectiveness and safety concerns, consumers prefer natural sources of antimicrobial agents. **Khalid *et al.* (2024)** developed nanocomposite films from carboxymethyl cellulose that combined with nanoencapsulated compounds from pomegranate extract. In compared to blank CMC film, the nanocomposite film had high properties, reducing the bacterial growth and extending the meat shelf-life (Fig. 2).

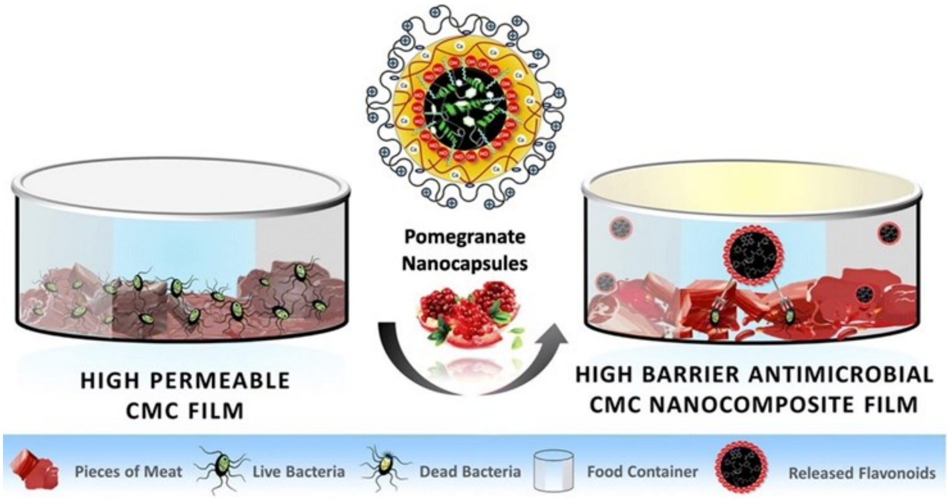

Figure (2). Carboxymethyl cellulose film combined with nanoparticles from pomegranate extract for the meat packaging (Adapted with permission from (Khalid *et al*. 2024), copyright 2024, ELSEVIER).

To increase the ground pork shelf life that kept for 14 days at 4°C, **Song *et al.* (2020)** prepared polyethylene terephthalate (PET) film with 8% rosemary oleoresin. The findings showed that adding of 8% rosemary decreased protein degradation and lipid oxidation. On the other hand, **Laorenza and Harnkarnsujarit (2023)** investigated that the biodegradable active packaging combined with extrusion-derived essential oils from ginger and lemon peel had inhibitory bacterial impact. The outcomes demonstrated a decrease in the overall viable count and inhibition against *Bacillus cereus* **Laorenza & Harnkarnsujarit (2023).** In order to increase the antibacterial activity of shrimp stored at 4 °C for 7 days, **Nazari *et al.* (2019)** evaluated the addition 5% cinnamon essential oil nanophytosomes incorporated with polyvinyl alcohol nanofiber and boric acid films. The findings showed that, in comparison to control and treated samples with cinnamon EO, samples wrapped in active films had lower *Pseudomonas aeruginosa* and TBC. Furthermore, a coating from chitosan functionalized with 1% Satureja plant essential oil nanoliposomes, **Pabast *et al.* (2018)** prevented microbial growth and lipid oxidation in lamb meat while, it was stored for 20 days at 4°C. Similar results were shown by **Esmaeili *et al.* (2020),** who found that cooked sausage wrapped in whey protein or chitosan film implanted with of garlic EO (2%) nanoliposomes during storage at 4°C for 50 days inhibited lipid oxidation and microbiological deterioration.

In order to successfully inhibit microbiological growth during cold storage of chicken sausages, **Mathew *et al.* (2019)** created biodegradable and active polyvinyl alcohol- montmorillonite films with ginger extract linked with Ag NPs. For environmentally friendly in situ ginger extract synthesis mediated Ag-NPs in the composite from AgNO3, a photo-assisted technique employing sunlight irradiation was used. The samples preserved in PVA-MMT-Ag NPs film showed reduction in TVC growth after 4 days of incubation at 4°C when compared to control samples. As a result, **Wang *et al.* (2020)** a chitosan- film combined with ZnO NPs to preserves pork at 4°C during a 7-day storage period. The outcome shown that the rate of growth of TBC was slowed down in comparison to the control and treatment. On the other hand, **Mohammadi *et al.* (2019)** showed a reduction in the total viable count, *Staphylococcus aureus* and lactic acid bacteria count (LABC) growth during storage with addition of 1% ZnO NPs to active packaging. Furthermore, it prevents the lipids oxidation and the proteins breakdown in chicken meat samples that are kept in carboxymethyl cellulose film for 9 days at 4°C. Furthermore, when addition of ZnO NPs (3%) to a film with agar-based made of *Gracilaria vermiculophylla* to extend the shelf life of smoked salmon kept at 4°C for 9 days **Baek & Song (2018).** This innovative active packaging extended the shelf life and preventing growth of *Salmonella Typhimurium* and *Listeria monocytogenes*.

EFSA statement on the risk assessment of titanium dioxide exposure from food additives (E 171) conducted by the ANSES (Food, Environmental, and Occupational Safety) agency. In this respect, ANSES recommended additional investigation of in vivo genotoxicity, EFSA considered this recommendation should be revisited once the ongoing work on the physiochemical characterization of the food additive titanium dioxide (E 171) is completed. However Titanium dioxide nanoparticles (TiO2 NPs) have antibacterial activity that can be attributed to multiple processes, such as direct interaction with bacterial cells, production of secondary oxidative products or the breakdown of toxic heavy metal ions **Biswas *et al.* (2020).** TiO2 NPs and titanium dioxide nanotubes (TiO2 NTs) have been used in active food packaging because of their antibacterial action, high thermal stability, promise as a UV absorber, and low toxicity to human cells. To increase the beef shelf life kept for 15 days at 4°C, **Feng ZhiBiao *et al.* (2019)** examined the antibacterial and antioxidant properties of adding TiO2 NPs and TiO2 NTs to an edible coating film based on whey protein nanofibrils. While there was a change from the control sample, The beef samples coated with film functionalized with TiO2 NPs and TiO2 NTs did not differ statistically significantly in their TBARs values over the course of storage. However, in comparison to the control and TiO2 NPs coating film sample, the TVC of samples coated with TiO2 NTs showed the reduction in count after 15 days. In this context, **Alizadeh-Sani *et al.* (2020)** effectively created an active biodegradable packaging from whey protein embedded with 2% rosemary oil essential oil (EO) and 1% TiO2 NPs as antioxidant and antimicrobial agents, as well as cellulose nanofiber as a filler, to preserve lamb meat kept for at 4°C 15 days. The outcome showed that during storage, lipid oxidation and microbiological growth were greatly inhibited in lamb meat, increasing its shelf life from 6 to 15 days.

In order to control the microbial over growth (fecal coliforms, TBC and *Staphylococcus aureus*), protein degradation (TVB-N) and oxidative rancidity (TBARs) of fish fillets and minced chicken during storage for 12 days at 2 to 4°C, **(Kanatt 2020)** investigated the impact of incorporating *amaranthus* leaf extract in PVA and gelatin film. According to these results, only samples that kept in active films started to deteriorate after 12 days, whereas the shelf life of the control samples were three days.

Despite the numerous benefits and and advantages of nanoparticles as in general and nano- oxides as special materials in food preservation as antibacterial and antioxidant, we would like to note once again the concerns of the European Food Safety Authority about the potential risk to the safety and health of consumers from consuming foods to which those inorganic nanoparticles are added which previously mentioned in this article and the requirements that would prove whether or not there is harm to consumer or not.

Antioxidant Agents

One of the main factors contributing to food spoilage is the oxidation of fats and lipids, which tends to reduce the shelf life of foods by changing their flavor and/or texture and impairing the functionality of meals high in protein, such as fish and meat **Dominguez *et al.* (2019).** By enhancing chemical stability, various polymers incorporate antioxidant chemicals to reduce these undesirable occurrences and prevent or delay food deterioration. Originally, the polymer was treated with a synthetic antioxidant, such as butylated hydroxy anisole (BHA) or butylated hydroxytoluene (BHT), in order to develop antioxidant packaging **Deshmukh & Gaikwad (2024).**

Combining EO with other antimicrobials and/ or antioxidants-especially nano emulsions-was shown to have a synergistic impact. Regarding this, pork meat that are ready-to-eat covered with *Artemisia sphaerocephala* Krasch gum film incorporated with 0.6% nano emulsion (poly-lysine, nisin and star anise EO) was successfully kept fresher longer **Liu *et al.* (2020).** Minced beef's shelf life of was extended for 23 days when kept at 4°C **Borzi *et al.* (2019),** who created a polyamide (nylon 6)-active film functionalized with 5% green tea extract, which is abundant in polyphenols, primarily in catechins. The findings demonstrated that the active film-wrapped samples' lipid, protein oxidation, and protein degradation were reduced during storage and extending the minced beef shelf life.

Carbon Dioxide Emitter and Absorber

The shelf life of food can be increased by optimizing the CO_2 level in active packaging. In the food sector, CO_2 works by a variety of intricate methods, such as cytoplasmic pH shifts, inhibition of bacterial enzymes, and modification of the bacterial cell membrane. By working together, these mechanisms cause the lag phase to lengthen and inhibited many spoilage bacterial cells **Yildirim *et al.* (2018).** Carbon dioxide has the ability to reduce microbial proliferation, oxidize and reduce substances, enhance sensory qualities and prolong product shelf life.

Oxygen Scavengers

Food spoilage is caused by multiple factors including enzymatic processes, microbiological growth, and chemical nutrient degradation **Singh *et al.* (2016).** Oxygen, in some cases, in packaged food or oxygen produced by the metabolic process of fresh products causes food to deteriorate. Oxygen from the metabolic reaction accelerate the rancidity of fat, color change, fast-growing of aerobic bacteria and decrease the nutritional value **Vermeiren *et al.* (2003).** Vacuum packing and modified atmosphere packaging (MAP) have been routinely used to remove oxygen from packages. However, this method is limited and cannot completely evacuate oxygen. Accordingly, oxygen scavengers are designed to remove any oxygen from the package up to a concentration of less than 0.01% **Gupta (2024).** A substance known as an oxygen scavenger is one that neutralizes oxygen chemically or enzymatically, protecting the food products from deterioration. Initially, iron-based scavengers were used in sachets to absorb oxygen, moisture and enzymes **Gaikwad & Lee (2017).** With the innovation, oxygen scavengers were integrated into the packing matrix to replace the pads and sachets.

Recent advancements in oxygen scavengers are predicated on the development of polymeric films with incorporated oxygen scavengers. The use of sodium carbonate and pyrogallic acid for LDPE-based oxygen scavenging was documented by **Singh *et al.* (2019).** It was found that the developed film was used to package peeled garlic, the oxygen concentration stabilized considerably more quickly at 5 ° C than it did at 25°C. Conversely, due to continuous respiration, oxygen and CO_2 in the control samples were not stabilized. The use of acetophenone, photocatalytic system (PCS), manganese chloride and natural rubber latex (NRL) in UV-activated based oxygen scavenging was described by **Ramakanth *et al.* (2022).** The oxygen concentration (21.9%) in the glass vial was lowered to 0% in 60 and 20 days using natural rubber latex with 3% weight PCS at 25°C and 45°C, respectively.

Migration of nanomaterials from packaging materials to food matrix

When using packaging or coating in food products, including hazard assessments for each substance on carcinogenicity, mutagenicity, nephrotoxicity, bioaccumulation, endocrine disruptor (ED), and genotoxicity, the migration rate of nanostructure materials is an additional factor that must be considered. Food packaging migration is the process by which an additive diffuses from the coating or from the polymeric matrix or into the food or food simulant (EFSA Panel on Food Contact Materials, enzymes and processing aids **CIP (2020).** This migration process may or may not be advantageous, depending on the nature of the substances. In most cases, it is anticipated that the active compound will migrate to the food packaging for active and intelligent packaging once it is in charge of safeguarding the packaged food **Souza *et al.* (2019).** However, toxic chemicals that are harmful for human health can also migrate; in this case, they are regarded as contaminants. A number of variables affect the migration process, including the contact time with the food during storage, temperature (during storage or during the heating process), the type of contact, the characteristics of the substances or migrants migrating (such as molecular weight, volatility, and polarity), and the properties of the food (such as composition, fat content, and properties) **Xue *et al.* (2019).** The degree of migration attained also affects the toxicity of nanostructures because higher concentrations of nanoparticles are linked to more harmful outcomes **DeLoid *et al.* (2017).** Nanostructure migration from the packaging film to food is shown in Fig. 3.

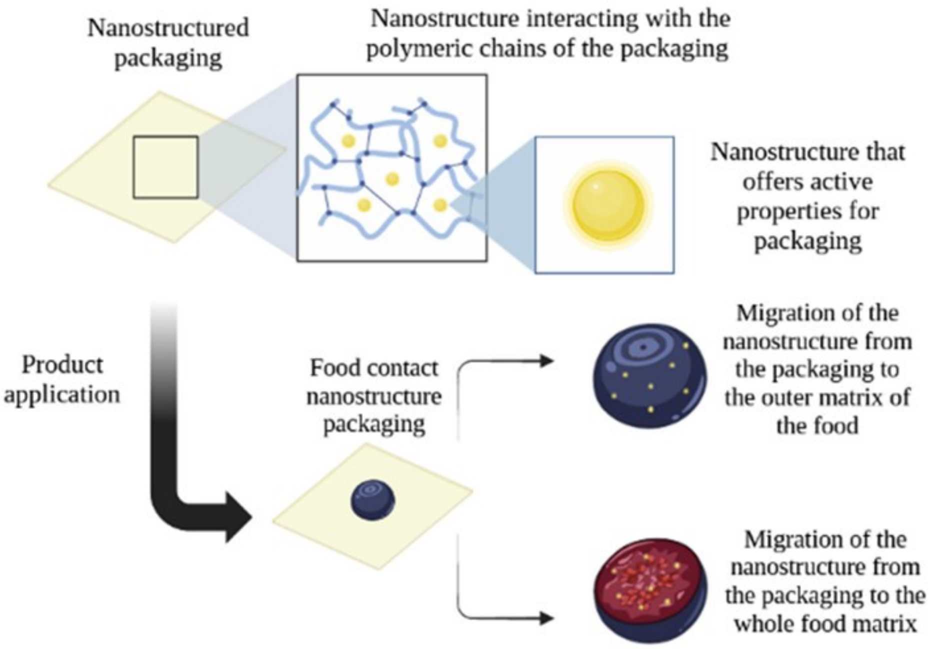

Figure (3). Nanostructure migration from a packaging film surface to food.

Conclusion

To increase the shelf life of food products, the food industry has made conscious efforts to use less additives directly. The application of nanotechnology to encapsulate active ingredients like antioxidants and antibacterials has demonstrated significant promise in the creation of novel active packaging for food products. By incorporating antioxidants and antimicrobials with nanomaterials into active packaging, oxidative stability and microbiological safety are greatly increased, resulting in longer shelf life for and a decrease in the quantity of antioxidants and antimicrobials required for meat processing.

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