Chapter 4
Application of Nanoparticles to Enhance the Microbial Quality and Shelf Life of Food Products

Saeed Paidari, Yasaman Esmaeili, Salam A. Ibrahim, Shima Vahedi, Sawsan Ali Al-Hilifi, and Nafiseh Zamindar

Introduction

Raw and processed food products help people to obtain their intended energy, but raw products begin to exhibit reactions to deterioration after harvest and caused great waste all over the world. Food preservation is one of the widely used to address food waste concerns. The objective of food preservation is to block metabolic processes and prohibit the growth of bacteria or fungus (Saravanan et al., 2021). Due to relatively recent changes in the lifestyle of consumers, there has been a concomitant increase in the demand for products that are ready-to-consume or minimally processed (Białkowska et al., 2020).

Consumers require microbially safe, fresh or fresh-tasting, nutritious, shelf-stable, and accessible products made using ecologically friendly technology. Inadequately performed food processing procedures such as peeling, slicing, or washing, can present a danger to public health, particularly if these products are

S. Paidari (✉)
Department of Food Science and Technology, Science and Research Branch, Islamic Azad University, Tehran, Iran

Y. Esmaeili · N. Zamindar
Department of Food Science and Technology, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran

S. A. Ibrahim
Food Microbiology and Biotechnology Laboratory, Food and Nutritional Science Program, North Carolina Agricultural and Technical State University, Greensboro, NC, USA

S. Vahedi
Department of Food Science and Technology, Damghan Branch, Islamic Azad University, Damghan, Iran

S. A. Al-Hilifi
Department of Food Science, College of Agriculture, University of Basrah, Basrah, Iraq

F. Ahmad et al. (eds.), *Microbial Biotechnology in the Food Industry*,
https://doi.org/10.1007/978-3-031-51417-3_4

handled and disseminated inappropriately. In addition, microbial contamination with pathogen microorganisms can cause illnesses and lowered nutrition content in foods. Consequently, the effective control of spoilages established by bacteria is one of the most critical aspects of food production, processing, transit, and storage (Jaiswal et al., 2019).

Nanotechnology is the technique used to manipulate nanoparticles for a variety of applications. It plays a critical role in food and agricultural industries by promoting plant growth, enhancing food security and quality, and improving public health in novel and inventive ways (Duncan, 2011a). In addition, nanoparticles are used as nano additives, nanocapsules, gelating compounds, anti-caking factors, etc. in the food industry. Food safety, conservation, and functionalization are thus the core functions of nanotechnology in food security (Ghosh et al., 2020).

Nanoparticles (NPs) are tiny substances ranging in size between 1 to 100 nm. They are non-soluble or bio-persistent by nature, may be manufactured by a variety of methods, and are used in a variety of fields of study, such as the medical, electrical, agricultural, and food industries (Duncan, 2011b). Due to their prospective antimicrobial properties, silver (Ag), gold (Au), zinc oxide (ZnO), titanium dioxide (TiO_2) and carbon NPs are produced tenfold more than other nanomaterials. These NPs are used in air purifiers, food packages, deodorants, band aids, toothpastes, acrylics, and other consumer products (Kumari et al., 2009). In addition, the strong antimicrobial activity of nanosized copper oxides (CuO) has led to their widespread use in commercial nano-biocides (Nair et al., 2010). Food nanotechnologies employ nanoparticles of different sizes to provide healthier, safer, and high - quality products. Nanotechnology in food product packaging has demonstrated significant potential for enhancing the material characteristics of packaging. Nanocomposite antibacterial packaged techniques are effective, and large surfaces and the elevated surface energy of nanofillers produce positive interfacial interactions among polymer bonds and NPs. As a result, NPs substantially enhance biopolymer qualities such as thermal, mechanical, barrier and antibacterial activities (Sharma et al., 2020). This chapter explores the potential uses and applications of various NPs in food processing, microbial quality, storage time, as well as the ways in which NPs can be effective in extending the storage life and improving the quality of various products.

Food-System Nanoparticles

Inorganic NPs

Various types of NPs that have been used in food items are mostly constituted of inorganic components such as Ag, iron oxide, TiO_2, silicon dioxide, and ZnO. These components can be crystalline or amorphous, spherical or non-spherical at ambient temperature, exhibit variable surface features, are dependent on the original materials and processing techniques for production and come in a range of sizes (Ghosh et al., 2019). Inorganic NPs, such as metallic NPs and nanoclays, attach to the pathogen cell membrane and cause inactivation by producing reactive oxygen compounds. Protein denaturation, DNA damage, and ion release may be attributable to reactive oxygen species (ROS) (Hoseinnejad et al., 2018).

Organic NPs

Organic NPs with antimicrobial capabilities include chitin nano-fibrils, nanofiber of cellulose or nanocrystals, and additional nanostructures generated from biopolymers using a solution casting technique to make carrageenan-based nanocomposites fortified with chitin nano-fibrils. Strong antibacterial action against *Listeria monocytogenes* was shown by the produced films. Additionally, grape seed extract is widely recognized for its significant antibacterial activity against Gram-positive (G+) microorganisms and has been used to generate antimicrobial biopolymer-based nanocomposite films for utilization in food packaging. (Jaiswal et al., 2019). Organic compounds may dissolve, accumulate, or be broken down in the mouth, stomach, small intestine or colon based on the composition and structures of the compounds. Organic NPs are assumed to be less hazardous than inorganic ones because they are broken down in the gastrointestinal tract (GIT) and are not bio-resistant (Ghosh et al., 2019).

Nanotechnology in Food Processing

Food processing refers to the way of preserving food using techniques to change the food into a state that is suitable for consumption. The main goals in food processing are to maintain the structure of the food and increase its storage period. The term nano-food refers to nanotechnology-processed, manufactured, secured, and packaged food. Nutritional supplementation, gelation and viscosification, nutrient delivery, vitamin supplements, and flavor nano-encapsulation are examples of nanomaterial-based food processing methods (Hossain et al., 2021). As gas and moisture barriers, edible nano-coatings (thin coatings around 5 nm) may be feasible for meat products, fruits, vegetables, cheese, processed food, and baked products. Nano-filters are applied to beetroot juice for discoloration without any damage to product flavor, and also, for production of lactose free milk by replacing lactose with other polysaccharides and making the milk appropriate for lactose-intolerant consumers (Bratovcic, 2020).

Advancement of NPs, or nano-textures, in food products as preservative factor or in packaging are subgenres of the use of nanotechnology in food processing. In general, nano-emulsions, surfactant microcapsules, emulsion multilayers, double or multiple emulsions, and reverse micelles are the techniques employed to produce nanostructured food items. Examples of nano-textured food include spreads, mayonnaise, cream, yogurts, and ice creams, etc. (Jayakar et al.). Nanotechnology is effective in a term of food-borne illnesses prevention and production of healthier foods with less fat, sugar, and salt content. It has been reported that TiO_2 is approved as an additive in gums, sauces, and baked products (Weir et al., 2012). Furthermore, CuO, ZnO and iron oxide, have been classified as GRAS (generally recognized as safe) components for animal and plant products by the European Food Safety Authority (EFSA). Nutralease (enhancing nanoparticles to transport nutraceuticals and pharmaceuticals), Neosino capsules (nutritional supplements) and nano green tea are the most prevalent developed nanotechnology-based items currently on the market (He et al., 2019; Paidari & Ibrahim, 2021).

Nanotechnology for Food Preservation

Due to their antibacterial and physiochemical capabilities, usage of NPs is a popular method against pathogenic bacteria in healthcare, crop protection, water purification, food safety and preservation (Baranwal et al., 2018). The processing and preservation aspects of nanoparticles include nano-encapsulation, nano-emulsions, nano-formulations, and noncomposites. These innovative and novel usages of nanotechnology have the ability to solve a variety of issues faced by food technologists. For example, food NPs have active capabilities that may minimize a variety of food supply problems. Because of the obvious advantages of nanotechnology, its applications in food have grown dramatically (Donsì et al., 2011). The promising achievements of nanotechnology may be attributed to its low pollution, efficiency of energy, and small space needs. In addition, nanotechnology has several uses in agricultural, food, and environmental safety, toxicity, and risk assessment. (Anvar et al., 2019; Kaphle et al., 2018; Paidari & Ahari, 2021).

Nano-antimicrobials may prevent food deterioration and extend storage life. Many metal and metal oxide NPs have been suggested as antibacterial agents. Also ROS produced by attachments of metallic NPs to the pathogen cell membrane, have unique physicochemical properties, and caused oxidative stress and cell damage (Prasad et al., 2016).

Yu et al. produced silica in-situ poly-vinyl alcohol (PVA)/chitosan (CS) based films that are organic, cost-effective and possess very beneficial mechanical properties. These films decreased moisture and oxygen permeability by 10.2% and 25.6%, respectively, and tripled the cherry preservation period compared to standard packaging.(Yu et al., 2018). Chitosan NPs (CSNPs) have outstanding bioactivity and physiochemical properties that contribute to their growing popularity in food preservation (Yang et al., 2010).

Nanotechnology in Food Packaging

Food packaging techniques are designed to ensure that food quality is maintained and the food is safe for consumption. The packaging provides physical protection from external shocks and vibrations, microbiological contamination and heat by absorbing oxygen and other gases that contribute to product deterioration (Dera & Teseme, 2020; Esmaeili et al., 2021, 2022).

Most of the NPs used in food packaging have potential antibacterial action and prevent microbial spoilage. Through the controlled release of antimicrobials from the packed substance, packaging material composed of a coating of starch colloids containing the antimicrobial agent works as a barrier against microorganisms. NPs are employed as incorporate enzymes, antioxidants,, flavors and anti-browning agents carrier and other bioactive substances to extend the storage time of opened packages (Nile et al., 2020) (Fig. 4.1).

Fig. 4.1 Nanotechnology role in food packaging

Edible Film Packaging

Increased consumer demand for naturally preserved foods has prompted the food industry to investigate alternative preservation techniques. For example, edible biopolymers from renewable resources or industrial wastes are used in various packaging techniques (Hassan et al., 2018). Due to their benefits over synthetic films and their potential in preserving food, edible coatings have attracted great attention (Galus & Kadzińska, 2015). Nanotechnology has improved the functionality of edible films for food applications in recent years. It is feasible to include functional agents such as antimicrobials, anti-browning agents, antioxidants, enzymes, flavors, and colors by incorporating charged lipid or colloidal particles into nano laminated edible films (Duran & Marcato, 2013). Emamifar and Bavaisi revealed that nano-ZnO in edible sodium alginate coatings increased antioxidant activity and decrease microbial load, vitamin C content and weight loss. After 20 days, untreated strawberries exhibited greater antioxidant activity and phenolic degradation than coated ones (Emamifar & Bavaisi, 2020).

In another study, biodegradable starch-pectin-TiO_2-NPs composite edible films were created from sweet potato starch and lemon peel pectin containing TiO2-NPs. A small concentration of TiO_2-NPs improved the mechanical and moisture barrier properties of starch-pectin coatings, making them appropriate for food-grade biodegradable packaging material with UV protection (Dash et al., 2019).

Wang et al. created a Cheddar cheese-preserving edible film incorporating whey protein isolate nanofibers and carvacrol. Results show that the edible films have antibacterial action against, *Salmonella enteritidis,* Staphylococcus. *aureus, Escherichia coli,* and *L. monocytogenes*. Additionally, the antioxidant capacity was increased. Consequently, the authors asserted that whey protein nanofibers coatings might enhance the attributes of fresh cheddar cheese during storage (Wang et al., 2019).

Soltanizadeh and Goli examined the effect of aloe vera and eugenol bio-nano-coating on the physical and chemical parameters of fried shrimp. The coating significantly reduced quality loss during cooking and absorption of oil through frying and slowed the oxidation process during the freeze storage of samples. However, higher eugenol concentrations resulted indetrimental effects on the texture attributes of fried samples, and the combination of 2% aloe vera and 3% eugenol nanoemulsion proved to be the best coating material (Sharifimehr et al., 2019).

Tabari evaluated the impact of adding carboxymethyl cellulose (CMC) NPs to sago starch on water absorption capacity, physiochemical characteristics density, and sealability of films. By increasing CMC NPs concentration, mechanical characteristics increased significantly ($P \leq 0.05$) and tensile strength and elongation parameter considerably ($P \leq 0.05$) decreased from 17.69 to 15.39. Consequently, this film may be utilized as an edible film for food products and pharmaceutical packaging in different sectors, notably the food industry (Tabari, 2018).

Using ZnO nanorods (ZnO-nr), Jafarzadeh et al. fabricated nanocomposite films by solvent casting. The ZnO-nr particles were uniformly dispersed across the film surface, as demonstrated by SEM pictures. The amount of ZnO-nr significantly affected semolina coating absorbance and adding ZnO-nr considerably decreased oxygen permeability and thermal sealability, as revealed by the results. The nanocomposite coatings absorbed more than 90% of the near infrared spectrum (Jafarzadeh et al., 2017). The edible films of whey proteins incorporating TiO_2 NPs displayed superior physiochemical, moisture barrier, and antimicrobial characteristics (Sani et al., 2017).

Nano-encapsulation

Encapsulation includes wrapping bioactive molecules with a barrier component or enclosing them inside shells or carriers.

Encapsulation's primary purpose is to shield the vital ingredient from damaging external factors such as light, humidity, and oxygen. This will extend the product shelf life and provide controlled encapsulation extraction, In addition, ease of handling, enhanced stability, prevention of oxidative stress, preservation of volatile substances, taste modification, moisture-triggered controlled release, pH-triggered controlled release, active compounds continuous delivery, flavor character change, long-lasting organoleptic impression, and improved bio-accessibility and effectiveness are other applications of encapsulation (Pradhan et al., 2015).

The small size of the bioactives inside the capsules facilitates their distribution to the intended location. Nanocapsules are preferable to microcapsules in terms of stability, solubility, and encapsulating efficiency (Malik et al., 2019). Various encapsulating processes, such as nanoemulsion, coacervation, the extrusion technique, fluidized bed coatings, spray chilling, and spray drying, have been utilized to create nano or micro-particle systems (Bajpai et al., 2018).

Most of the bioactive molecules such as lipids, proteins, polysaccharides, and minerals are susceptible to the high acidity and enzyme activity of the mucosal lining of the GI tract. Encapsulation of these bioactive components promotes their absorption in food items, which is difficult to do in their un-encapsulated state due to their low water solubility (Singh et al., 2017).

Based on wall material chemical structures that are used for nano-encapsulation of food components, nanostructures are divided into three types: (1) lipid-base nanosystems, such as archeosomes, solid lipid NPs, colloidosomes, nanocochleates, and nanoliposomes; (2) polymeric-type nanosystems, such as, carbohydrate-based NPs, pectin, chitosan nanofibers, cellulose, dextran, guar gum, alginate, and starch; and (3) protein-base nanosystems, such as zein ultrafine fibers, milk protein nanotubes and corn protein (Ghosh et al., 2019). Liposome is an indication of a nanotransporter that is utilized for nano-encapsulation of various components. Nano-transporters are applied for carrying nutraceuticals, minerals, proteins, vitamins, antimicrobial compounds, and additives. Due to the superior solubility and specificity of the encapsulated elements, lipid-based encapsulation techniques are more effective than other alternative encapsulation systems (Dera & Teseme, 2020).

Carbohydrate NPs used for oil encapsulation are digestible or indigestible polysaccharides such as sodium, alginate, pectin, and cellulose. Physicochemical stability and solubility of algal oil NPs demonstrate a system efficiency of 98.57 (Wang et al., 2020).

Mohammadi et al. investigated the influence of a CSNPs coating containing *Zataria multiflora* EO on the storage life and antioxidant activity of cucumber. In this study CSNPs-*Z. multiflora* composites with a weight ratio of 1:0.25 were prepared and had an acceptable encapsulation efficiency and load capacity. After 21 days of storage at 10 ± 1 °C, cucumbers with CSNPs -*Z. multiflora* composites exhibited superior quality compared to those with simply CSNPs coating or distilled water treatment (Control) (Mohammadi et al., 2016). Lipids, β-carotene, nisin, coenzyme Q10, oregano essential oil (EO), and particular probiotics are nanoencapsulated nowadays. Release time of encapsulated EO delayed and extended by utilizing CS/cashew gum. Encapsulated samples exhibited potential bactericidal effect against *Stegomyia aegypti* larvae (Abreu et al., 2012; Esmaeili et al., 2021, 2022). Imran et al. created soy and marine lecithin-based liposomal nano-delivery technologies for encapsulating the food preservative nisin (Imran et al., 2015). In another study, 1-octenyl succinic anhydride refined starch (OSA-ST) was used for coenzyme Q10 encapsulation. Coenzyme Q10 dissolved in rice bran oil and added into OSA-ST solution. Results indicated that the dietary supplement coenzyme Q10 had been effectively nano-encapsulated with this combination and particle size of this mixture was about 200–300 nm (Cheuk et al., 2015). Zhang et al. revealed that compared to non-capsulated thymol EO, thymol encapsulated inside a zein NPs successfully inhibited the development of G+ pathogens (Zhang et al., 2014).

Nanoemulsion

Nanoemulsions are applied in the manufacturing of salad dressings, sweeteners, flavored oils, customized drinks, and other processed products. Using a variety of inputs such as heat, pH, ultrasound waves, etc., nanoemulsions assist in the release of various flavors. They effectively preserve the sensorial attributes and protect them from oxidation and enzyme processes. Compared to traditional emulsions, nanoemulsions serve as exceptional carriers for many bioactive substances by providing premier features such as high optical clarity, physical properties such as texture and aggregation, and increased bioavailability (McClements & Rao, 2011).

Nano-emulsions are oil-in-water emulsions and range in size from 50 to 200. The nano-droplet size provides nanoemulsions with remarkable transparency. When added to food, nanoemulsions display rheological and textural properties that are highly stable through extended time periods (Malik et al., 2019). Various foodborne pathogens, such as Gram-negative (G-) bacteria, are strongly inhibited by nanoemulsions (Nile et al., 2020).

Nano-emulsions are produced by distributing liquid phase in water phase in a continuous process. The components utilized to create nano-emulsion are lipophilic, with the lipophilic component being extensively incorporated into the oil phase. Numerous factors, including the molecular and physicochemical features of the component, dictate the position of the lipophilic component inside the nano-emulsion. Nanoemulsions have the physical attributes of hydrophobicity, surface activities, oil-water diffusion index, dispersion, and melting temperature. By creating nanoemulsions, several lipophilic substances are encapsulated. Nano-emulsions are preferred over conventional emulsions due to their smaller droplets, larger surface area, and faster digestion and absorption by digestive enzymes (Pradhan et al., 2015).

Due to their activity, and non-toxicity, nano-emulsions in edible coatings have recently attracted significant attention. However, the nano-system is not well commercialized. Nano-emulsions in edible coatings include flavor, coloring, antioxidant agents, and antimicrobials for meats, dairy, and fruits application (Aswathanarayan & Vittal, 2019). As antimicrobial agents, nano-emulsion based oregano EO was added to low-fat sliced cheese in order to improve its storage period (Artiga-Artigas et al., 2017).

Antimicrobial Properties of Nanoparticles

Pathogens and antimicrobial-resistant organisms that cause spoilage in food products are a significant public health concern; thus, several studies have been conducted with the purpose of enhancing recent antimicrobial methods. Metal NPs such as Ag, Zn, Cu, gold (Au), and titanium (Ti) exhibit diverse antibacterial activity features, with potencies and activity spectra that have been recognized and used for decades (Malarkodi et al., 2014). The antibacterial properties and efficiency of NPs are significantly impacted by the composition and their droplet size (Khezerlou et al., 2018) (Table 4.1).

Recently, Muhammad Bilal Khan Niazi et al. produced biodegradable nanocomposites for antibacterial application in food packaging. Both G+ and G- organisms were susceptible to the antibacterial capabilities of the coatings, and a powerful antibacterial effect was found against G- bacteria (*Escherichia coli (DH5-alpha)*) (Sarwar et al., 2018).

CSNPs were created using ion gelation for the fabrication of starch-based nanocomposites. The antibacterial properties of starch/CSNPs films were investigated by a disc diffusion study in vitro and microbial count in film-wrapped cherry tomatoes in vivo experiments. For all bacteria studied, including *Bacillus cereus, Staphylococcus aureus, E. coli,* and *Salmonella typhimurium*, the inhibitory zone of starch/CSNPs films (15% and 20% w/w) was identified (Shapi'i et al., 2020).

Ag was the most common inorganic antimicrobial NP (Zinjarde, 2012). Various plastic and biodegradable coatings benefit greatly from the antibacterial impact of Ag. In addition, Ag NPs have several biological uses (Khezerlou et al., 2018) (Fig. 4.2).

Table 4.1 Bio-nanocomposite coatings as packaging to increase the microbiological stability of food products

Bio-nanocomposite	Food product	Results	References
Semolina/ ZnO- NPs & nanokaolin	Low-moisture Mozzarella	The bio-nanocomposite coatings maintained the physical and sensory qualities of cheese and inhibited microbiological activity for 72 days.	Jafarzadeh et al. (2019)
Gelatin/cellulose nanofibrils/ag NPs	Fruits and vegetables	Appeared significantly effective against *E. coli* and *S. aureus.*	Li et al. (2019a, b)
Pectin/nanohybrid-layered double-hydroxide salicylate	Apricots	Enhanced pectin elongation at breakpoint; enhanced water vapor barrier characteristics; extended the storage period.	Gorrasi and Bugatti (2016)
PLA/PBAT/nanocrystal cellulose-silver nanohybrids	–	Antimicrobial properties were exhibited against *E. coli* and *S. aureus*.	Ma et al. (2016)
Chitosan and mandarin EO Nano-emulsion	Green beans	Decrease in the *L. monocytogenes* population	Donsì et al. (2015)
Chitosan–silver nanocomposite	–	Antimicrobial properties against *L. monocytogenes, E. coli, S. aureus,* and *S. typhimurium*.	Rhim et al. (2013)
Pullulan films/NP (silver or ZnO NPs)/ oregano or rosemary EOs	Turkey deli meat	The antibacterial impact of pullulan nanocomposites was retained at low temperatures (< 25 °C) but was drastically diminished at temperatures over >25 °C.	Khalaf et al. (2013)
PLA and AgNO3	Fresh-cut vegetables	Exhibited strong antifungal and antibacterial activities with increasing Ag concentration.	Martínez-Abad et al. (2013)
Cellulose absorber/Cu	Melon and pineapple juices	Strong antifungal action, decreasing yeasts and molds related to deterioration.	Llorens et al. (2012)
Sodium alginic acid silver-montmorillonite nanoparticles	Fiordilatte cheese	Promoted microbiological stability by inhibiting *Pseudomonas* spp. growth.	Gammariello et al. (2011)
Silver NPs immobilized in cellulose and collagen	Sausage	Antibacterial efficacy against *E. coli* and *S.aureus*	Fedotova et al. (2010)

Recent investigations have shown that Ag NPs are safe for application for packaging and films in the food industry with no measurable or negligible quantities of migration from saturated containers into food samples and food simulants. Nanocomposites provide high stability, which is crucial for preserving antibacterial action and decreasing the chance of metal ion migration into preserved foods (Aziz et al., 2019).

Several researchers have reported the green production of Ag NPs from silver salts utilizing parsley (*Petroselinum crispum*) leaf extract, celery leaf extract, etc. Apple and cucumber extraction are effective for the production of Ag NPs (10 nm)

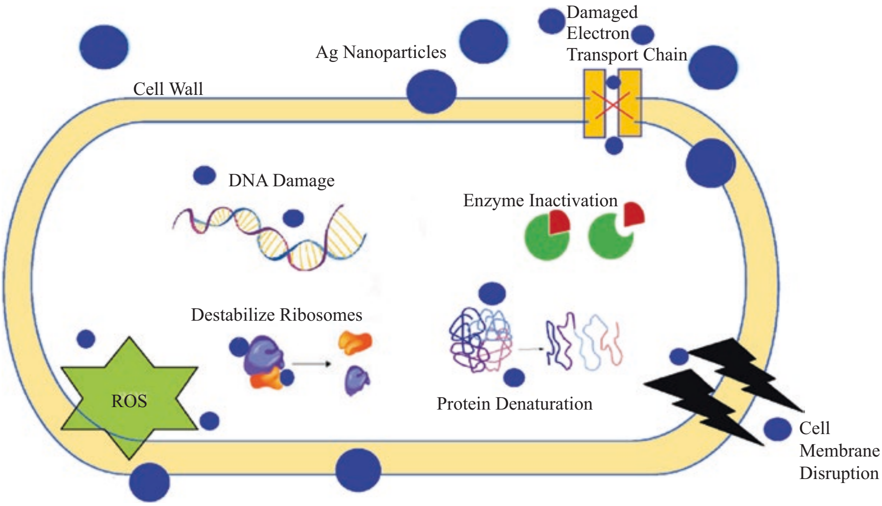

Fig. 4.2 Antimicrobial mechanism of Ag NPs

among fruit extracts. The effect of PLA nanocomposites containing bergamot EO, TiO_2 and Ag NPs on the storage time of mango samples at ambient temperature for 15 days was evaluated by Chi et al. Conclusions proved that PLA/NPs films could preserve the freshness of mango, extend its storage life up to 15 days and delay the weight loss of samples (Chi et al., 2019).

Ag NPs were also tested against *S. typhimurium, Listeria monocytogenes, Vibrio parahaemolyticus,* and *E. coli*. According to the results, Ag NPs exhibited significant antimicrobial impacts. Thus, Ag NPs are a viable option for disinfecting surfaces and equipment that come into contact with food products (Khezerlou et al., 2018).

Shahrokh and Emtiazi discovered that Ag NPs at small concentrations (0.2 ppm) stimulated bacterial activity. As a result, the researchers proposed using an optimal concentration of Ag NPs for different nanomaterials in order to minimize biofilm development (Shahrokh & Emtiazi, 2009).

ZnO is a safe supplement for food applications and coatings that have direct contact with food and the human skin and body (Ravindranadh & Mary, 2013). In fact, ZnO NPs have antibacterial effect against both G+ and G- bacteria and are high pressure and high temperature resistant (Khezerlou et al., 2018). Compared to micro-particles, ZnO NPs have excellent antibacterial activity due to their surface area (Seil & Webster, 2012). According to Emamifar and Bavaisi, inserting nano-ZnO in edible sodium alginate coatings boosted its antioxidant activity anddecreased the quantity of oxygen needed for the oxidative stress of anthocyanin and phenolic compounds (Emamifar & Bavaisi, 2020).

The antibacterial impacts of ZnO NPs against pathogens and spoilage microorganisms in food products was investigated by Espitia et al. ZnO NPs exhibited no significant antibacterial effect *against Pseudomonas aeruginosa, Lactobacillus plantarum,* or *L. monocytogenes* but showed substantial antibacterial action against *Saccharomyces cerevisiae, Salmonella choleraesuis, S. aureus, E. coli,* and *Aspergillus niger* (Espitia et al., 2013).

Due to their nontoxicity, polyvalent impacts, high capacity to be functionalized, detection efficiency and photothermal activities, gold (Au NPs) are regarded as useful in the creation of antibacterial agents (Lima et al., 2013; Lokina & Narayanan, 2013). Researchers have developed an EO droplet emulsified with gold NPs and have also used NPs to encapsulate peppermint and cinnamaldehyde EOs (Schmitt et al., 2016).

Based on the findings, Au NPs reduced *Salmonella typhi* and *E. coli* colonies by 90–95%. According to the researchers, the distribution and hardness of Au NPs on the medium were the primary parameters influencing the bactericidal characteristics (Lima et al., 2013).

Clay NPs are composed of mineral silicate layers. Based on their chemical composition and form, these NPs are categorized into montmorillonite(MMT), hectorite, kaolinite, bentonite, and hydroxyapatite (Mierzwa et al., 2013). In nanomaterials applications, MMT is the nanoclay that is utilized most often. Depending on the surface modification of the clay layers, MMT may be dispersed in a polymeric combination in order to produce a nanocomposite, (Shameli et al., 2011).

Paulraj Kanmani et al. determined the antimicrobial properties of gelatin, Ag NPs, and nanoclay bioactive nanocomposites against *E. coli* and *L. monocytogenes*. Ag NPs revealed significant antimicrobial properties against both pathogens, but clay NPs were only effective against G+ (*L. monocytogenes*) pathogens (Kanmani & Rhim, 2014). In another study, the antibacterial impact of Cu NPs/ MMT clay was examined. The composition exhibited excellent antimicrobial effects against *E. coli, S. aureus, Pseudomonas aeruginosa,* and *Enterococcus faecalis*. (Bagchi et al., 2013).

Application of NPs in Food Products

Nanotechnology in Fruits and Vegetables Preservation

Fruits and vegetables are at the top of most shoppers' lists, particularly with regard to vitamin, mineral, antioxidant, and fiber content. However, due to their high water content (about 75–95%), fruits and vegetables face a limited storage life with consequent rapid degradation and an unattractive appearance during storage (Otoni et al., 2017). Nevertheless, it is possible to extend the storage time for fruits and vegetables by using proper packaging techniques. Nanocomposite antimicrobial packaging technologies are ideal options to address storage time considerations through enhanced mechanical, barrier, heat, and antibacterial qualities (Jafarzadeh et al., 2019) (Table 4.2).

Table 4.2 Application of nanoparticles for fruits and vegetables preservation

Fruits or vegetables	Nano-components	Advantages	References
Cut papaya	Chitosan/ZnO	The coating dramatically reduced microbial growth in fresh-cut papaya during storage.	Lavinia et al. (2019)
Banana	Isolate soy protein (ISP)/ ZnO NP	Nanocomposite film may delay banana ripening and loss of weight, titratable acidity, prevent changes in sensory attributes, total soluble sugar, fungal growth and firmness during storage.	Li et al. (2019a)
Black grape	Phthalate/ cellulose acetate// chitosan ZnO NPs	The storage life of black grapes by use of ZnO NPs increased up to 9 days.	Indumathi et al. (2019)
Vegetables and fruits	Chitosan/ZnO/ Melissa EO	Improved antimicrobial properties of chitosan coating.	Sani et al. (2019)
Orange fruit	Carnauba wax/ Clay NPs	Significantly improved the sensory acceptance of oranges, nutrition value, loss of weight, and respiration rate.	Motamedi et al. (2018)
Carrot	ZnO NPs	ZnO NPs may lower the overall number of colony-forming units (CFU) during storage, thus extending the storage period up to 40 days.	Xu et al. (2017)
Pomegranate	ZnO NPs	Nano coating reduced yeast and mold and weight loss.	Saba and Amini (2017)
Strawberries	ZnO NPs	ZnO NPs prevented microbial growth, delayed weight loss, and preserved strawberry nutrients.	Sogvar et al. (2016)
Cantaloupes	Chitosan/Ag/TiO_2	Prevents microorganism development and has strong antibacterial action against target microorganisms.	Lin et al. (2015)

Fruits can be categorized as climacteric or non- climacteric where fruits that can ripen after harvesting are climacteric and those that cannot ripen after harvesting are non- climacteric (Farcuh et al., 2018). As fruits and vegetables are still living tissues after harvesting, they have a limited storage period and can degrade rapidly during storage and transit due to chemical reactions, physiological aging, and microbiological infections. Consequently, there is often a decrease in the edibility of these products, resulting in a considerable annual loss of fresh fruits.

Due to the absence of effective shelf-life extension techniques, about 20–40% of fruits and vegetables spoil and deteriorate annually. Furthemore, by appropriate preservation method, ripening of fruits and vegetables delayed and the shelf life extend, microbiological contamination limited and transpiration of products as a freshness-maintenance strategy facilitated. Researchers have suggested several methods such as MAP packaging, waxing, and biodegradable composites for preserving vegetables and fruits. Among these methods, bio-nanocomposites or edible coatings are well recognized for their ability to preserve the postharvest quality of fresh fruits and vegetables (Jafarzadeh et al., 2021).

The impacts of isolate soybean protein (ISP) film and ISP/CIN/ZnO NPs composite coating on the postharvest quality of bananas during their storage time were investigated. The bio-nanocomposite covering was shown to maintain positive banana attributes by delaying ripening and reducing oxygen transport in samples (Li et al., 2019a).

Lavinia et al. demonstrate the application of CS and ZnO NPs as a novel coating on fresh papaya. Results have shown that the incorporation of nanocomposite coating in samples may significantly limit microbial activity during storage compared to uncoated samples and nanocomposite treatment may provide an alternate technique for the preservation of freshly sliced papaya after harvest and process (Lavinia et al., 2019). Chi et al. demonstrated that the polylactide (PLA) nanocomposite containing Ag NPs and TiO_2 NPs may effectively prevent the loss of mango firmness during storage. In addition, as compared to PLA films, nanocomposite films have the potential to limit vitamin C degradation, color and total acidity changes, and inhibition of microbial load in mangos (Chi et al., 2019).

Ethylene generation and respiration rates among fruits and vegetables can vary. During the ripening stage, fruits release ethylene and increase their respiration rate. Non-climacteric fruits generate a small quantity of ethylene and do not react to treatment with ethylene (Tripathi et al., 2016). Cherries, grapes, lemons, oranges, blueberries, raspberries, cucumbers, pomegranates, and watermelons, which are non-climacteric, must remain on the tree until they reach complete physiological ripening. Once harvested, these fruits will no longer continue to ripen, produce sugar, or acquire taste. Researchers have suggested the use of edible coatings and nanocomposite films to increase the shelf life of these fruits, which are very important due to their nutritional value, unique sensory attributes, and bioactive components (Chen et al., 2018). According to Fadeyibi et al., cassava starch bio-nanocomposites modified with ZnO NPs enhanced the storage period of cucumbers (Fadeyibi et al., 2020).

Strawberry was coated with a nano-biodegradable coating composed of sodium alginate and ZnO NPs generated by Emamifar et al. ZnO NPs significantly improved the water resistance of the coatings and, as a consequence, decreased strawberry weight loss. At the conclusion of storage (20 days), the uncoated fruits show higher weight loss in comparison with coated fruits with nano-biodegradable coating (Emamifar & Bavaisi, 2020).

Salama et al. used aloe vera gel, alginate, and TiO_2 NPs for bio-nanocomposite coatings preparation for extending the shelf life of tomatoes and an edible film based on carboxymethyl cellulose (CMC) for green bell pepper smart packaging. The results demonstrated that edible films significantly postponed spoilage and weight loss in tomatoes (Salama & Aziz, 2020). Sarojini and Rajarajeswari produced a biodegradable cellulose acetate phthalate/CS coating that was applied to black grapes and had varying percentages of ZnO NPs. The coatings containing ZnO NPs (5%) increased the storage period of black grapes up to 9 days (Indumathi et al., 2019).

Kumar et al. created bio-nanocomposite coatings using agar and ZnO NPs for green grapes. The findings showed that green grapes remained fresh up to 21 days vs. films containing 4% ZnO NPs (Kumar et al., 2019). Kaewklin et al. demonstrated the use of active packaging including CS/TiO_2 NPs for the preservation of tomatoes at 20 °C. The packed tomatoes exhibited less deterioration than the control film samples. Additionally, coatings containing NPs delayed the maturation process of tomatoes (Kaewklin et al., 2018).

Nanotechnology in Cheese Preservation

Cheeses are particularly sensitive to surface contamination by microorganisms due to their favorable acidity and high water content (Proulx et al., 2017). The majority of studies on cheese storage and shelf life have focused on concerns related to contamination caused by microorganisms. In addition, the increased moisture loss in certain cheeses due to the lack of a packing barrier may increase product hardness and lead to undesirable organoleptic qualities (Mei et al., 2020). Nano-systems are potential antimicrobial agents in the food industry, and different studies have examined the effect of bio-nanocomposites on a variety of cheese products, focusing on NPs (Resa et al., 2016).

El-Sayed et al. examined the effect of CS/guar gum/Roselle calyx extract (RE)-ZnO bio-nanocomposites for coating of Ras cheese. In addition, the physiochemical, microbial, and sensory aspects of Ras cheese among ripening in comparison to uncoated cheese were examined. Coated samples with a bio-nanocomposite layer comprising 3% RE-ZnO NPs exhibited significant effects against yeasts, molds, and other microorganism growth for approximately 3 months (El-Sayed et al., 2020).

Amjadi et al. determined the effectiveness of the gelatin-based nanocomposite comprising CS nanofiber (CSNF) and ZnO NPs for packing chicken fillets and cheese. The nanocomposite coating of samples considerably inhibited the development of inoculated bacteria ($p \leq 0.05$). Moreover, the sensory qualities of packed samples with CSNF and ZnO NPs were acceptably maintained during the storage time (Amjadi et al., 2019).

In another study, ecofriendly, cost-effective, and sustainable materials containing chitosan, PVA, glycerol, and TiO_2-NPs were created. Karish was manufactured, coated with a bio-nanocomposite comprising 1, 2, and 3% TiO2-NPs, and then refrigerated. The quality of covered Karish cheese was acceptably maintained until the end of the storage period; however, uncoated samples showed surface fungal growth and after 15 days, the quality of control sample was unacceptable. Karish cheese covered with a bio-nanocomposite containing 3% TiO_2-NPs was rated highest in terms of acceptance at the end of the storage period (Youssef et al., 2018).

Divsalar et al. used chitosan-cellulose, nisin, and ZnO NPs for packing ultra-filter white cheese and to increase its shelf life. Findings revealed that the nisin-containing bio-nanocomposite layer enhanced the storage time of ultra-filter white cheese and inhibited the development of microorganisms on the cheese surface layer for 14 days at 4 °C (Divsalar et al., 2018).

Nanotechnology in Seafood Preservation

Due to their low-calorie content, omega 3 fatty acid, vitamins, minerals, and protein content, aqua food products (AFPs) are often favored by customers. However, microorganisms, enzymes, and chemical processes quickly deteriorate AFPs. In response to changing consumer preferences with regard to safer food products, researchers have concentrated on using nanotechnology in AFPs preservation (Çiçek & Özoğul, 2022). The foundation of nanotechnology for the preservation of AFPs are NPs. The majority of applications for NPs have been employed to maintain AFPs. TiO_2 NPs contain strong antibacterial properties and can suppress aquatic pathogens in vitro (Noman et al., 2019).

Mehdizadeh et al. examined the efficiency of Cs-zein coating containing free and nano-encapsulated *Pulicaria gnaphalodes* (Vent.) *boiss* extract on quality attributes of rainbow trout stored at 4 °C for 14 days. By utilizing this coating, peroxide value and thiobarbituric acid decreased during storage (Mehdizadeh et al., 2021). The edible coating developed by Ag NPs, *Satureja rechingeri* extract, and PVA effectively inhibited growth of *S. aureus, E. coli*, psychrophilic bacteria and mesophiles on rainbow trout fillets (Kavakebi et al., 2021). Kargar et al. investigated the antimicrobial effects of Ag/Cu/ZnO NPs generated by chemical reduction technique in order to increase the shelf life of caviar during the storage period (14 days). Results indicated that the total amounts of volatile nitrogen and thiobarbituric acid decreased significantly (Ahari et al., 2021).

Maghami et al. studied the impact of CSNPs loaded with fennel EOs and the modified atmosphere packaging (MAP) technology on the biochemical, microbial, and sensory attributes of Huso huso fish fillets during storage. The findings demonstrated that coating fish fillets with CSNPs and fennel EO considerably decreased the peroxide value and thiobarbituric acid value in compared to the control samples, thereby extending the product storage life (Maghami et al., 2019).

Durmuş et al. studied the effect of nano-emulsions based on trading oils (hazelnut oil, corn oil, canola oil, soybean oil, olive oil, and sunflower oil) on vacuum-packed sea bass fillets. The shelf life of samples treated with nano-emulsion kept at 2 ± 2 °C was extended by approximately 2–4 days. Fish fillets treated with hazelnut and corn oil groups exhibited lowest bacterial growth and lactic acid bacteria. Results proved that the storage time of fish samples was extended up to 4 days with nano-emulsions of canola, corn, soybean, and hazelnut oils vs. only 2 days by emulsions of olive and sunflower oils (Durmus et al., 2019).

To preserve the silver carp fish ball, Wei et al. developed a composite CS film contain ZnO/ TiO_2 and SiOx (ZTS-CS). The textural change and freshness indicators of fish ball were extended as prepared films have significant antibacterial activities and the gas permeability of the films was appropriate. Moreover, the quality of fish ball coated with ZTS-CS was maintained for 24 days vs. about 5 days for the control samples (Wei et al., 2018).

Mizielinska et al. examined the firmness and microbial load of cod (*Gadus morhua*) fillets packaged with a methyl hydroxypropyl cellulose coating modified with ZnO NPs. The coating reduced gumminess in the samples which significantly improved the texture quality. Mesophilic and psychotropic bacteria counts decreased in coated Baltic cod (***Gadus morhua***) at 5 °C for 144 h (Mizielińska et al., 2018).

Ramezani, et al. reported that due to the size effect, bulk CS coating is less effective than CSNPs at inhibiting microbial loads on fillets of silver carp *(Hypophthalmicthys molitrix*) stored at 4 °C for 12 days. The total psychrotrophic and mesophile bacteria counts remarkably decreased in samples coated with CSNPs (Ramezani et al., 2015). Budhijanto, Nugraheni, and Budhijanto discovered that CSNPs are more efficient than chitosan in antibacterial compounds when applied to fresh tilapia (*Oreochromis* sp.) at cold temperatures. Compared to samples preserved at ambient temperature (25 °C) and untreated with CSNPs, samples kept at low temperatures (10–15 °C) and covered with CSNPs had a substantial positive impact on preventing the development of microorganisms (Budhijanto et al., 2015).

Nanotechnology in Beverage Preservation

Nanotechnology is not novel to the food and beverage industry, as several novel nano-based approaches have already been used in functional and nutraceutical food applications, production, and processing. Utilizing colloid technology, food production may be enhanced over an extended preservation time. This is due to the utilization of nanoscale-sized ingredients in the majority of beverages and foods such as dairy products. Therefore, the decrease in size of these substances at the nanoscale range should be considered (Chaturvedi & Dave, 2020).

In many sauces, beverages, oils, and juices, NPs have shown a variety of electrochemical and visual characteristics. The incorporation of nano-emulsified bioactives and flavors to beverages has no impact on the appearance of the product (Rhim et al., 2013). A recent study demonstrated that CS nano-composite may also be employed for the clarifying, stabilization, and encapsulating of alcoholic, non-alcoholic, and dairy-based drinks, juices, teas, and coffees (Morin-Crini et al., 2019).

Toxicological, Safety, and Migration Issues of Metal NPs in Food Products

Toxicological Aspects of NPs

Nanotechnology science continues to expand, and along with this growth has come an increase in public health concerns regarding the toxicity and environmental effects of nanomaterials. In addition to functionalization, agglomeration, and net particle response, dynamic, kinematic, and enzymatic features- along with enzymatic activity- increase the toxicity of NPs (Zou et al., 2016). Toxicokinetic problems generated by NPs are primarily attributable to their persisting insolubility and nondegradable features (López-Serrano et al., 2014). As the size of metal NPs decreases, their toxicity increases. NPs are highly reactive chemicals that easily penetrate membranes and capillaries, generating toxico-kinetic and toxico-dynamic effects (Hajipour et al., 2012).

NPs can enter the body by ingestion, skin contact or inhalation (Maisanaba et al., 2015). Once they enter the biological environment, NPs will inevitably interact with biomolecules in the bloodstream, such as proteins, carbohydrates, and lipids (Farhoodi, 2016). Some NPs link to enzymes and proteins which stimulates the generation of reactive oxygen species (ROS) and oxidative stress. ROS production induces mitochondrial degradation and cell death (Hajipour et al., 2012).

ZnO NPs exhibited genotoxicity in the human epidermis even though ZnO in bulk size is non-toxic, indicating the importance of particle size (Sharma et al., 2009).

Vishwakarma et al. evaluated effects of AgNPs and Ag nitrate on the growth of hydroponic mustard (*Brassica* spp.). Both chemicals affected the length of root, fresh weight, ascorbate peroxidase, total chlorophyll and carotenoid composition, protein content, catalase activity, oxidation, DNA degradation, compound aggregation, and plant cell growth (Vishwakarma et al., 2017). Echegoyen and Nern detected Ag migration in all three samples of industrial AgNPs plastic containers, with total Ag migration varying from 1.66 to 31.46 ng/cm^2 (Echegoyen & Nerín, 2013). To eliminate the challenges related with nanotechnology in the food sector, the bioavailability, behavior, and toxicity of NPs in the environment should be thoroughly investigated (Lugani et al., 2021).

Safety of Food Products

Food safety is a worldwide health concern, and food safety measures help to ensure that preparation and consumption will not harm the health of consumers (Pal, 2017). Recent developments in nanotechnology have changed the food industry with regard to food processing, security, and safety, in addition to advancements in improving nutraceutical content, prolonging storage time, and minimizing packaging waste (Wesley et al., 2014). Pathogens, pesticides, and other pollutants in food represent significant health risks to humans. Nanotechnology advancements have accelerated solutions to food safety challenges with microbiological contamination and enhanced toxin identification, and storage time (Inbaraj & Chen, 2016).

Another prospective application of nanotechnology is for detection of levels of toxic elements pathogens, and microbial load in food systems. The interesting new concept of combining biology and nanotechnology into sensors is promising, since the reaction time to detect a possible danger would be dramatically lowered. This will result in increased food processing system safety. A research program in Iowa State University by Launois revealed that Ag NPs might boost the safety of the worldwide food supply (Launois, 2008). Currently, Ag NPs cannot be directly added to food products due to a lack of research on their detrimental effects on human health and ecological systems. In order to develop food-related applications such as microbe-resistant materials and non-biofouling surfaces, the research program examines how Ag NPs may operate as antimicrobial agents in meals (Alfadul & Elneshwy, 2010).

The U.S. Food and Drug Administration (FDA) is charged with securing human health by regulating the safety of substances that are directly in contact with food. For example, the FDA plays a significant role in testing the safety of NPs contained in food products and nanoscale food ingredients (Paradise, 2019). The FDA has published a number of nanotechnology-related reports and suggestions for research, analysis, and regulatory policy in order to assist the sector. Based on comments by the FDA Commissioner (Paradise, 2010), nanotechnology has been acknowledged for dealing with nanotechnology-based food products. Moreover, according to the standards of European nations, nanomaterials (100 nm or less) may only be used if they are allowed and mentioned in rules of Annex I, and their migration levels in food products must be below detectable limits.

Migration of Metal NPs into Food Products

Determining the optimum migration of NPs into food is one of the food industry's primary issues. Migration is defined as the mass transfer of particles with a low molecular weight (Zamindar et al., 2020).

The migration of heavy metals from nanomaterials is a cause for major concern (He et al., 2015). In the case of long-term agglomeration, the distribution of heavy metals into food items has negative consequences. For example, metal and metal oxide NPs, including Ag (McShan et al., 2014), and CuO (Karlsson et al., 2013), ZnO increase intracellular ROS levels, causing lipid oxidation and DNA damage (Fukui et al., 2012). Allergies and the release of heavy metals as the migration phenomenon are the two main safety concerns of NPs. AuNPs depict a good safety profile. Considering AuNPs, as well as other metal NPs have the potential of toxicity. AuNPs are capable of migration from packaging to food matrix and finally, they will be released in the human body after food consumption which is a toxin for different cells and tissues (Bindhu & Umadevi, 2014). In recent years, Simpson et al. made, analyzed, and validated carbon NPs (66 nm) with glycerol for detecting heavy metal ions with a 0.30 ppm detection limit (Simpson et al., 2018). Lingamdinne et al. demonstrated that NPs of iron oxide that are produced and reused without affecting stability may reduce heavy metals in products (Lingamdinne et al., 2017).

Amal M. Metak et al. studied AgNP migration from nanosilver sheets and juice packing. Nanosilver-coated films generate substantial migration levels (0.03 mg L^{-1}), and this is cause for concern regardless of whether the metal is in the form of NPs or ions. However, no chemical or biological alterations were detected in the food items analyzed (Metak et al., 2015).

In another investigation, a migration experiment was conducted in order to see how time and temperature affected the migration of CuNP/AgNP from polyethylene nanocomposites to chicken breasts. According to the findings, neither time nor temperature had a major impact on migration. Migration of copper and silver varied between 0.024 and 0.049 mg/dm^2 and 0.003 and 0.005 mg/dm^2, respectively (Cushen et al., 2014).

Cushen et al. studied AgNP migration from nanocomposite PVC on chicken breasts, and findings revealed migration levels ranging from 0.03 to 8.4 mgkg^{-1} (Cushen et al., 2013).

Conclusion

Nanotechnology has revolutionized the food processing and preserving industry. It is an innovative technology that offers a promising route for developing novel packaging components. By mixing polymeric materials with organic, inorganic, or organic-inorganic hybrid NPs, functional packaging films with mechanical, thermal and antimicrobial properties are possible. Nanocomposites can be used to create flexible, fire-resistant, antimicrobial, and transparent barrier coatings. NPs in food packaging may also detect microbial infection. For widespread use of nanocomposites as packaging materials, further research is needed in order to extend shelf life, protect food quality, and promote commercialization.

However, due to their ultramicroscopic size, NPs are readily absorbed by cells in the human body which could have harmful consequences. Moreover, because of the increased bioavailability of NPs, toxicity is increased and could damage the immune system. As the mobility of NPs within biological systems is still unclear, silver NPs, for instance, may effectively make cells resistant to any other antibiotics. Due to their high toxicity, various other NPs, such as TiO_2 and ZnO, contribute to environmental contamination. It is thus necessary to create antibacterial NPs that are antibacterial and that do not negatively affect the environment. In conclusion, the major problem with employing nanotechnology in the food industry is that NPs are still being explored and have not yet been well described; as a result, the extent of risk that they potentially pose to biological functions is unknown and the public should be informed about the health, safety, and environmental impacts of nanotechnology as it is introduced and developed within the food system.

References

Abreu, F. O., Oliveira, E. F., Paula, H. C., & de Paula, R. C. (2012). Chitosan/cashew gum nanogels for essential oil encapsulation. *Carbohydrate Polymers, 89*(4), 1277–1282.

Ahari, H., Kakoolaki, S., & Mizani, M. (2021). Antimicrobial effects of silver/copper/titanium dioxide-nanocomposites synthesised by chemical reduction method to increase the shelf life of caviar (Huso huso). *Iranian Journal of Fisheries Sciences, 20*(1), 13–31.

Alfadul, S., & Elneshwy, A. (2010). Use of nanotechnology in food processing, packaging and safety–review. *African Journal of Food, Agriculture, Nutrition and Development, 10*(6).

Amjadi, S., Emaminia, S., Nazari, M., Davudian, S. H., Roufegarinejad, L., & Hamishehkar, H. (2019). Application of reinforced ZnO nanoparticle-incorporated gelatin bionanocomposite film with chitosan nanofiber for packaging of chicken fillet and cheese as food models. *Food and Bioprocess Technology, 12*(7), 1205–1219.

Anvar, A., Haghighat Kajavi, S., Ahari, H., Sharifan, A., Motallebi, A., Kakoolaki, S., & Paidari, S. (2019). *Evaluation of the antibacterial effects of Ag-Tio2 nanoparticles and optimization of its migration to sturgeon caviar (Beluga).*

Artiga-Artigas, M., Acevedo-Fani, A., & Martín-Belloso, O. (2017). Improving the shelf life of low-fat cut cheese using nanoemulsion-based edible coatings containing oregano essential oil and mandarin fiber. *Food Control, 76*, 1–12.

Aswathanarayan, J. B., & Vittal, R. R. (2019). Nanoemulsions and their potential applications in food industry. *Frontiers in Sustainable Food Systems, 3*, 95.

Aziz, N., Faraz, M., Sherwani, M. A., Fatma, T., & Prasad, R. (2019). Illuminating the anticancerous efficacy of a new fungal chassis for silver nanoparticle synthesis. *Frontiers in Chemistry, 7*, 65.

Bagchi, B., Kar, S., Dey, S. K., Bhandary, S., Roy, D., Mukhopadhyay, T. K., Das, S., & Nandy, P. (2013). In situ synthesis and antibacterial activity of copper nanoparticle loaded natural montmorillonite clay based on contact inhibition and ion release. *Colloids and Surfaces B: Biointerfaces, 108*, 358–365.

Bajpai, V. K., Kamle, M., Shukla, S., Mahato, D. K., Chandra, P., Hwang, S. K., Kumar, P., Huh, Y. S., & Han, Y.-K. (2018). Prospects of using nanotechnology for food preservation, safety, and security. *Journal of Food and Drug Analysis, 26*(4), 1201–1214.

Baranwal, A., Srivastava, A., Kumar, P., Bajpai, V. K., Maurya, P. K., & Chandra, P. (2018). Prospects of nanostructure materials and their composites as antimicrobial agents. *Frontiers in Microbiology, 9*, 422.

Białkowska, A., Majewska, E., Olczak, A., & Twarda-Clapa, A. (2020). Ice binding proteins: Diverse biological roles and applications in different types of industry. *Biomolecules, 10*(2), 274.

Bindhu, M., & Umadevi, M. (2014). Silver and gold nanoparticles for sensor and antibacterial applications. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 128*, 37–45.

Bratovcic, A. (2020). Nanomaterials in food processing and packaging, its toxicity and food labeling. *Acta Scientific Nutritional Health, 4*(9), 07–13.

Budhijanto, B., Nugraheni, P. S., & Budhijanto, W. (2015). Inhibition of microbial growth by nanochitosan for fresh tilapia (Oreochromissp) preservation. *Procedia Chemistry, 16*, 663–672.

Chaturvedi, S., & Dave, P. N. (2020). Application of nanotechnology in foods and beverages. In *Nanoengineering in the beverage industry* (pp. 137–162). Elsevier.

Chen, Y., Grimplet, J., David, K., Castellarin, S. D., Terol, J., Wong, D. C., Luo, Z., Schaffer, R., Celton, J.-M., & Talon, M. (2018). Ethylene receptors and related proteins in climacteric and non-climacteric fruits. *Plant Science, 276*, 63–72.

Cheuk, S. Y., Shih, F. F., Champagne, E. T., Daigle, K. W., Patindol, J. A., Mattison, C. P., & Boue, S. M. (2015). Nano-encapsulation of coenzyme Q10 using octenyl succinic anhydride modified starch. *Food Chemistry, 174*, 585–590.

Chi, H., Song, S., Luo, M., Zhang, C., Li, W., Li, L., & Qin, Y. (2019). Effect of PLA nanocomposite films containing bergamot essential oil, TiO2 nanoparticles, and Ag nanoparticles on shelf life of mangoes. *Scientia Horticulturae, 249*, 192–198.

Çiçek, S., & Özoğul, F. (2022). Nanotechnology-based preservation approaches for aquatic food products: A review with the current knowledge. *Critical Reviews in Food Science and Nutrition*, 1–24.

Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M., & Cummins, E. (2013). Migration and exposure assessment of silver from a PVC nanocomposite. *Food Chemistry, 139*(1–4), 389–397.

Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M., & Cummins, E. (2014). Evaluation and simulation of silver and copper nanoparticle migration from polyethylene nanocomposites to food and an associated exposure assessment. *Journal of Agricultural and Food Chemistry, 62*(6), 1403–1411.

Dash, K. K., Ali, N. A., Das, D., & Mohanta, D. (2019). Thorough evaluation of sweet potato starch and lemon-waste pectin based-edible films with nano-titania inclusions for food packaging applications. *International Journal of Biological Macromolecules, 139*, 449–458.

Dera, M. W., & Teseme, W. B. (2020). Review on the application of food nanotechnology in food processing. *American Journal of Engineering and Technology Management, 5*, 41–47.

Divsalar, E., Tajik, H., Moradi, M., Forough, M., Lotfi, M., & Kuswandi, B. (2018). Characterization of cellulosic paper coated with chitosan-zinc oxide nanocomposite containing nisin and its application in packaging of UF cheese. *International Journal of Biological Macromolecules, 109*, 1311–1318.

Donsì, F., Annunziata, M., Sessa, M., & Ferrari, G. (2011). Nanoencapsulation of essential oils to enhance their antimicrobial activity in foods. *LWT-Food Science and Technology, 44*(9), 1908–1914.

Donsì, F., Marchese, E., Maresca, P., Pataro, G., Vu, K. D., Salmieri, S., Lacroix, M., & Ferrari, G. (2015). Green beans preservation by combination of a modified chitosan based-coating containing nanoemulsion of mandarin essential oil with high pressure or pulsed light processing. *Postharvest Biology and Technology, 106*, 21–32.

Duncan, T. V. (2011a). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of Colloid and Interface Science, 363*(1), 1–24.

Duncan, T. V. (2011b). The communication challenges presented by nanofoods. *Nature Nanotechnology, 6*(11), 683–688.

Duran, N., & Marcato, P. D. (2013). Nanobiotechnology perspectives. Role of nanotechnology in the food industry: A review. *International Journal of Food Science & Technology, 48*(6), 1127–1134.

Durmus, M., Ozogul, Y., Küley Boga, E., Uçar, Y., Kosker, A. R., Balikci, E., & Gökdogan, S. (2019). The effects of edible oil nanoemulsions on the chemical, sensory, and microbiological changes of vacuum packed and refrigerated sea bass fillets during storage period at 2±2° C. *Journal of Food Processing and Preservation, 43*(12), e14282.

Echegoyen, Y., & Nerín, C. (2013). Nanoparticle release from nano-silver antimicrobial food containers. *Food and Chemical Toxicology, 62*, 16–22.

El-Sayed, S. M., El-Sayed, H. S., Ibrahim, O. A., & Youssef, A. M. (2020). Rational design of chitosan/guar gum/zinc oxide bionanocomposites based on Roselle calyx extract for Ras cheese coating. *Carbohydrate Polymers, 239*, 116234.

Emamifar, A., & Bavaisi, S. (2020). Nanocomposite coating based on sodium alginate and nano-ZnO for extending the storage life of fresh strawberries (Fragaria× ananassa Duch.). *Journal of Food Measurement and Characterization, 14*(2), 1012–1024.

Esmaeili, Y., Zamindar, N., Paidari, S., Ibrahim, S. A., & Mohammadi Nafchi, A. (2021). The synergistic effects of aloe vera gel and modified atmosphere packaging on the quality of strawberry fruit. *Journal of Food Processing and Preservation, 45*(12), e16003.

Esmaeili, Y., Zamindar, N., & Mohammadi, R. (2022). The effect of polypropylene film containing nano-hydroxyapatite on physicochemical and microbiological properties of button mushrooms (Agaricus bisporus) under modified atmosphere packaging. *Journal of Food Measurement and Characterization*, 1–14.

Espitia, P. J. P., Soares, N. D. F. F., Teófilo, R. F., Vitor, D. M., Coimbra, J. S. D. R., de Andrade, N. J., de Sousa, F. B., Sinisterra, R. D., & Medeiros, E. A. A. (2013). Optimized dispersion of ZnO nanoparticles and antimicrobial activity against foodborne pathogens and spoilage microorganisms. *Journal of Nanoparticle Research, 15*(1), 1–16.

Fadeyibi, A., Osunde, Z. D., & Yisa, M. G. (2020). Effects of period and temperature on quality and shelf-life of cucumber and garden-eggs packaged using cassava starch-zinc nanocomposite film. *Journal of Applied Packaging Research, 12*(1), 3.

Farcuh, M., Rivero, R. M., Sadka, A., & Blumwald, E. (2018). Ethylene regulation of sugar metabolism in climacteric and non-climacteric plums. *Postharvest Biology and Technology, 139*, 20–30.

Farhoodi, M. (2016). Nanocomposite materials for food packaging applications: Characterization and safety evaluation. *Food Engineering Reviews, 8*(1), 35–51.

Fedotova, A., Snezhko, A., Sdobnikova, O., Samoilova, L., Smurova, T., Revina, A., & Khailova, E. (2010). Packaging materials manufactured from natural polymers modified with silver nanoparticles. *International Polymer Science and Technology, 37*(10), 59–64.

Fukui, H., Horie, M., Endoh, S., Kato, H., Fujita, K., Nishio, K., Komaba, L. K., Maru, J., Miyauhi, A., & Nakamura, A. (2012). Association of zinc ion release and oxidative stress induced by intratracheal instillation of ZnO nanoparticles to rat lung. *Chemico-Biological Interactions, 198*(1–3), 29–37.

Galus, S., & Kadzińska, J. (2015). Food applications of emulsion-based edible films and coatings. *Trends in Food Science & Technology, 45*(2), 273–283.

Gammariello, D., Conte, A., Buonocore, G., & Del Nobile, M. A. (2011). Bio-based nanocomposite coating to preserve quality of Fior di latte cheese. *Journal of Dairy Science, 94*(11), 5298–5304.

Ghosh, C., Bera, D., & Roy, L. (2019). Role of nanomaterials in food preservation. In *Microbial nanobionics* (pp. 181–211). Springer.

Ghosh, T., Mondal, K., & Katiyar, V. (2020). Current prospects of bio-based nanostructured materials in food safety and preservation. In *Food product optimization for quality and safety control* (pp. 111–164). Apple Academic Press.

Gorrasi, G., & Bugatti, V. (2016). Edible bio-nano-hybrid coatings for food protection based on pectins and LDH-salicylate: Preparation and analysis of physical properties. *LWT-Food Science and Technology, 69*, 139–145.

Hajipour, M. J., Fromm, K. M., Ashkarran, A. A., de Aberasturi, D. J., de Larramendi, I. R., Rojo, T., Serpooshan, V., Parak, W. J., & Mahmoudi, M. (2012). Antibacterial properties of nanoparticles. *Trends in Biotechnology, 30*(10), 499–511.

Hassan, B., Chatha, S. A. S., Hussain, A. I., Zia, K. M., & Akhtar, N. (2018). Recent advances on polysaccharides, lipids and protein based edible films and coatings: A review. *International Journal of Biological Macromolecules, 109*, 1095–1107.

He, X., Aker, G., Huang, M. J., Watts, J., & Hwang, H.-M. (2015). Metal oxide nanomaterials in nanomedicine: Applications in photodynamic therapy and potential toxicity. *Current Topics in Medicinal Chemistry, 15*(18), 1887–1900.

He, X., Deng, H., & Hwang, H. (2019). La aplicación actual de la nanotecnología en la alimentación y la agricultura. *Journal of Food and Drug Analysis, 27*(1), 1–21.

Hoseinnejad, M., Jafari, S. M., & Katouzian, I. (2018). Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Critical Reviews in Microbiology, 44*(2), 161–181.

Hossain, A., Skalicky, M., Brestic, M., Mahari, S., Kerry, R. G., Maitra, S., Sarkar, S., Saha, S., Bhadra, P., & Popov, M. (2021). Application of nanomaterials to ensure quality and nutritional safety of food. *Journal of Nanomaterials, 2021*.

Imran, M., Revol-Junelles, A.-M., Paris, C., Guedon, E., Linder, M., & Desobry, S. (2015). Liposomal nanodelivery systems using soy and marine lecithin to encapsulate food biopreservative nisin. *LWT-Food Science and Technology, 62*(1), 341–349.

Inbaraj, B. S., & Chen, B. (2016). Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. *Journal of Food and Drug Analysis, 24*(1), 15–28.

Indumathi, M., Sarojini, K. S., & Rajarajeswari, G. (2019). Antimicrobial and biodegradable chitosan/cellulose acetate phthalate/ZnO nano composite films with optimal oxygen permeability and hydrophobicity for extending the shelf life of black grape fruits. *International Journal of Biological Macromolecules, 132*, 1112–1120.

Jafarzadeh, S., Alias, A., Ariffin, F., & Mahmud, S. (2017). Characterization of semolina protein film with incorporated zinc oxide nano rod intended for food packaging. *Polish Journal of Food and Nutrition Sciences, 67*(3), 183–190.

Jafarzadeh, S., Rhim, J. W., Alias, A. K., Ariffin, F., & Mahmud, S. (2019). Application of antimicrobial active packaging film made of semolina flour, nano zinc oxide and nano-kaolin to maintain the quality of low-moisture mozzarella cheese during low-temperature storage. *Journal of the Science of Food and Agriculture, 99*(6), 2716–2725.

Jafarzadeh, S., Nafchi, A. M., Salehabadi, A., Oladzad-Abbasabadi, N., & Jafari, S. M. (2021). Application of bio-nanocomposite films and edible coatings for extending the shelf life of fresh fruits and vegetables. *Advances in Colloid and Interface Science, 291*, 102405.

Jaiswal, L., Shankar, S., & Rhim, J.-W. (2019). Applications of nanotechnology in food microbiology. In *Methods in microbiology* (Vol. 46, pp. 43–60). Elsevier.

Jayakar, V., Lokapur, V., & Shantaram, M. *The role of nanotechnology in food processing and food packaging industries*.

Kaewklin, P., Siripatrawan, U., Suwanagul, A., & Lee, Y. S. (2018). Active packaging from chitosan-titanium dioxide nanocomposite film for prolonging storage life of tomato fruit. *International Journal of Biological Macromolecules, 112*, 523–529.

Kanmani, P., & Rhim, J.-W. (2014). Physical, mechanical and antimicrobial properties of gelatin based active nanocomposite films containing AgNPs and nanoclay. *Food Hydrocolloids, 35*, 644–652.

Kaphle, A., Navya, P., Umapathi, A., & Daima, H. K. (2018). Nanomaterials for agriculture, food and environment: Applications, toxicity and regulation. *Environmental Chemistry Letters, 16*(1), 43–58.

Karlsson, H. L., Cronholm, P., Hedberg, Y., Tornberg, M., De Battice, L., Svedhem, S., & Wallinder, I. O. (2013). Cell membrane damage and protein interaction induced by copper containing nanoparticles – Importance of the metal release process. *Toxicology, 313*(1), 59–69.

Kavakebi, E., Anvar, A. A., Ahari, H., & Motalebi, A. A. (2021). Green biosynthesized Satureja rechingeri Jamzad-Ag/poly vinyl alcohol film: Quality improvement of Oncorhynchus mykiss fillet during refrigerated storage. *Food Science and Technology, 41*, 267–278.

Khalaf, H., Sharoba, A., El-Tanahi, H., & Morsy, M. (2013). Stability of antimicrobial activity of pullulan edible films incorporated with nanoparticles and essential oils and their impact on Turkey deli meat quality. *Journal of Food and Dairy Sciences, 4*(11), 557–573.

Khezerlou, A., Alizadeh-Sani, M., Azizi-Lalabadi, M., & Ehsani, A. (2018). Nanoparticles and their antimicrobial properties against pathogens including bacteria, fungi, parasites and viruses. *Microbial Pathogenesis, 123*, 505–526.

Kumar, S., Boro, J. C., Ray, D., Mukherjee, A., & Dutta, J. (2019). Bionanocomposite films of agar incorporated with ZnO nanoparticles as an active packaging material for shelf life extension of green grape. *Heliyon, 5*(6), e01867.

Kumari, M., Mukherjee, A., & Chandrasekaran, N. (2009). Genotoxicity of silver nanoparticles in Allium cepa. *Science of the Total Environment, 407*(19), 5243–5246.

Launois, A. (2008). *Nanoparticles could improve food safety*.

Lavinia, M., Hibaturrahman, S., Harinata, H., & Wardana, A. (2019). Antimicrobial activity and application of nanocomposite coating from chitosan and ZnO nanoparticle to inhibit microbial growth on fresh-cut papaya. *Food Research, 4*, 307–311.

Li, K., Jin, S., Li, J., & Chen, H. (2019a). Improvement in antibacterial and functional properties of mussel-inspired cellulose nanofibrils/gelatin nanocomposites incorporated with graphene oxide for active packaging. *Industrial Crops and Products, 132*, 197–212.

Li, J., Sun, Q., Sun, Y., Chen, B., Wu, X., & Le, T. (2019b). Improvement of banana postharvest quality using a novel soybean protein isolate/cinnamaldehyde/zinc oxide bionanocomposite coating strategy. *Scientia Horticulturae, 258*, 108786.

Lima, E., Guerra, R., Lara, V., & Guzmán, A. (2013). Gold nanoparticles as efficient antimicrobial agents for Escherichia coli and Salmonella typhi. *Chemistry Central Journal, 7*(1), 1–7.

Lin, B., Luo, Y., Teng, Z., Zhang, B., Zhou, B., & Wang, Q. (2015). Development of silver/titanium dioxide/chitosan adipate nanocomposite as an antibacterial coating for fruit storage. *LWT-Food Science and Technology, 63*(2), 1206–1213.

Lingamdinne, L. P., Chang, Y.-Y., Yang, J.-K., Singh, J., Choi, E.-H., Shiratani, M., Koduru, J. R., & Attri, P. (2017). Biogenic reductive preparation of magnetic inverse spinel iron oxide nanoparticles for the adsorption removal of heavy metals. *Chemical Engineering Journal, 307*, 74–84.

Llorens, A., Lloret, E., Picouet, P. A., Trbojevich, R., & Fernandez, A. (2012). Metallic-based micro and nanocomposites in food contact materials and active food packaging. *Trends in Food Science & Technology, 24*(1), 19–29.

Lokina, S., & Narayanan, V. (2013). Antimicrobial and anticancer activity of gold nanoparticles synthesized from grapes fruit extract. *Chemical Science Transactions, 2*(S1), S105–S110.

López-Serrano, A., Olivas, R. M., Landaluze, J. S., & Cámara, C. (2014). Nanoparticles: A global vision. Characterization, separation, and quantification methods. Potential environmental and health impact. *Analytical Methods, 6*(1), 38–56.

Lugani, Y., Oberoi, S., & Rattu, G. (2021). Nanotechnology in food industry–Applications and future perspectives. In *Sustainable agriculture reviews* (Vol. 55, pp. 71–92). Springer.

Ma, P., Jiang, L., Yu, M., Dong, W., & Chen, M. (2016). Green antibacterial nanocomposites from poly (lactide)/poly (butylene adipate-co-terephthalate)/nanocrystal cellulose–silver nanohybrids. *ACS Sustainable Chemistry & Engineering, 4*(12), 6417–6426.

Maghami, M., Motalebi, A. A., & Anvar, S. A. A. (2019). Influence of chitosan nanoparticles and fennel essential oils (Foeniculum vulgare) on the shelf life of Huso huso fish fillets during the storage. *Food Science & Nutrition, 7*(9), 3030–3041.

Maisanaba, S., Pichardo, S., Puerto, M., Gutierrez-Praena, D., Camean, A. M., & Jos, A. (2015). Toxicological evaluation of clay minerals and derived nanocomposites: A review. *Environmental Research, 138*, 233–254.

Malarkodi, C., Rajeshkumar, S., Paulkumar, K., Vanaja, M., Gnanajobitha, G., & Annadurai, G. (2014). Biosynthesis and antimicrobial activity of semiconductor nanoparticles against oral pathogens. *Bioinorganic Chemistry and Applications, 2014*, 1–10.

Malik, A., Erginkaya, Z., & Erten, H. (2019). *Health and safety aspects of food processing technologies*. Springer.

Martínez-Abad, A., Ocio, M., Lagarón, J., & Sánchez, G. (2013). Evaluation of silver-infused polylactide films for inactivation of Salmonella and feline calicivirus in vitro and on fresh-cut vegetables. *International Journal of Food Microbiology, 162*(1), 89–94.

McClements, D. J., & Rao, J. (2011). Food-grade nanoemulsions: Formulation, fabrication, properties, performance, biological fate, and potential toxicity. *Critical Reviews in Food Science and Nutrition, 51*(4), 285–330.

McShan, D., Ray, P. C., & Yu, H. (2014). Molecular toxicity mechanism of nanosilver. *Journal of Food and Drug Analysis, 22*(1), 116–127.

Mehdizadeh, A., Shahidi, S.-A., Shariatifar, N., Shiran, M., & Ghorbani-HasanSaraei, A. (2021). Evaluation of chitosan-zein coating containing free and nano-encapsulated Pulicaria gnaphalodes (Vent.) Boiss. extract on quality attributes of rainbow trout. *Journal of Aquatic Food Product Technology, 30*(1), 62–75.

Mei, L. X., Nafchi, A. M., Ghasemipour, F., Easa, A. M., Jafarzadeh, S., & Al-Hassan, A. (2020). Characterization of pH sensitive sago starch films enriched with anthocyanin-rich torch ginger extract. *International Journal of Biological Macromolecules, 164*, 4603–4612.

Metak, A. M., Nabhani, F., & Connolly, S. N. (2015). Migration of engineered nanoparticles from packaging into food products. *LWT-Food Science and Technology, 64*(2), 781–787.

Mierzwa, J. C., Arieta, V., Verlage, M., Carvalho, J., & Vecitis, C. D. (2013). Effect of clay nanoparticles on the structure and performance of polyethersulfone ultrafiltration membranes. *Desalination, 314*, 147–158.

Mizielińska, M., Kowalska, U., Jarosz, M., & Sumińska, P. (2018). A comparison of the effects of packaging containing nano ZnO or polylysine on the microbial purity and texture of cod (Gadus morhua) fillets. *Nanomaterials, 8*(3), 158.

Mohammadi, A., Hashemi, M., & Hosseini, S. M. (2016). Postharvest treatment of nanochitosan-based coating loaded with Zataria multiflora essential oil improves antioxidant activity and extends shelf-life of cucumber. *Innovative Food Science & Emerging Technologies, 33*, 580–588.

Morin-Crini, N., Lichtfouse, E., Torri, G., & Crini, G. (2019). Applications of chitosan in food, pharmaceuticals, medicine, cosmetics, agriculture, textiles, pulp and paper, biotechnology, and environmental chemistry. *Environmental Chemistry Letters, 17*(4), 1667–1692.

Motamedi, E., Nasiri, J., Malidarreh, T. R., Kalantari, S., Naghavi, M. R., & Safari, M. (2018). Performance of carnauba wax-nanoclay emulsion coatings on postharvest quality of 'Valencia' orange fruit. *Scientia Horticulturae, 240*, 170–178.

Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science, 179*(3), 154–163.

Nile, S. H., Baskar, V., Selvaraj, D., Nile, A., Xiao, J., & Kai, G. (2020). Nanotechnologies in food science: Applications, recent trends, and future perspectives. *Nano-Micro Letters, 12*(1), 1–34.

Noman, M. T., Ashraf, M. A., & Ali, A. (2019). Synthesis and applications of nano-TiO2: A review. *Environmental Science and Pollution Research, 26*(4), 3262–3291.

Otoni, C. G., Avena-Bustillos, R. J., Azeredo, H. M., Lorevice, M. V., Moura, M. R., Mattoso, L. H., & McHugh, T. H. (2017). Recent advances on edible films based on fruits and vegetables – A review. *Comprehensive Reviews in Food Science and Food Safety, 16*(5), 1151–1169.

Paidari, S., & Ahari, H. (2021). The effects of nanosilver and nanoclay nanocomposites on shrimp (Penaeus semisulcatus) samples inoculated to food pathogens. *Journal of Food Measurement and Characterization, 15*(4), 3195–3206.

Paidari, S., & Ibrahim, S. A. (2021). Potential application of gold nanoparticles in food packaging: A mini review. *Gold Bulletin, 54*(1), 31–36.

Pal, M. (2017). Nanotechnology: A new approach in food packaging. *Journal of Food: Microbiology, Safety & Hygiene, 2*(02), 8–9.

Paradise, J. (2010). Nanobiotechnology and the food and drug administration. *Food and Drug Law Institute Update*, 23–35.

Paradise, J. (2019). Regulating nanomedicine at the food and drug administration. *AMA Journal of Ethics, 21*(4), 347–355.

Pradhan, N., Singh, S., Ojha, N., Shrivastava, A., Barla, A., Rai, V., & Bose, S. (2015). Facets of nanotechnology as seen in food processing, packaging, and preservation industry. *BioMed Research International, 2015*.

Prasad, A., Mahato, K., Chandra, P., Srivastava, A., Joshi, S. N., & Maurya, P. K. (2016). Bioinspired composite materials: Applications in diagnostics and therapeutics. *Journal of Molecular and Engineering Materials, 4*(01), 1640004.

Proulx, J., Sullivan, G., Marostegan, L., VanWees, S., Hsu, L., & Moraru, C. (2017). Pulsed light and antimicrobial combination treatments for surface decontamination of cheese: Favorable and antagonistic effects. *Journal of Dairy Science, 100*(3), 1664–1673.

Ramezani, Z., Zarei, M., & Raminnejad, N. (2015). Comparing the effectiveness of chitosan and nanochitosan coatings on the quality of refrigerated silver carp fillets. *Food Control, 51*, 43–48.

Ravindranadh, M. R. K., & Mary, T. R. (2013). Development of ZnO nanoparticles for clinical applications. *Journal of Chemical, Biological and Physical Sciences (JCBPS), 4*(1), 469.

Resa, C. P. O., Gerschenson, L. N., & Jagus, R. J. (2016). Starch edible film supporting natamycin and nisin for improving microbiological stability of refrigerated Argentinian Port Salut cheese. *Food Control, 59*, 737–742.

Rhim, J.-W., Park, H.-M., & Ha, C.-S. (2013). Bio-nanocomposites for food packaging applications. *Progress in Polymer Science, 38*(10–11), 1629–1652.

Saba, M. K., & Amini, R. (2017). Nano-ZnO/carboxymethyl cellulose-based active coating impact on ready-to-use pomegranate during cold storage. *Food Chemistry, 232*, 721–726.

Salama, H. E., & Aziz, M. S. A. (2020). Optimized alginate and Aloe vera gel edible coating reinforced with nTiO2 for the shelf-life extension of tomatoes. *International Journal of Biological Macromolecules, 165*, 2693–2701.

Sani, M. A., Ehsani, A., & Hashemi, M. (2017). Whey protein isolate/cellulose nanofibre/TiO2 nanoparticle/rosemary essential oil nanocomposite film: Its effect on microbial and sensory quality of lamb meat and growth of common foodborne pathogenic bacteria during refrigeration. *International Journal of Food Microbiology, 251*, 8–14.

Sani, I. K., Pirsa, S., & Tağı, Ş. (2019). Preparation of chitosan/zinc oxide/Melissa officinalis essential oil nano-composite film and evaluation of physical, mechanical and antimicrobial properties by response surface method. *Polymer Testing, 79*, 106004.

Saravanan, A., Kumar, P. S., Hemavathy, R., Jeevanantham, S., Kamalesh, R., Sneha, S., & Yaashikaa, P. (2021). Methods of detection of food-borne pathogens: A review. *Environmental Chemistry Letters, 19*(1), 189–207.

Sarwar, M. S., Niazi, M. B. K., Jahan, Z., Ahmad, T., & Hussain, A. (2018). Preparation and characterization of PVA/nanocellulose/Ag nanocomposite films for antimicrobial food packaging. *Carbohydrate Polymers, 184*, 453–464.

Schmitt, J., Hajiw, S., Lecchi, A., Degrouard, J., Salonen, A., Impéror-Clerc, M., & Pansu, B. (2016). Formation of superlattices of gold nanoparticles using ostwald ripening in emulsions: Transition from fcc to bcc structure. *The Journal of Physical Chemistry B, 120*(25), 5759–5766.

Seil, J. T., & Webster, T. J. (2012). Antimicrobial applications of nanotechnology: Methods and literature. *International Journal of Nanomedicine, 7*, 2767.

Shahrokh, S., & Emtiazi, G. (2009). Toxicity and unusual biological behavior of nanosilver on gram positive and negative bacteria assayed by microtiter-plate. *European Journal of Biological Sciences, 1*(3), 28–31.

Shameli, K., Ahmad, M. B., Zargar, M., Yunus, W. M. Z. W., Rustaiyan, A., & Ibrahim, N. A. (2011). Synthesis of silver nanoparticles in montmorillonite and their antibacterial behavior. *International Journal of Nanomedicine, 6*, 581.

Shapi'i, R. A., Othman, S. H., Nordin, N., Basha, R. K., & Naim, M. N. (2020). Antimicrobial properties of starch films incorporated with chitosan nanoparticles: In vitro and in vivo evaluation. *Carbohydrate Polymers, 230*, 115602.

Sharifimehr, S., Soltanizadeh, N., & Goli, S. A. H. (2019). Physicochemical properties of fried shrimp coated with bio-nano-coating containing eugenol and Aloe vera. *LWT, 109*, 33–39.

Sharma, V., Shukla, R. K., Saxena, N., Parmar, D., Das, M., & Dhawan, A. (2009). DNA damaging potential of zinc oxide nanoparticles in human epidermal cells. *Toxicology Letters, 185*(3), 211–218.

Sharma, R., Jafari, S. M., & Sharma, S. (2020). Antimicrobial bio-nanocomposites and their potential applications in food packaging. *Food Control, 112*, 107086.

Simpson, A., Pandey, R., Chusuei, C. C., Ghosh, K., Patel, R., & Wanekaya, A. K. (2018). Fabrication characterization and potential applications of carbon nanoparticles in the detection of heavy metal ions in aqueous media. *Carbon, 127*, 122–130.

Singh, T., Shukla, S., Kumar, P., Wahla, V., Bajpai, V. K., & Rather, I. A. (2017). Application of nanotechnology in food science: Perception and overview. *Frontiers in Microbiology, 8*, 1501.

Sogvar, O. B., Saba, M. K., Emamifar, A., & Hallaj, R. (2016). Influence of nano-ZnO on microbial growth, bioactive content and postharvest quality of strawberries during storage. *Innovative Food Science & Emerging Technologies, 35*, 168–176.

Tabari, M. (2018). Characterization of a new biodegradable edible film based on Sago Starch loaded with Carboxymethyl cellulose nanoparticles. *Nanomedicine Research Journal, 3*(1), 25–30.

Tripathi, K., Pandey, S., Malik, M., & Kaul, T. (2016). Fruit ripening of climacteric and non climacteric fruit. *Journal of Environmental and Applied Bioresearch, 4*(1), 27–34.

Vishwakarma, K., Upadhyay, N., Singh, J., Liu, S., Singh, V. P., Prasad, S. M., Chauhan, D. K., Tripathi, D. K., & Sharma, S. (2017). Differential phytotoxic impact of plant mediated silver nanoparticles (AgNPs) and silver nitrate (AgNO3) on *Brassica* sp. *Frontiers in Plant Science, 8*, 1501.

Wang, Q., Yu, H., Tian, B., Jiang, B., Xu, J., Li, D., Feng, Z., & Liu, C. (2019). Novel edible coating with antioxidant and antimicrobial activities based on whey protein isolate nanofibrils and carvacrol and its application on fresh-cut cheese. *Coatings, 9*(9), 583.

Wang, Y., Zheng, Z., Wang, K., Tang, C., Liu, Y., & Li, J. (2020). Prebiotic carbohydrates: Effect on physicochemical stability and solubility of algal oil nanoparticles. *Carbohydrate Polymers, 228*, 115372.

Wei, X. Q., Li, X. P., Wu, C. L., Yi, S. M., Zhong, K. L., Sun, T., & Li, J. R. (2018). The modification of in situ SiOx chitosan coatings by ZnO/TiO2 NPs and its preservation properties to silver carp fish balls. *Journal of Food Science, 83*(12), 2992–3001.

Weir, A., Westerhoff, P., Fabricius, L., Hristovski, K., & Von Goetz, N. (2012). Titanium dioxide nanoparticles in food and personal care products. *Environmental Science & Technology, 46*(4), 2242–2250.

Wesley, S. J., Raja, P., Raj, A. A., & Tiroutchelvamae, D. (2014). Review on-nanotechnology applications in food packaging and safety. *International Journal of Engineering Research, 3*(11), 645–651.

Xu, J., Zhang, M., Bhandari, B., & Kachele, R. (2017). ZnO nanoparticles combined radio frequency heating: A novel method to control microorganism and improve product quality of prepared carrots. *Innovative Food Science & Emerging Technologies, 44*, 46–53.

Yang, H.-C., Wang, W.-H., Huang, K.-S., & Hon, M.-H. (2010). Preparation and application of nanochitosan to finishing treatment with anti-microbial and anti-shrinking properties. *Carbohydrate Polymers, 79*(1), 176–179.

Youssef, A. M., El-Sayed, S. M., El-Sayed, H. S., Salama, H. H., Assem, F. M., & Abd El-Salam, M. H. (2018). Novel bionanocomposite materials used for packaging skimmed milk acid coagulated cheese (Karish). *International Journal of Biological Macromolecules, 115*, 1002–1011.

Yu, Z., Li, B., Chu, J., & Zhang, P. (2018). Silica in situ enhanced PVA/chitosan biodegradable films for food packages. *Carbohydrate Polymers, 184*, 214–220.

Zamindar, N., Anari, E. S., Bathaei, S. S., Shirani, N., Tabatabaei, L., Mahdavi-Asl, N., Khalili, A., & Paidari, S. (2020). Application of copper nano particles in antimicrobial packaging: A mini review. *Acta Scientific Nutritional Health, 4*(5), 14–18.

Zhang, Y., Niu, Y., Luo, Y., Ge, M., Yang, T., Yu, L. L., & Wang, Q. (2014). Fabrication, characterization and antimicrobial activities of thymol-loaded zein nanoparticles stabilized by sodium caseinate–chitosan hydrochloride double layers. *Food Chemistry, 142*, 269–275.

Zinjarde, S. (2012). Bio-inspired nanomaterials and their applications as antimicrobial agents. *Chronicles of Young Scientists, 3*(1), 74–74.

Zou, L., Zheng, B., Zhang, R., Zhang, Z., Liu, W., Liu, C., Xiao, H., & McClements, D. J. (2016). Enhancing the bioaccessibility of hydrophobic bioactive agents using mixed colloidal dispersions: Curcumin-loaded zein nanoparticles plus digestible lipid nanoparticles. *Food Research International, 81*, 74–82.