PLANT SCIENCE TODAY
Vol x(x): xx-xx
https://doi.org/10.14719/pst.6503

eISSN 2348-1900

REVIEW ARTICLE

Nanotechnology in post-harvest and shelf life enhancing: Revolutionizing food preservation

Divya Nagarajan[1], Javeed Iqbal[2]*, Ayesha Aslam[2], Nadia Bhatti[2], Aziz Ur Rehman[2], Muhammad Irfan[2], Sharif Ahmed[3], Muhammad Tanveer Altaf[4], Waqas Liaqat[5], Chukwuma Ogbaga[6], Agalya Jasmin[1], Jothika Manokaran[1], Vijayalakshmi Shankar[7], Ayman El Sabagh[4], Karthika Rajendran[1*]

[1]Department of Genetics and Plant Breeding, VIT School of Agricultural Innovations and Advanced Learning (VAIAL), VIT University, Vellore 632 014, Tamil Nadu, India

[2]Department of Chemistry, University of Sahiwal, Sahiwal 57000, Pakistan

[3]Soil and Environmental Sciences Division, Nuclear Institute of Agriculture (NIA), Tandojam 70060, Pakistan

[4]International Rice Research Institute, Dhaka 1213, Bangladesh

[5]Department of Field Crops, Faculty of Agriculture, Sirrt University, Sirrt 56100, Turkey

[6]Independent Researcher, Middlesbrough, North Yorkshire TS1, United Kingdom

[7]CO_2 Research and Green Technologies Centre, VIT University Vellore 632 014, Tamil Nadu, India

*Correspondence email - karthika.rajendran@vit.ac.in

Received: 03 December 2025; Accepted: 22 August 2025; Available online: Version 1.0: 27 November 2025

Cite this article: Divya N, Javeed I, Ayesha A, Nadia B, Aziz UR, Muhammad I, Sharif A, Muhammad TA, Waqas L, Chukwuma O, Agalya J, Jothika M, Vijayalakshmi S, Ayman ES, Karthika R. Nanotechnology in post-harvest and shelf life enhancing: revolutionizing food preservation. Plant Science Today (Early Access). https://doi.org/10.14719/pst.6503

Abstract

Nanotechnology, a rapidly evolving discipline, shows remarkable promises for revolutionizing a wide range of industries, offering innovative solutions to long-lasting challenges. In the research Within the food sector, packaging and preservation, the application of nanoparticles (NPs) represents a significant breakthrough, enhancing product freshness, safety and reducing waste. Widely studied NPs such as copper oxide (CuO), silver (Ag), magnesium oxide (MgO), titanium dioxide (TiO_2), silicon dioxide (SiO_2), zinc oxide (ZnO), carbon dots, graphene, chitosan and mesoporous particles have demonstrated remarkable potential in extending product's freshness and reduce safety risks by inhibiting microbial growth and lowering spoilage in tomato, broccoli, spinach and other green vegetables. This review highlights the utilization of NPs, including Ag, ZnO, TiO_2, SiO_2, nanoclay and nanochitosan as well as nanoencapsulation techniques, in food systems. Furthermore, it explores how nanotechnology can revolutionize food packaging and preservation by enabling more effective, efficient and environmentally sustainable practices, ultimately contributing to a greener and more secure global food supply chain.

Keywords: food preservation; nanochitosan; nanocomposites; nanoparticles; nanotechnology

Introduction

The impact of population increases on the demand for high-quality food, as well as the issues it poses for food preservation. The estimates suggest that between 30 and 40 % of food globally, produced is never actually consumed and ends up discarded (1). The FAO has found that each year, nearly 1.3 billion tons of food produced for human consumption is either lost or wasted worldwide (2). Reducing post-harvest losses would enhance the availability of food suitable for human consumption and improve the global food supply, hence reducing the demand for intensive production that affects the environment (3).

Postharvest losses include the degradation of food in terms of both quantity (volume or amount of product) and quality (nutrient value, colour, acceptability and edibility) between harvest and consumption. Quantity losses are more prevalent in developing countries (4), while quality losses are more common in developed countries. FAO reports that developing countries waste 20-30 % of their horticultural produce. Food waste has become a major problem in many industrial sectors. In Turkey's smallholder processed fruit business, post-harvest handling and storage losses range from 30 to 20 % (5). Improper post-harvest management practices can cause more than 40 % of vegetable losses in developing and underdeveloped nations (6).

Post-harvest food losses are influenced by several factors, including the type of food, harvest timing, harvesting and post-harvest handling methods, packaging materials, processing techniques and storage conditions and the distance to food distribution. Other factors that affect post-harvest food losses include poor transportation, a lack of infrastructure and limited market accessibility. Addressing postharvest losses is imperative in reducing food waste globally. Research is needed to explore the impact of food storage practices on reducing both quantity and quality losses in industrialized and developing nations. Implementing effective food storage techniques directly reduces postharvest losses and ensures a more sustainable food production network, ultimately contributing to global food security efforts.

All across the world, there is a need for effective preservation techniques. The primary focus of food preservation is to reduce waste and extend the storing capacity of food (7). Several techniques have been used to preserve the food since ancient times. The evolution of preservation techniques is illustrated in Fig. 1. In the last few years, the focus on sustainable food storage solutions by implementing smart packaging and monitoring systems to enhance the quality and shelf life of food products increased. It not only benefits the environment, but also contributes to a more resilient and adaptable food distribution chain. Moreover, this can help reduce food waste and ensure that food reaches those in need more efficiently. Furthermore, these innovative storage solutions can also help address challenges such as food decay and potential safety hazards.

Generally, highly degradable food products including fruits and vegetables go through multiple phases before reaching the consumer. Some are sold in adjacent village markets, while others must pass through a complex network of aggregators, transporters, storage operators, processors and merchants before arriving in small towns and cities. Fruits and vegetables can deteriorate rapidly after harvesting due to various biochemical processes, which raises serious concerns about product stability during transit and storage as well. Using effective postharvest preservation strategies, particularly for highly perishable foods is critical for safe transportation. In fact, they must be maintained cool and clean throughout its supply chain to avoid contamination and deterioration. Any disturbance in the cold chain or mishandling of food can jeopardise its safety and nutritional value. *Botrytis cinerea*, or grey mould disease, is a prominent postharvest pathogen that causes rot in many commercially important fruits and vegetables throughout both the growing season and storage (8). Managing this disease during storage is essential, as it can survive at low temperatures (-0.5 ℃) and rapidly infect fruits and vegetables. Packaging is an important component of the food supply chain, protecting products from contamination by pollutants, dirt, microbes and chemicals. Effective packaging materials should be safe, lightweight, non-reactive and durable enough to withstand physical and environmental stresses. Conventional plastics used in food packaging are difficult to break down, resulting in environmental problems.

Food packaging has improved in response to changing consumer demands as material science and technology have advanced. The use of nanotechnology, also known as nanoscience, in agricultural production and post-production handling is gaining popularity these days because it can reduce post-harvest losses, increase food quality and production efficiency and control microbial growth and development. Nanotechnology is a new generation of packaging that increases strength, quality and packaging beauty by reducing the influence of gases and damaging UV radiation (9). Nanoparticles (NPs) in post-harvest packaging reduce waste, improve package performance and enhance thermal stability, preserving food freshness and reheatability. They also provide stronger barriers against gases, UV rays, moisture and volatile compounds, while enabling antimicrobial and nano-biodegradable materials (10).

Nanotechnology focuses on materials under 100 nm in size with a high surface-to-volume ratio, offering notable industrial and scientific potential (11). Nano packing is one of the new approaches used in food packaging to ensure safety. It can help prevent rotting and physical damage to fruits and vegetables during transportation (12). Many studies suggest that employing nano-packing material enhances physicochemical and physiological quality when compared to standard packing material (9, 11). Moreover, the NPs, for instance, silver (Ag) NPs, protect the packaging materials and are very effective against different types of infections, germs, viruses and fungi (13). The use of nano-packing provides a viable approach for increasing the shelf life of fruits, vegetables and other horticulture crops during long-term storage.

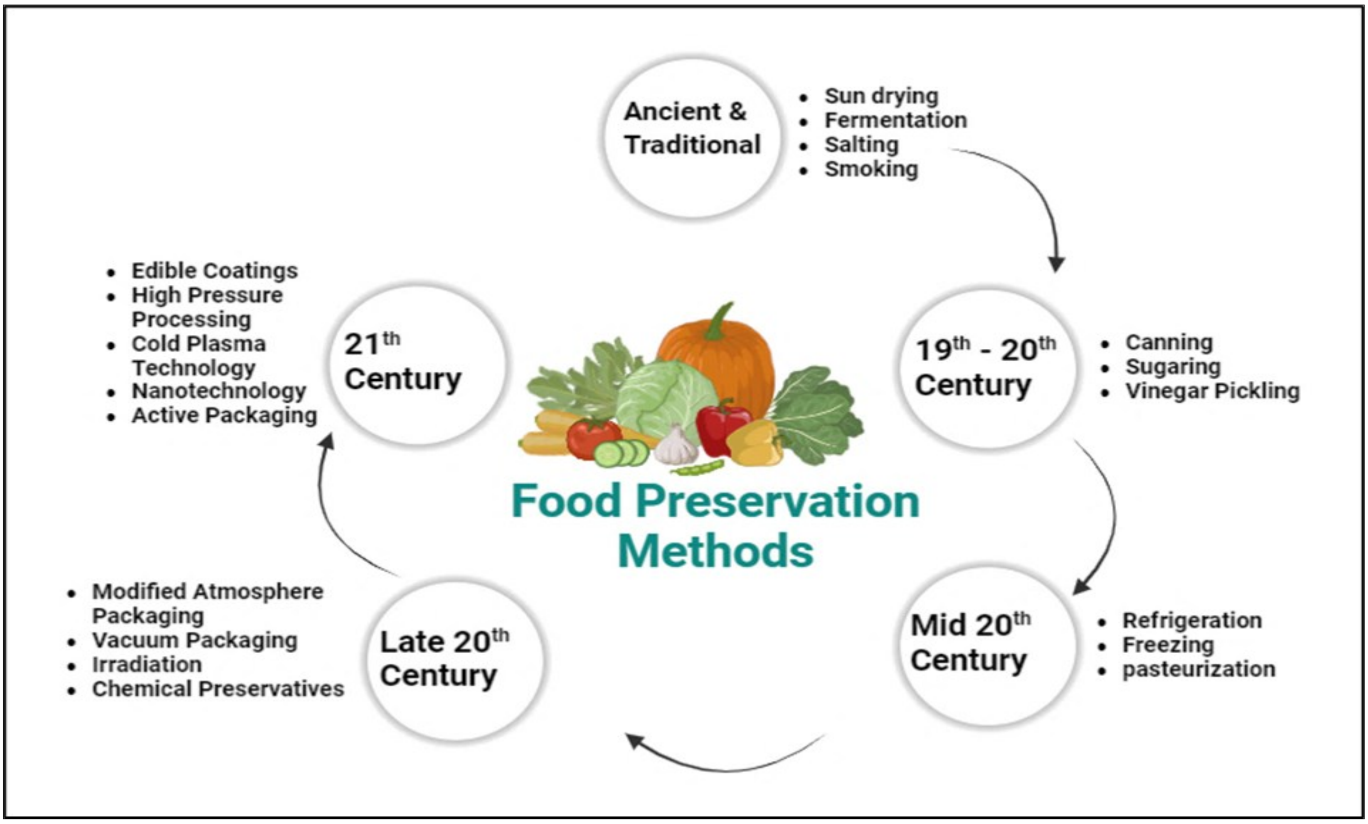

Fig. 1. Food preservation techniques evolved over time from sun drying to active packaging.

Now-a-days, nanotechnology is utilized to coat food, food wrap and packaging to provide additional protection. Examples of nanotechnology used in post-harvest packaging include nano sensors, nanocomposites, nano capsulation and nano emulsions (14). Due to its crucial role in the efficient transportation and preservation of food to end consumers, food packaging has grown to be the world's third largest sector (11). The main process of packaging systems is to give containment for easy handling, transportation and distribution; protect and preserve the quality of food against adverse internal and external conditions; deliver on time information about the product's quality and ensure convenience for consumers (14, 15). The review article examines the global scenario in food preservation, analyses the reasons for the food deterioration, particularly fruits and vegetables and summarizes the utilization of nanotechnology-based solutions to improve packaging and preserve fruits and vegetables more effectively.

Reasons for the food deterioration

Generally, fruits and vegetables deteriorate due to physical, chemical and biological reasons. Details are discussed as follows.

Chemical changes

Fresh foods lose sensory quality due to two types of chemical changes that occur during preparation and storage: lipid oxidation and non-enzymatic browning. Chemical interactions can induce colour and flavour changes in food during the production and storage (16). The presence of catalysts, typically transition metals such as iron and copper, high temperatures, light, water activity and local O_2 concentrations all influence the rate and direction of lipid oxidation and may result in non-enzymatic browning (17). They can be considerably reduced by controlling these factors.

Taste changes

Long-chain fatty acid-derived compounds produced by enzymes are necessary for the development of various flavours in fruits and vegetables. These interactions could result in very unpleasant flavours. When it comes to keeping desirable volatile components inside packages or allowing undesirable components to leak through from the surrounding air, the permeability of packing materials is crucial (18).

Nutritional changes

Light is one of four major variables that influence nutritional breakdown and packaging can influence it to varying degrees. The nutritional profile of fruits and vegetables is also affected by their O_2 concentration, heat level and water consumption (19).

Physical changes

Caking, a significant undesirable physical change in food, is caused by moisture absorption from inadequate packing barriers. There are two reasons for this: either the package integrity failed during storage or the packing material was chosen improperly. Increased cohesion is often associated with increased absorption of moisture (20).

Biological changes

Microbiological changes: Commonly, foods are classified as nonperishable, semi-perishable, or perishable based on their stability (21). The mechanical integrity of a package, particularly the lack of breaks and seal imperfections, is vital for safeguarding packaged food from contamination or germs. Microorganisms can have a positive or negative impact on food quality, depending on whether they are introduced during the preservation process or grow unintentionally, causing spoilage. Food microorganisms are divided into two categories: bacteria and fungi, which include yeasts and moulds. Because they develop more quickly than fungi, bacteria usually dominate them in favourable environments. Pathogenic bacteria such as *Escherichia coli* O157:H7, *Aeromonas hydrophila* and *Listeria monocytogenes* can be detected in both fresh and lightly processed fruits and vegetables.

Macrobiological changes

It is mostly due to insect problems. Warm, humid conditions enhance insect growth; yet most insects will not reproduce at temperatures below 10 °C or above 35 °C. For insects to reproduce successfully, their meal must have at least 11 % moisture. Rats and mice can carry disease-causing organisms in their feet and digestive systems, such as *Salmonella* serotypes linked to human illnesses caused by food (22).

Various technologies and methods used in food preservation and packaging

Conventional methodologies and their impact on food preservation

Reducing temperature is a popular physical preservation technique for increasing shelf life; by decreasing the temperature by 4 °C, for example, mushrooms have higher levels of Vitamin D2, which prolongs their survival (23). However, it is expensive to maintain and can harm vegetable tissues at such a low temperature. Historically, a range of conventional technologies have been used as the foundation for food preservation. For example, cold storage uses radiation, chemicals and biological agents in addition to decreasing the temperature. The details are as follows.

Radiation usage

Radiations such as ultraviolet light (UV-C) have been used to preserve food. Vitamin D2 levels in brown mushrooms increased when subjected to a UV-C light exposure of 2.0 kJ/m^2 (23). These high -frequency radiations have adequate strength to offer the highest level of disinfection. The disadvantage of using such radiations is that they are powerful enough to damage the texture and structure of vegetables.

Applying chemical substances

Chemicals with strong disinfectant capabilities, such as chlorine, are commonly employed to preserve many fruits and vegetables (24). However, some chemical agents are prohibited due to their high additive content and the risk of foodborne illness.

Utilizing biological agents

Using a biological agent as a preservation strategy is much more successful and has shown a lot of attention due to its environmental benefits. Nisin-incorporated cellulose sheets were reported to drastically reduce the cell number of *L. monocytogenes* in mangoes while maintaining their structure (25).

Nanotechnology: A developing technology for reducing food deterioration

The use of conventional methods such as heating, freezing and drying have a number of disadvantages, including shrinkage and nutrient loss in the food. Furthermore, heating is projected to contribute to nearly 29 % of the energy expenditure in the food processing domain (17). On the other hand, biologically induced preservation, while safer and more successful, still requires the support of other scientific breakthroughs, one of which is nanotechnology. When compared to usual packaging methods, nanotechnology packaging has more advantages, such as better mechanical barriers, heat resistance and biodegradable qualities. The storage life of fruits and vegetables has now become longer due to developing nanotechnology, which may also solve current postharvest issues. Recently, fruit and vegetable shelf lives have been increased by using nanotechnology to reduce post-harvest losses. In addition to enhancing proper food handling and quality assurance nanotechnology has a profound impact on food science. It can be used to identify and monitor pollutants, extend shelf life and storage and apply antibacterial or health additives (26). Nanometals are efficient antibacterial agents against a number of common pathogens. silver (Ag), zinc oxide (ZnO) and titanium dioxide (TiO_2) are commonly incorporated as antimicrobial agents and additives in various consumer, industrial and healthcare products. Using NPs in edible films to improve the shelf life of vegetables and fruits is a novel pathogen-control strategy in food nanotechnology. Active food packaging systems are now being developed to replace traditional packaging techniques and they are more effective in preserving food against microbial infections (27).

Nanotechnology is widely employed in food processing (28) and agriculture (29) described above; nanomaterials are materials with a single-dimensional structure of less than 100 nm (30). Nanomaterials differ from their macroscopic counterparts in a variety of ways, including extraordinary hardness, barrier and optical properties, when materials shrink from macroscale to nanoscale. These distinct material properties are crucial to the use of NPs in the preservation of fruits and vegetables. Nanoscience has been effectively applied to fruits through food coatings, which are thin layers of edible substances typically added by immersing the fruits in a coating solution. These coatings have become one of the most notable advancements in food technology in recent years. They are designed to carry a range of beneficial compounds, including colourants, flavours and nutrients, as well as agents that prevent browning and inhibit microbial growth, thus enhancing shelf life and reducing the risk of contamination. Various application techniques, such as dipping, spraying and coating, allow for precise control over moisture, gas exchange and oxidation. The inclusion of nanoparticles (NPs) improves the effectiveness of these coatings by increasing their surface area, enhancing their barrier properties and boosting preservation performance. Antimicrobial NPs are often incorporated into edible coatings and films (ECFs) to further protect the fruit (31). Post-harvest challenges have decreased with the advent of nanotechnology. Silicon dioxide (SiO_2) and titanium dioxide (TiO_2) are the two nanoparticles most widely used in food packaging. Furthermore, food processing, packaging and preservation operations often employ nanomaterials such as nanofibers, nanotubes, nano whiskers (nanorods), nanosheets, nano capsules, nano sensors, solid-lipid NPs, nanocomposites and nano bar codes (28, 32).

Techniques using nanotechnology to enhance the post-harvest longevity of fruits and vegetables

Standard approaches for preserving fruits and vegetables are grouped under three preservation methods: physical, chemical and biological preservation (33-35). Even though each preservation method focusses on a different aspect of these three core components, they are all important for keeping quality. Fig. 2 depicts the systematic application of major technologies in vegetable shelf life and postharvest storage.

1. The regulation of senescence, which controls respiration.

2. Regulating microorganisms, which is primarily accomplished by regulating spoilage bacteria.

3. Controlling internal water loss by regulating ambient humidity (36).

However, as Table 1 illustrates, there are certain inherent challenges with traditional shelf-life approaches. In order to address growing customer concerns regarding food safety and freshness,

Table 1. Disadvantages of popular methods for extending vegetable shelf life

Shelf-life strategies	Disadvantages
Frozen storage	High expenditure, the possibility for freezing and oven frost injuries.
Irradiation process at hydrostatic pressure	Costly, currently developing technology, challenging to manage irradiation setting.
Edible coating	high moisture permeability, quick absorption of moisture, a short shelf life and difficulty controlling the concentration and thickness of the edible coating.

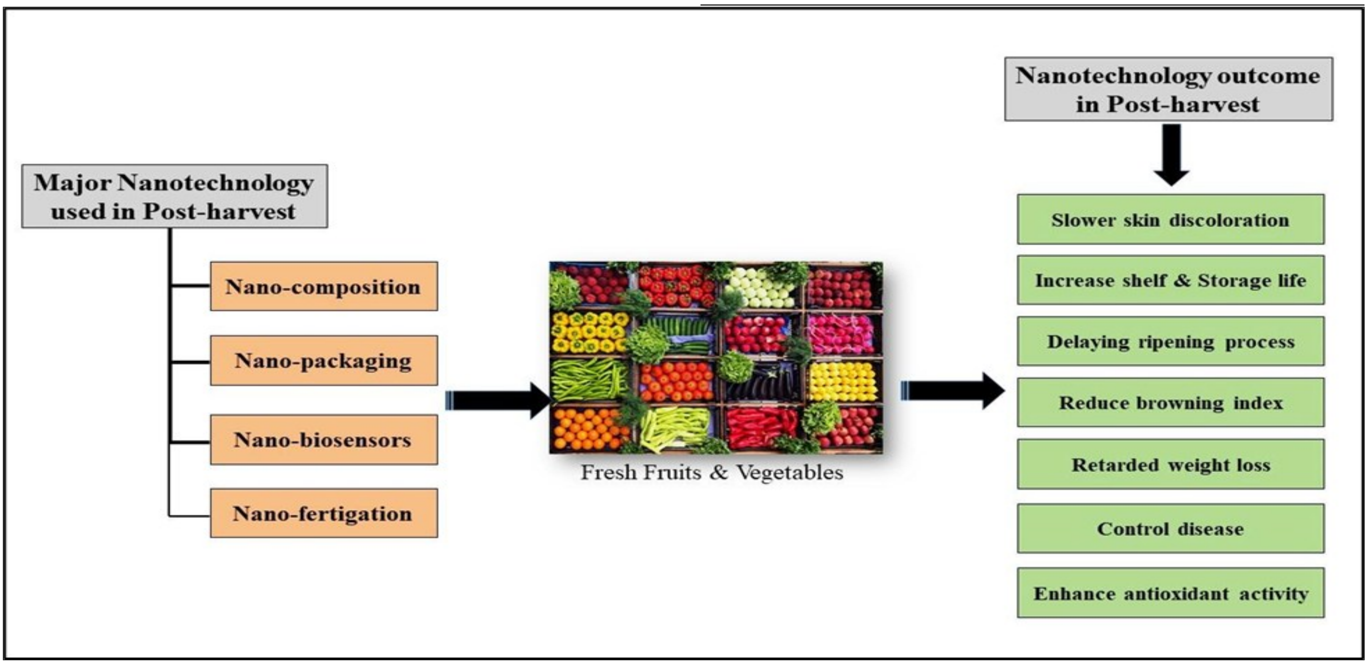

Fig. 2. The systematic use of major nanotechnology in vegetable shelf life and post-harvest storage.

new methods of preserving fruits and vegetables must be developed.

Fruit and vegetable shelf life is significantly extended by nano packaging. To reduce food loss, food packaging is developed using both organic and inorganic NPs, or mixed NPs. There are three categories of nano-packaging for food materials: improved, active and intelligent/smart packaging (15, 37, 38). Better mechanical and physical qualities are enhanced by improved packing. Antibacterial, antioxidant and UV-absorbing qualities are present in active packaging. In contrast, controlled food conditions are a component of intelligent packaging. The classification of nano packaging is given in Fig. 3.

Nanostructure development in food preservation

Sol-Gel Synthesis

Sol-gel synthesis is a widely used technique for preparing nanoparticles and nanostructured materials. In this method, a solution (sol) of metal precursors is converted into a gel that can be dried and processed into nanoparticles. The sol-gel process allows for precise control over particle size and morphology, which is crucial for creating nanoparticles with desired properties, such as high surface area and stability. In food preservation, sol-gel synthesized nanoparticles can be used to create coatings that enhance the shelf life of food by providing protection against moisture, oxygen and contaminants (39, 40). This method is beneficial because it's relatively simple, cost-effective and can be adapted to produce a variety of nanomaterials such as silica, titanium dioxide and other metal oxide nanoparticles.

Electrospinning

Electrospinning is another important technique used to create nanofibers from polymers or biopolymers. A polymer solution which is usually made up of polymer (gluten, zein, gelatin) and solvent (water, acetic acid, deionized water, distilled water, formic acid) is subjected to a high-voltage electric field, which causes the solution to be drawn into fine fibers that can range from 10 to 1000 nm in diameter. These fibres can be used in food packaging to create nanofiber-based films or mats. The nanofibers produced by electrospinning have a high surface area-to-volume ratio, which is ideal for the encapsulation of active compounds like preservatives, antioxidants, or antimicrobial agents. The electro spun nanofiber films can improve food shelf life by providing a barrier to external contaminants, enhancing the release of active ingredients and maintaining food quality over time (41, 42). Electrospinning is particularly useful for producing biocompatible and biodegradable packaging materials that can degrade more easily in the environment.

Nanoprecipitation

Nanoprecipitation is a technique used to produce nanoparticles by dissolving a material in a solvent and then adding it to a nonsolvent, causing the material to precipitate out as nanoparticles. This method is commonly used to create polymeric nanoparticles for encapsulation applications in food preservation. Nanoprecipitation allows for the control of particle size and distribution, which is important for ensuring consistent release of active compounds. These nanoparticles can be used to encapsulate vitamins, flavors and preservatives, improving their stability and bioavailability while extending food shelf life (43, 44).

Emulsion Polymerization

Emulsion polymerization is a technique used to create nanoparticles by polymerizing monomers in an emulsion system. This process is typically used for creating polymeric nanoparticles, which can be used in food packaging and preservation. The size and properties of the nanoparticles can be controlled by adjusting factors such as the monomer concentration, temperature and surfactant type. These nanoparticles can act as carriers for bioactive compounds or preservatives, providing controlled release and enhancing the effectiveness of food preservation (45, 46). Emulsion polymerization is useful for creating stable nanoparticles with uniform size distribution, which is critical for the consistent performance of food packaging materials.

Advanced nanoparticles in food systems

Carbon dots

Carbon dots are fluorescent nanoparticles that are employed as sensors that carry a great potential in biosensing and bioimaging in the food industry and it was identified and categorized as a novel class of carbon nanomaterial with a size of less than 10 nm (47). A sensor using carbon quantum dots (CQDs) and manganese di-oxide (MnO_2) was created to detect ascorbic acid (vitamin C) in fruits, vegetables and liquids. The technique relies on fluorescence

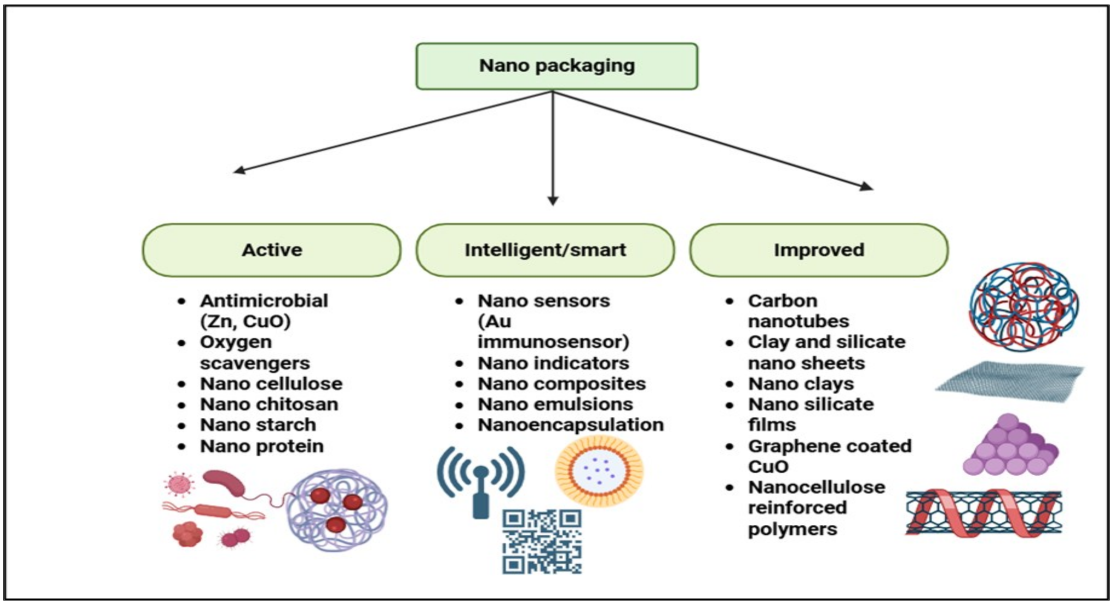

Fig. 3. Classification of nano packaging.

recovery, where vitamin C decreases MnO_2 and restores the CQD signal (48). FRET (Forster Resonance Energy Transfer) system was employed for melamine detection in milk employing carbon dots (CDs) and gold nanoparticles (AuNPs) with a detection limit of 36 nM (49). Employing CDs to detect tannic acid in wine based on its capacity to quench fluorescence, with a low detection limit of 0.018 mg/L (50). CD-aptamer complexes were employed to identify the pathogen in eggshell and tap water with good specificity and sensitivity, with a limit of detection (LOD) of 50 CFU/mL (51). A fluorescent "on-off-on" sensor was built using CDs, AuNPs and aptamers to detect AFB1 in food samples, with an ultra-low limit of detection of 5 pg/mL (16 pM) (52).

Mesoporous silica materials

Mesoporous materials have demonstrated great potential in the food sector, particularly for catalysis and enzyme immobilization. Sulfonic acid-functionalized mesoporous silica (SMPS) was used as a catalyst to synthesize fatty acid monoesters, which are vital food emulsifiers (53-56). Similarly, the use of nanoporous materials with single-site catalytic centers to produce food-related compounds like nylon-6 (57). Solid acid catalysts have also substituted severe conditions in reactions such as the Claisen rearrangement, which produces flavor and smell (58). Enzyme immobilization on nanoparticles has advanced biocatalysis, with silica, magnetite and gold nanoparticles supporting enzymes in food and pharmaceutical applications (59). Immobilized xylitol dehydrogenase on epoxy-silica nanoparticles to efficiently convert xylitol to L-xylulose, revealing the possibility for large-scale rare sugar synthesis. In recent decades, increased awareness of environmental and food safety concerns has resulted in the development of sophisticated sensing devices for hazardous chemicals such as nitrite and biogenic amines (60, 61). While standard nitrite detection methods frequently fail in complicated samples, biosensors based on nitrite-reducing enzymes provide great selectivity and stability (62).

Graphene

Graphene's planar shape and chemical structure provide it with significant advantages over other materials for the construction of sensors and biosensors. For example, the graphene sheet's atomic thickness and extremely high surface-to-volume ratio make it highly sensitive to changes in local environmental conditions, which is a significant advantage in the sensing field because all carbon atoms interact directly with analytes, resulting in higher sensitivity than silicon nanowires or carbon nanotubes and contributing to the fabrication of improved electrochemical sensors and biosensors. Patulin was recognized as a key risk factor in the processing of fruits and beverages due to its severe health effects and higher chemical stability in acidic environments. Using different methods before and after food processing can affect the quantities of patulin in the final product. The magnetic graphene oxide (MGO) nanocomposite has emerged as one of the future generations of resources for the elimination of several hazardous components and compounds, both organic and inorganic. Graphene's unique features make it an ideal material for biosensor development. The study describes the development of graphene-based biosensors capable of detecting numerous foodborne infections and poisons, thereby enabling real-time monitoring of food safety (63).

Improved packaging

The improved packaging method of fruits and vegetables is given in Fig. 4.

Carbon nanotubes

Carbon nanotubes enhance thermal and mechanical properties while also providing protection. They are used in food packaging, specifically as antibacterial and intelligent sensors. Carbon nanotubes can be either single or multiwalled (64). Polyamides with carbon nanotubes can be used to elevate the elastic modulus and structural strength of several polymers (65). Single-walled carbon nanotubes combined with cobalt mesoarylporphyrin are used to create chemo resistive detectors that are able to identify the production of amines during food spoilage (66). Carbon nanotube-based gas sensors combined with wireless chips are utilized to create thin and transparent packaging films that give information about the standard of food products. Dates can be protected from fungi growth for 90 days by using packaging made of carbon nanotubes and polyethylene (67).

Clay and silicate nanosheets

Clay helps in moisture control and antimicrobial activity, whereas silica helps in controlling moisture within the package and it is mainly used for sensitive food products. Nano clays are the most investigated nano -fillers due to their outstanding performance, ease of processing, low cost and widespread availability. Clays used to create nanocomposites are typically bidimensional platelets with lengths of several micrometres and thicknesses of roughly 1 nm (68). The interaction between polymers and layered silicates leads to the formation of two types of nano-scale structures: exfoliated and intercalated nanocomposites. Exfoliated nanocomposites have broad and random penetration of the polymer matrix with clay layers (69). Intercalated nanocomposites develop organized multilayer structures when polymer chains penetrate the clay's interlayer area (70) exploited nanocomposites are known for their superior properties, which result from the ideal interactions between clay and polymer. The increased

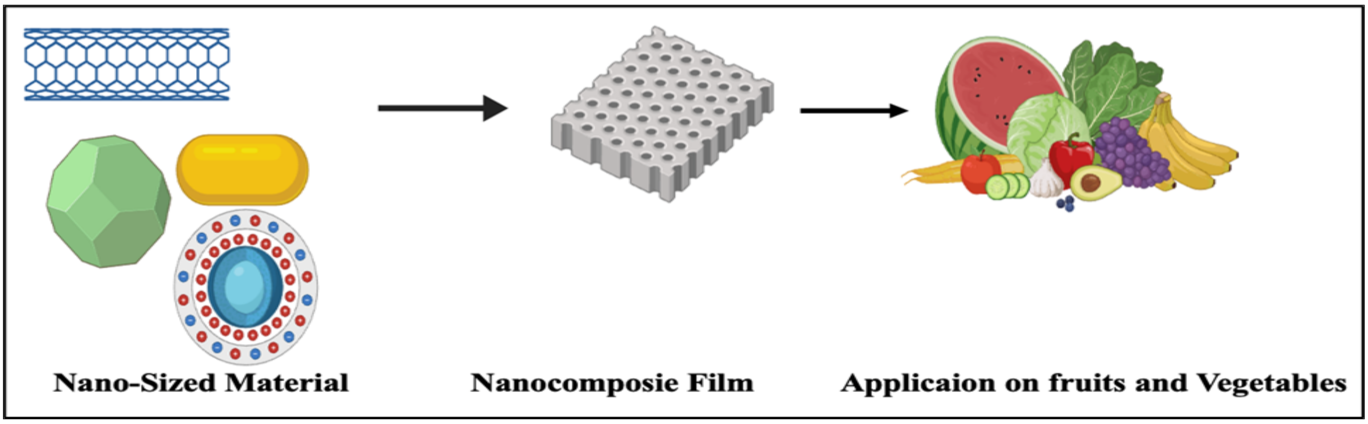

Fig. 4. Application of nanomaterials for packaging fruits and vegetables.

tortuosity of the diffusion pathway for permeants contributes to enhanced gas and moisture protection properties in polymer-clay nanocomposites (23). Montmorillonite clay is commonly employed as a nanocomponent in various polymers. It is a 2:1 layered phyllosilicate with an octahedral alumina sheet sandwiched between two tetrahedral silica sheets (71). Montmorillonite, owing to its high surface area, cation exchange capacity and swelling behavior, is an ideal nanomaterial for polymer composites and nano-packaging with intercalated blueberry extract (72).

Polyvinyl - ZnO Powder

A novel nano-packaging was created by applying a layer of nano ZnO powder to polyvinyl chloride (PVC) film. A 12-day study at 4 °C was conducted to evaluate its effect on the preservation quality of fresh-cut 'Fuji' apples. The nano-packaging significantly reduced fruit deterioration and extended storage by up to six days compared to the control (PVC film) (73).

Low-density polyethylene

By preventing browning, limiting microbiological growth, maintaining the activity of beneficial chemicals (ascorbic acid, titratable acid) and improving overall visual quality, low-density polyethylene packaging based on nano $CaCO_3$ significantly slows down the ripening process (74). It was reported to extend the shelf life of strawberries in cold storage; several concentrations of nano ZnO (0.03 %, 0.07 % and 0.5 %) were employed. According to a study (80), nano ZnO (0.5 %) was the most successful concentration at delaying ripening processes and reducing microbial populations (75).

Chitosan-based nano silica film

Using tetra ethoxy silane as a precursor and in situ sol-gel procedures, new chitosan with a nano-silica coating was developed. This study showed that the superior semi-permeable chitosan/nano-silica film significantly increased the shelf life of fresh fruit, decreased its browning index, delayed weight loss and suppressed the growth of malondialdehyde content and polyphenol oxidase activity (76). Chitosan nanoparticle postharvest treatment could increase antioxidant activity while also extending cucumber storage time (77). The chitosan nanoparticle (avg. 102.4 - 370 nm diameter) coating was created to assess the impact on banana skin colour during the ripening phase. A scanning electron microscope (SEM) revealed that coated bananas had smoother skin than non-coated bananas. In addition, nanoparticle-coated bananas showed 0.2 % slower skin discolouration after 2-3 days (78).

Graphene-coated copper oxide (CuO) nanotechnology

An electrochemical immunosensor based on graphene coated with a copper oxide (CuO) cysteine system was developed to identify *Escherichia coli* (79). The type of electrically charged immunosensor that the author discovered has a large surface area and good conductivity properties. Examining the contact angle, the microstructure of nanocomposites and the morphological arrangement of bioelectrodes can lead to improved sensitivity and efficacy.

Active packaging

Active packaging is designed to preserve and protect food through mechanisms activated by intrinsic and/or external stimuli. By incorporating nanotechnology into food packaging, the carrier component of active packaging can adapt to both internal and external influences, prolonging shelf life and improving food product quality (14). The incorporation is accomplished through a variety of approaches, including coating, immobilization, sachets and pads.

Nanocellulose

Cellulose, a polysaccharide that provides plants their strength, is the most prevalent polymer found in their cell walls. Nanocellulose refers to cellulose at the nanoscale, typically appearing as nanofibres or nanocrystals with diameters under 100 nm and lengths spanning a few micrometres (80). It is an excellent material for the manufacture of high-strength, lightweight and cost-effective nanocomposites (81). Plants can be utilized to extract nanocellulose by chemical and mechanical methods. Nanocellulose has excellent barrier qualities because of their high hydrogen bonding capacity, which allows them to construct thick, robust surfaces that are impermeable to molecules. Nanocelluloses have excellent barrier characteristics. Cellulosic NPs have a large specific surface area and can form hydrogen bonds. The substance may create a strong, dense network that is very challenging for other molecules to penetrate through due to its ability to make hydrogen bonds (82). When utilized as a filler, coating, self-standing thin film, or composite material, nanoscale cellulose demonstrates very intriguing and promising properties (83).

Cellulose microfibrils are bundles of elongated molecules mostly produced by plants. These molecules are stabilized by a network of solid H bonds, resulting in cellulose, a relatively stable polymer with diameters ranging from 2 to 20 nm (84). Cellulose nanofibers are an attractive class of nanomaterials as they increase the activity of NPs by increasing surface area (85). Nanocellulose serves as a potential substitute for conventional petroleum-derived materials due to its superior biodegradability. Nanocellulose increases the strength, thermal properties and modulus of polymers while providing excellent moisture barrier properties to polymer films, while it limits elongation (86).

Nano starch

The two polymers that comprise starch are amylose and amylopectin. Starch is a complex polymer. To produce nano starch, starch granules are broken down through a range of physical and chemical processes (87). In composite materials, starch NPs, also referred to as starch nanocrystals, are utilized as nanofillers to improve the materials' mechanical, malleable, biodegradable, water-impermeability, thermal and barrier properties (88). Starch is found in the form of distinct, partially crystalline granules composed of linear amylose and branched amylopectin. Crystalline starch must be isolated from amorphous and crystalline complexes before it can be converted into nano starch. It is widely used in food packaging due to its low cost, non-toxicity, easy availability and biodegradability (10). Nano starch crystals are possible natural binders that are less expensive than synthetic emulsion latexes. Incorporating inorganic elements and synthetic polymers into starch can increase its water resistance (23). Nano starch crystals are a viable filler for flexible food packaging because they have improved mechanical and barrier properties. The thickness of starch crystalline particles was typically 6-8 nm, resulting in improved tensile strength and decreased elongation. Starch crystal particles typically had a thickness of 6-8 nm and showed increased tensile strength along with reduced elongation properties (62).

Nano protein

Nanoparticles derived from proteins are integrated into food packaging systems to reinforce structural integrity and reduce permeability, including water resistance (89). Studies have shown that peanut protein NPs improve the strength, temperature resistance and moisture barrier properties of protein-starch-based biocomposites (90). Additionally, zein NPs enhance the mechanical strength and moisture barrier properties of films made from whey protein isolate (91).

Nano chitosan

Chitosan is mostly derived from marine by-products, from which chitosan nanoparticles (CNPs) are produced. These functionalized nanostructures are nontoxic, biocompatible and biodegradable. CNPs have proven suitable potential as green fillers for reinforcing various biodegradable composites used in food packaging. CNPs are an effective means of improving the mechanical, barrier and physical properties of biocomposites. Moreover, the hydrophobic nature of CNPs, their ability to produce hydrogen and their covalent interaction with biopolymers, which reduce the rates of moisture transport, enhance their moisture impermeability. Furthermore, due to the chelation effect and ionic interactions between NPs and bacterial cell surfaces, which restrict nutrition transport and result in cell death, they have antibacterial properties as well (55).

Rapid killing by Zn, CuO NPs

Active packaging inhibits the proliferation of harmful microorganisms, including pathogenic microbes and spoilage agents. Recently, the creation of an electrode sensor capable of both rapid bacterial destruction and ultrasensitive identification was developed. The nickel porous electrode is coated with zinc copper oxide nanoparticles (92). As predicted, the wrapped electrode sensor could kill all bacteria in 20 min after capturing 70 to 80 % of them. Furthermore, this wrapped nanoelectrode has a sensitivity of 10 CFU/mL.

Silver NPs

Silver NPs (AgNPs), in particular, they exhibit broad antimicrobial properties and can be integrated into edible or non-degradable polymers for active food packaging (93). AgNPs-based antimicrobial packaging is a potentially effective type of active food packaging that extends food shelf life and reduces the risk of infections. Biopolymers based on silver NPs are used in active packaging. Silver NPs combined with polymers reduce infections more effectively. The edible coatings are made using AgNPs and are still on a laboratory scale (94). The study conducted to evaluate the storage life extension of fruits and vegetables using edible coating indicated that in apples and bananas, shelf-life extension and decay were prevented. In cherry tomatoes, cucumber, citrus, grapes and guava (95), edible coatings of different nanoparticles promote quality maintenance and extend the storage life. In mushrooms, the matrix of various nano coatings enhances storage quality (96). During cold storage, the physicochemical quality of bell pepper was maintained and *Alternaria alternata* development was suppressed by an edible nano-chitosan coating loaded with α-pinene. Active packaging films and coatings infused with silver nanoparticles (AgNPs) help extend food shelf life and inhibit microorganism growth. This is due to the controlled release of NPs onto food surfaces, which are thought to serve as hotspots for bacterial growth and activity. Furthermore, it is believed that these procedures may reduce the number of preservatives added to food to retain its quality and extend shelf life (97).

Due to the electrostatic attraction between the negatively charged cell membrane of microorganisms and the positive charge of silver ions produced by the oxidation of AgNPs, when microbes are exposed to AgNPs, the nanoparticles tend to adhere to the cell wall or membrane of the microbes. AgNPs are also highly attracted to the proteins in the microbial cell wall that contain sulfur. AgNPs' attachment to microbial membranes results in permanent morphological alterations to the cell membrane's structure. The permeability of the cell membrane and the integrity of the lipid bilayer may also be compromised as a result. The cell's ability to routinely regulate activity can be impacted by changes in cell shape, which can lead to increased permeability of the cell membrane. For example, the release of silver ions from nanoparticles will alter potassium ion (K^+) transport and release, which will impact cellular transport activities. Increased permeability of cell membranes can also result in the loss or leakage of cellular components such as cytoplasm, proteins, ions and ATP, the cellular energy reserve, which can lead bacteria to exhibit the ghost cell phenomenon. In bacteria, the ghost cell effect happens when the cell or microbial contents are expelled, leaving a hollow envelope of the microorganism (98). Direct interactions between the silver nanoparticles and the microbial cells are also possible. Inhibiting respiratory chain enzymes or interfering through covering permeability to phosphate and protons (e.g., interrupting transmembrane electron transfer, oxidizing cell components, disrupting, penetrating the cell covering or reactive oxygen species (ROS), or dissolving heavy metal ions that cause damage) are some examples of how silver ions can be studied to uncouple respiratory electron transport from oxidative phosphorylation. Due to the existence of pathogen strains, the food business is mainly affected and failure to recognize a disease could have disastrous consequences. Despite a significant improvement in overall food security, bacterial contamination has led to the emergence of unequal and foodborne outbreaks (99).

Gold NPs

The antibacterial, antifungal and anticancer activities of gold NPs (AuNPs) can be evaluated from many perspectives. Furthermore, extensive studies have been conducted on AuNP complexes, including chemicals and antibiotics. Researchers have evaluated the antifungal activity of chemically and green-synthesized AuNPs against common pathogens like *Candida albicans*. Size, shape and concentration are the main factors determining fungicidal activity in AuNPs, which have been demonstrated to have substantial antifungal properties. Since the majority of researchers believe that AuNPs and many other NPs can have antimicrobial effects on hazardous organisms, the usage of AuNPs in coatings and packaging has caused controversy. The most controversial of the many gram-positive and gram-negative bacteria that have been investigated is *E. coli*. The size and shape of nanoparticles (NPs) are crucial factors, but the synthesis method and reducing agent can also influence the final outcome. Consequently, gold nanoparticles (AuNPs) are highly recommended as antibacterial agents for premium, luxury products like caviar (100).

Zinc oxide NPs

Zinc is an important vitamin that can be added to foods and nutritional supplements (101). Zinc oxide NPs (ZnO NPs) show antibacterial activity against several bacteria, including *Salmonella enteritidis*, *E. coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, etc., because ZnO NPs release Zn^{2+} ions and ROS, damaging cell organelles and inducing cell death. Their incorporation into polymers enhances mechanical barrier and antibacterial properties. Due to their commercial availability, pure ZnO NPs are easily integrated into various matrices like PLA, PHB and PHBV. In a Study with Zn NP, along with chitosan and gum Arabic, by using dipping method it was reported that the consistency of bananas was retained for a longer period and shelf life was prolonged for more than 17 days (102). In a similar study with Zn NPs with carrageenan by using dipping method resulted in increased antimicrobial properties and maintained the shelf life of the whole mango fruit (103).

ZnO nanoparticles' precise mode of action is still a mystery. However, several mechanisms are responsible for the antimicrobial activity of these nanoparticles, such as the release of antimicrobial ions (104), the interaction of nanoparticles with microorganisms, which damages the integrity of bacterial cells (105) and the formation of ROS due to the effect of light radiation (106). The antibacterial activity of zinc oxide has been attributed to interactions with bacterial cell membranes and the infliction of damage on the bacterial surface. Accordingly (105), suggested that the direct interaction of nanoparticles with the bacterial membrane and the generation of ROS in the vicinity of the bacterial membrane account for a portion of ZnO's antibacterial activity. On the other hand, one plausible theory about the toxicity of ZnO against S. cerevisiae is the release of Zn^{2+} antibacterial ions (104). This author claims that the solubility of Zn^{2+} ions in the medium containing the microorganisms may be the cause of the toxicity of ZnO nanoparticles. However, concentration and duration determine how soluble metal oxides like ZnO and Al_2O_3 work (59). Therefore, the microbe may develop a comparatively high tolerance to low amounts of solubilized Zn^{2+}.

The effect of ZnO NPs highly related on the plant species, soil pH and exposure time. Zinc availability from ZnO nanoparticles (ZnO NPs) was higher in soils with low pH than in calcareous soils with higher pH. As a result, ZnO NPs had a bigger effect on beans in acidic soil, but tomatoes responded better in alkaline soils. Furthermore, plant stress indices such as malondialdehyde (MDA), protein content and antioxidant enzyme activity (e.g., SOD, CAT) varied throughout time (15-90 days) depending on ZnO NP concentration (3, 20 and 225 mg/kg). ZnO nanoparticles have a strong influence on plant photosynthesis. Photosynthesis is an essential and delicate physiological function for plants. It can be enhanced or hampered by adjusting photosynthetic efficiency, photochemical fluorescence and quantum yield. ZnO NPs boost essential photosynthetic enzymes such as Rubisco, PEP carboxylase and carbonic anhydrase as well as chlorophyll content and activity, hence increasing photosynthetic rate and production (107). Investigation done to identify how ZnO NPs alter a natural mechanism in specific beneficial bacteria that produce the plant hormone indole-3-acetic acid (IAA) (108). This hormone promotes plant growth and is produced utilizing a chemical known as tryptophan. The researchers discovered that when these bacteria were exposed to ZnO NPs, their ability to produce IAA decreased. This most likely occurred because ZnO NPs interfered with how tryptophan was employed in the process. In contrast, copper oxide (CuO) nanoparticles stimulated the bacteria's production of IAA. As a result, ZnO may inhibit and CuO can stimulate a plant growth hormone by influencing how bacteria use tryptophan.

Titanium dioxide NPs

Titanium dioxide NPs (TiO_2 NPs) are employed in many food-related applications, including food additives and food packaging nanocomposites. TiO_2-NPs enhance packaging properties, block UV light and act as stable food colourants. Their antibacterial effect stems from the generation of ROS and free radicals, which kill bacteria (10^4).

Active food packaging (AFP) uses titanium dioxide (TiO_2) nanoparticles to protect light-sensitive foods because of their high refractive index and UV sensitivity. TiO_2 improves the packaging's mechanical strength and microbiological resistance when paired with biopolymers like chitosan, which naturally has antibacterial qualities. Water and oxygen are absorbed by the chitosan layer and then diffuse to the TiO_2 layer. Reactive oxygen species (ROS) produced by TiO_2 under UV radiation oxidize and destroy microorganisms. Fresh produce deterioration and discoloration are slowed by these ROS because they also break down ethylene, a plant hormone that causes ripening. Because of this, TiO_2 based AFP is a better option than conventional materials like paper (109). In a study the coating made up of $TiO_2$with chitosan and sodium tripolyphosphate delayed the decay rate and maintained the hardness level throughout the storage period upto 21 days (110). In blueberries, chitosan coating of TiO_2NP increases storage quality by decreasing the ripening and decay (111).

Enzyme immobilization system

Enzymes are utilized in a variety of food-related processes, but they have several disadvantages, including their susceptibility to acidity, temperature and enzyme-interfering compounds during processing. Enzymes such as lactase or cholesterol reductase can be immobilized and integrated into packaging materials as an alternative to introducing them directly into the food matrix (112). Enzymes can boost the value of food items while also meeting the demands of consumers with enzyme deficiencies (113). Enzyme immobilization at the nanoscale offers superior efficiency over conventional methods due to increased surface area and improved diffusion (114).

O_2 scavengers

Food degradation is caused by O_2 in numerous ways. Direct oxidation promotes rancid flavours and discolouration of food products. Aerobic microbes can degrade food due to the indirect effects of O_2 (115). Oxygen scavengers, often in sachets with agents like ferrous carbonate or iron oxide, help maintain low O_2 levels when integrated into packaging. NPs are being used to develop a new plastic type that prohibits the penetration of O_2 (116). Packaging films created by mixing TiO_2 NPs with various polymers can be used for a variety of O_2-sensitive food goods. Nanocrystalline TiO_2 coatings on glass or acetate films remove ethylene via photocatalysis, creating a low-oxygen environment that delays fruit ripening (117). This method offers cost-effective and smart food packaging for extending shelf life and lowering agricultural product spoiling losses (118).

Intelligent/smart packaging

Intelligent packaging technologies provide real-time insight into the quality of packed food, hence improving communication and marketing functions (14). It incorporates nanotechnology-based sensors inside the food products. They can interact with food contents and external environmental factors; the use of intelligent packaging has the potential to provide useful information for improving product distribution efficiency (119).

Nano sensors

When integrated into packaging systems, nanosensors provide an exact scenario of the products and are used to identify food spoilage (120). It is preferable to use food packaging methods that limit O_2 exposure rather than those that allow unlimited access. This requires packing under vacuum or nitrogen gas, as well as the usage of irreversible O_2 sensors. TiO_2 nanocomposite thin films could be placed on glass to develop an O_2 sensitive food packaging system (75). It was developed and characterized an opto-chemical CO_2 sensor in terms of CO_2 sensitivity and cross-sensitivity (121). According to a study, food packaging may employ optical gas sensors that use pH sensitive dyes to detect CO_2 (122, 123). A quick, effective and economical method of identifying food-borne illnesses caused by various microbes is urgently required. Microbial sensors with nanoparticles feature distinct optical and electrical traits and highly functional surfaces. Quantum dots with attached antibodies are widely explored for detecting bacteria (85).

Nano indicators

Intelligent packaging helps in detecting spoilage of products by changing their colour. Intelligent/smart packaging systems use a wide range of nano-indicators, including humidity, freshness and time-temperature indicators. It is important to monitor humidity levels to ensure package integrity and food quality (85). The usage of a nanocrystalline cellulose sheet is to build a humidity indicator that developed blue-green and became red-orange when the humidity level was high. Commercially, indicators reflecting freshness levels are used to monitor food quality by detecting microbial by-products are used in intelligent packaging (124). These indicators are sensitive to microbial metabolites produced when food spoils, such as volatile sulphides and amines (125). Temperature fluctuations have a major impact on food quality. Therefore, consistent temperature regulation is required during food storage. Time and temperature indicators track changes in the temperatures to which the products are exposed and highlight irreversible changes such as physical characteristics, shape and colour in response to temperature (126).

Nanocomposite

Smart packaging plays a role such as a barrier, providing strength and increasing durability. Nanocomposites consist of two or more distinct phases at the nanoscale, one continuous phase (the polymer component) and the other dispersed phase (the reinforcing ingredient). The addition of nanocomposites to packaging material increases strength and thermal stability (127). Food storage and transportation can benefit from the heat and gas barrier properties of nanocomposites, which extend the storage life of food beyond harvest (128). Starch-based nanocomposite films with flax cellulose nanocrystals have improved tensile strength and water resistance. Polymer-silicate nanocomposites have superior attributes, including high-temperature stability, mechanical strength and improved gas barrier qualities (12, 129).

Nano emulsions

Nanoparticle coatings can be used to supply useful compounds like antimicrobials, flavours, antioxidants and ripening inhibitors. Coatings also prevent decay, delay ripening and provide shine or gloss to coated objects while preventing water loss, chilling and mechanical damage. Flavor may be altered by coatings due to delayed ripening or anaerobic respiration leading to increased ethanol. These coatings are made from natural macromolecules like sugars, proteins and lipids, or their combinations. Coating PVC film with ZnO NPs improves its antibacterial properties (130). Chitosan is a linear polysaccharide composed of glucosamine and N-acetylglucosamine units. It is hypothesised to have a dual effect on host-pathogen interactions, promoting plant defensive responses and antifungal activity (131). Deacetylated chitin, a natural antibacterial component, prevents postharvest deterioration in fruits and vegetables (132, 133). Due to its low mammalian toxicity and eco-friendly nature in controlling plant diseases, using chitosan to prevent pre- and postharvest infections increased the quality of fruits and vegetables (134-136).

Nanoencapsulation

Nano-encapsulation is a technology for packing materials into tiny forms using methods such as nano-composite, nano-emulsification and nano-structuration. The resulting product has a wide range of features, including controlled core release. The system nano encapsulation has several advantages, including ease of handling, enhanced stability, pH-triggered control release, moisture control and increased bioavailability and efficacy. The food industry's major aim is to extend the storage life of its products, which can be achieved with an encapsulating protective covering.

Nanoencapsulation is an advanced technology used to encapsulate bioactive substances, such as nutrients, preservatives and drugs, within nanoparticles. This technology utilizes methods such as nano-composite formation, nano-emulsification and nano-structuration, resulting in highly stable encapsulation systems at the nanoscale. The size of the nanoparticles (typically ranging from 10 to 1000 nm) allows for more efficient delivery and controlled release of the encapsulated compounds compared to traditional encapsulation methods (137). The nanoencapsulation system consists of liposomes. These are spherical vesicles with a lipid bilayer that can encapsulate both hydrophilic and hydrophobic substances. Liposomes are often used for encapsulating vitamins, antioxidants, or flavour compounds in the food and pharmaceutical industries. They offer controlled release and enhanced bioavailability of encapsulated substances (138). Micelles are self-assembled structures made from amphiphilic molecules (both hydrophobic and hydrophilic regions). Micelles are used for encapsulating hydrophobic molecules and are beneficial in improving the solubility and stability of poorly water-soluble substances (139). Polymeric Nanoparticles- These are made from biodegradable polymers and can encapsulate a wide range of compounds, from nutrients to preservatives. Their ability to degrade over time makes them suitable for controlled and sustained release applications (140).

Traditional encapsulation techniques, such as simple physical entrapment or spray-drying, often rely on larger particle sizes and lack the fine control over release mechanisms that nanoencapsulation offers. While traditional methods provide some protection to the encapsulated materials, they do not offer the same level of precision in terms of release control, stability, or bioavailability enhancement (141). Nanoencapsulation, on the other hand, can provide. Better stability Nanoparticles provide a more stable environment for sensitive substances, protecting them from degradation due to heat, light, or oxygen exposure (142). Controlled release- Nanoencapsulation systems allow for controlled release based on specific triggers such as pH, temperature, or moisture, ensuring that nutrients or preservatives are released when needed (143). Increased bioavailability- The small size of nanoparticles enables better absorption of encapsulated substances in the body or in food products, enhancing their effectiveness (144).

Benefits of nanoencapsulation

Nanoencapsulation offers several significant benefits in the food and pharmaceutical industries. It extends shelf life by protecting nutrients and preservatives from oxidation and spoilage, which helps maintain product quality for longer periods (145). Additionally, it enables targeted delivery of active ingredients, ensuring that they reach specific sites within the body or product, thereby increasing their efficacy (146). Nanoencapsulation also enhances bioavailability, as nanoparticles can easily penetrate biological membranes, improving the absorption and effectiveness of encapsulated nutrients or drugs (147). Furthermore, it plays a crucial role in moisture control, preventing spoilage and maintaining product quality by managing the moisture content in food products (148). Overall, nanoencapsulation represents a major advancement in food science and pharmaceuticals, offering a more efficient and controlled method for delivering bioactive substances compared to traditional techniques.

Gold (AU)-based immunosensor NPs

Belong to smart packaging because gold nanoparticles can efficiently detect signals and have good electrical conductivity and stability. Using gold (Au) nanoparticles, an immunological sensor for the quantitative identification of gram-positive bacteria was created (149). It was that the detection limits for *Staphylococcus aureus* and *Lactobacillus* species were 120 CFU/mL and 105 CFU/mL respectively. It is important to note that experiments have shown that this nano Au immune sensor is effective at detecting gram-positive bacteria in the samples of sugarcane.

Detection of food structure

Smart packaging tracks environmental conditions and material integrity to assess and convey product quality. By obtaining structural information at the nanoscale, researchers can better understand the properties of fruits and vegetables and explain how food quality changes as a result of processing and storage (124). One of the most well-established methods for detecting nanoscale materials is atomic force microscopy (AFM), which can produce high-resolution single-molecule imaging with minimal sample damage and without the need for various sample preparation processes, such as fluorescent dying or gold spraying. It also does minimal harm to the sample. A liquid imaging technique capable of capturing images in a physiologically relevant state is a critical research requirement for biological substances. Recent studies analyzed the force spectra of dextran, xanthan gum and pectin. AFM was used to assess pectin depolymerization in Chinese cherries during storage, revealing that pectin breakdown led to cell wall degradation. A nano SiO_2 and chitosan coating was found to enhance firmness and prolong shelf life by preventing pectin chain degradation (150).

Environmental sustainability of nanotechnology in food preservation

Nanotechnology has the potential to significantly extend the shelf life of food and improve preservation methods, but it also raises important environmental concerns. One major issue is the biodegradability of nanoparticles used in food packaging. Many nanoparticles may not easily break down in the environment, leading to pollution if they accumulate in soil or water, potentially harming plants and animals. Researchers are addressing this by developing biodegradable nanoparticles from natural materials such as chitosan or starch, which break down more readily in nature (151). Another concern is the toxicity of certain nanoparticles, especially those made from metals like silver, which are designed to kill bacteria and preserve food. However, if these particles leak into food or the environment, they could pose risks to human health or wildlife, especially by accumulating in the food chain or affecting aquatic organisms. Thus, it is crucial to ensure that nanoparticles used in food packaging are safe and do not cause harm (152). Furthermore, the lack of clear regulations on the use of nanoparticles in food packaging poses a challenge currently. While there are some regulations in the U.S. and European countries, they are still evolving and stronger standards are needed to ensure the safety of both humans and the environment (153). The environmental impact of nanoparticles also extends beyond their biodegradability and toxicity, requiring a comprehensive understanding of their entire lifecycle from production to disposal. This includes factors such as energy consumption, carbon footprint and recycling potential, all of which can contribute to pollution if not properly managed (154). To mitigate these risks, scientists are exploring more sustainable nanomaterials, such as biodegradable and non-toxic nanoparticles made from plant-based polymers or proteins, which degrade more quickly and are safer for the environment (148). By focusing on the development of these materials and establishing clear safety regulations, we can ensure that the benefits of nanotechnology in food preservation are realized without compromising the health of the environment.

Nanotechnology regulations and safety standards

Nanotechnology regulations in food safety vary significantly. Different authorities adapt various approaches to oversee the safety evaluation and labelling requirements all over the world. The European Union mandates the labelling of food products containing nanomaterials; similarly, the FDA evaluates them on a case-by-case basis without a labelling requirement (155). The National Centre for Nanoscience and Technology (NCNST), at China, is responsible for setting national nanotechnology standards for that country. A special protocol for characterizing nanomaterials and establishing safety standards for manufacturing was developed by NCNST in 2003. In 2005, the commission about nanotechnology established by the NCNST, begin standardizing and regulating nanomaterial engineering, manufacturing and safety evaluation. Established under the Food Standards Australia New Zealand (FSANZ) Act, FSANZ operates as an autonomous agency of the Australian government responsible for creating food regulatory measures. FSANZ employs various methods to assess and manage risks associated with food and packaging nanomaterials. FSANZ established a Scientific Nanotechnology Advisory Group (SNAG), including expertise in nanotechnology, nanotoxicology and nano safety, to ensure safe use of food nanomaterials. In India, the launch of the Nano Mission raises health and environmental concerns about nanotechnology. Regulatory activities for new nanomaterials in the food business aim to address public concerns about nanotechnology regulation status through scientific knowledge and legal direction (156). Moreover, copper oxide, iron oxide and zinc oxide have been classified as GRAS (Generally Recognized as Safe) substances by the European Food Safety Authority (EFSA) for application in animal and plant products. This categorization indicates that these metal oxide nanoparticles are deemed safe under certain conditions and are authorized for use in applications like feed additives, micronutrient delivery and antibacterial agents in food packaging. The GRAS designation facilitates the incorporation into agricultural and food systems, particularly in the preservation of green vegetables, due to their efficacy and low toxicity when used appropriately (157). EFSA has set a permissible threshold for silver (Ag) migration from packaging to water is 0.05 mg/L and 0.05 mg/kg to food products (158).

Microbiome disruption by packaging nanoparticles

Nanoparticles utilized in food packaging, such as silver or zinc oxide, may transfer into food and may affect human health, particularly the gut microbiota (159). Depending on NP size, dose and exposure length, studies show decreasing levels of helpful bacteria like *Lactobacillus* and *Faecalibacterium prausnitzii* and increasing levels of potentially harmful taxa like Bacteroides and *Prevotella*. Zinc oxide nanoparticles (ZnO NPs) were observed to diminish microbial diversity and disturb the equilibrium between Firmicutes and Bacteroidetes in avian and pig models, resulting in microbiota alterations linked to inflammation.

Titanium dioxide (TiO_2) and silicon dioxide (SiO_2) nanoparticles, commonly utilized in food packaging and additives, have exhibited varying yet occasionally substantial effects on microbial diversity and intestinal barrier integrity (160).

Conclusion

NPs are extremely reactive and mobile because of their nano size. These characteristics may increase the risk of toxicity. Therefore, it is important to address the harmful impacts of these particles while dealing with them. They have the potential to alter the body's natural microbiome. Their bulk, size, chemical makeup, and features are all essential considerations when determining their effect on the target. Nanotechnology is currently the most potential solution in the food preservation and packaging units. It has numerous benefits for prolonging shelf life, enhancing the physiochemical properties of food packaging materials, detecting microbial action on food, and reducing contamination of food products compared to conventional approaches. Nanocomposites impregnated with silver or zinc oxide nanoparticles can reduce bacterial proliferation on perishable goods such as spinach, lettuce, and broccoli, hence prolonging their freshness during storage and transportation. Ag NPs, which are well-recognized for their extensive antibacterial efficacy, would extend the shelf life of strawberries and mushrooms by inhibiting microbial proliferation. Though the use of nano-based technology in the food business, such as nanocomposites and NPs, has numerous benefits, it also has a significant disadvantage in terms of toxicity, which may be integrated into the food and create adverse effects on humans. Many nations have developed particular legislation and guidelines for assessing the danger of utilizing nanomaterials in food packaging, such as REACH in the European Union, which protects the safety of food packaging materials. In the near future, numerous experiments, research, knowledge of nanomaterial toxicity, and risk assessment and management should be carried out. Eventually, the food packaging sector will replace its current limitations with the use of nanotechnology, which has enormous potential. Because of their enhanced effectiveness and targeted delivery, iron and zinc oxide NPs would have been mostly employed in the agricultural sector. Further, FDA engineered nanomaterials, depending on its nature (organic, inorganic, or mixed), would be designed to utilize biotechnological or synthetic methods to address specific agricultural or postharvest requirements. These optimized nanostructures demonstrated significant efficacy in prolonging the shelf life and preserving the nutritional integrity of leafy green crops, including spinach, kale, and cabbage, by mitigating microbial deterioration and maintaining chlorophyll levels throughout the storage.

Acknowledgements

Authors contributions and support in the preparation of manuscript shall be acknowledged.

Authors' contributions

All authors contributed to the content of the manuscript and approved for publication.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A. Global food losses and food waste. FAO Rome; 2011.
2. FAO. Food Losses and Waste in Europe and Central Asia. Rome,Italy; 2014.
3. Trostle R. Global agricultural supply and demand: factors contributing to the recent increase in food commodity prices. 2008
4. Kitinoja L, Gorny JR. Postharvest technology for small-scale produce marketers: economic opportunities, quality and food safety. 1999
5. Kader AA, Rolle RS. The role of post-harvest management in assuring the quality and safety of horticultural produce. Vol. 152. Food and Agriculture Org.; 2004.
6. Bai L, Liu M, Sun Y. Overview of food preservation and traceability technology in the smart cold chain system. Foods. 2023;12 (15):2881. https://doi.org/10.3390/foods12152881
7. Sridhar A, Ponnuchamy M, Kumar PS, Kapoor A. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: a review. Environ Chem Lett. 2021;19:1715-35. https://doi.org/10.1007/s10311-020-01126-2
8. Sommer NE, Fortlage RJ, Edwards DC. Postharvest diseases of selected commodities. 1992
9. Peelman N, Ragaert P, De Meulenaer B, Adons D, Peeters R, Cardon L, et al. Application of bioplastics for food packaging. Trends Food Sci Technol. 2013;32(2):128-41. https://doi.org/10.1016/j.tifs.2013.06.003
10. Alhendi A, Choudhary R. Current practices in bread packaging and possibility of improving bread shelf life by nanotechnology. Int J Food Sci Nutr. 2013;3(4):55-60.
11. Sharma C, Dhiman R, Rokana N, Panwar H. Nanotechnology: an untapped resource for food packaging. Front Microbiol. 2017;8:1735.https://doi.org/10.3389/fmicb.2017.01735
12. Wesley SJ, Raja P, Raj AA, Tiroutchelvamae D. Review on-nanotechnology applications in food packaging and safety. Int J Eng Res. 2014;3(11):645-51.https://doi.org/10.17950/ijer/v3s11/1105
13. Saharan BS, Sharma D, Sahu R, Sahin O, Warren A. Towards algal biofuel production: a concept of green bio energy development. Innov Rom Food Biotechnol. 2013;12:1.
14. Manjunatha SB, Biradar DP, Aladakatti YR. Nanotechnology and its applications in agriculture: A review. J farm Sci. 2016;29(1):1-13.
15. Thiruvengadam M, Rajakumar G, Chung IM. Nanotechnology: current uses and future applications in the food industry. 3 Biotech. 2018;8:1-13. https://doi.org/10.1007/s13205-018-1104-7
16. Lim LT. Active and intelligent packaging materials; 2019. https://doi.org/10.1016/B978-0-444-64046-8.00248-2
17. Pal M. Nanotechnology: a new approach in food packaging. J Food Microbiol Saf Hyg. 2017;2(02):8-9. https://doi.org/10.4172/2476-2059.1000121
18. Sridhar A, Ponnuchamy M, Kumar PS, Kapoor A. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: a review. Environ Chem Lett. 2021;19:1715-35. https://doi.org/10.1007/s10311-020-01126-2
19. Pardo G, Zufía J. Life cycle assessment of food-preservation technologies. J Clean Prod. 2012;28:198-207. https://doi.org/10.1016/j.jclepro.2011.10.016
20. Bai L, Liu M, Sun Y. Overview of food preservation and traceability

technology in the smart cold chain system. Foods. 2023;12 (15):2881.https://doi.org/10.3390/foods12152881

21. Rossini K, Noreña CPZ, Brandelli A. Changes in the color of white chocolate during storage: potential roles of lipid oxidation and non-enzymatic browning reactions. J Food Sci Technol. 2011;48:305-11.https://doi.org/10.1007/s13197-010-0207-x
22. Emadpour M, Ghareyazie B, Kalaj YR, Entesari M, Bouzari N. Effect of the potassium permanganate coated zeolite nanoparticles on the quality characteristic and shelf life of peach and nectarine. 2015
23. Linde GA, Laverde Jr A, Colauto NB. Changes to taste perception in the food industry: use of cyclodextrins. In: Handbook of Behavior, Food and Nutrition. Springer; 2011. p. 99-118 https://doi.org/10.1007/978-0-387-92271-3_8
24. Verma DK, Thakur M, Srivastav PP, Karizaki VM, Suleria HAR. Effects of drying technology on physiochemical and nutritional quality of fruits and vegetables. In: Emerging Thermal and Nonthermal Technologies in Food Processing. Apple Academic Press; 2020. p. 69 -116 https://doi.org/10.1201/9780429297335-3
25. Cyras VP, Manfredi LB, Ton-That MT, Vázquez A. Physical and mechanical properties of thermoplastic starch/montmorillonite nanocomposite films. Carbohydr Polym. 2008;73(1):55-63. https://doi.org/10.1016/j.carbpol.2007.11.014
26. Elik A, Yanik DK, Istanbullu Y, Guzelsoy NA, Yavuz A, Gogus F. Strategies to reduce post-harvest losses for fruits and vegetables. Strategies. 2019;5(3):29-39.
27. Guan W, Zhang J, Yan R, Shao S, Zhou T, Lei J, et al. Effects of UV-C treatment and cold storage on ergosterol and vitamin D2 contents in different parts of white and brown mushroom (*Agaricus bisporus*). Food Chem. 2016;210:129-34. https://doi.org/10.1016/j.foodchem.2016.04.023
28. Meireles A, Giaouris E, Simões M. Alternative disinfection methods to chlorine for use in the fresh-cut industry. Food Research International. 2016;82:71-85. https://doi.org/10.1016/j.foodres.2016.01.021
29. Barbosa AAT, de Araújo HGS, Matos PN, Carnelossi MAG, de Castro AA. Effects of nisin-incorporated films on the microbiological and physicochemical quality of minimally processed mangoes. Int J Food Microbiol. 2013;164(2-3):135-40. https://doi.org/10.1016/j.ijfoodmicro.2013.04.004
30. Pradhan N, Singh S, Ojha N, Shrivastava A, Barla A, Rai V, et al. Facets of nanotechnology as seen in food processing, packaging and preservation industry. Biomed Res Int. 2015;2015 (1):365672.https://doi.org/10.1155/2015/365672
31. Tayel AA, Sorour NM, El-Baz AF, Wael F. Nanometals appraisal in food preservation and food-related activities. In: Food preservation. Elsevier; 2017. p. 487-526. https://doi.org/10.1016/B978-0-12-804303-5.00014-6
32. Bouwmeester H, Brandhoff P, Marvin HJP, Weigel S, Peters RJB. State of the safety assessment and current use of nanomaterials in food and food production. Trends Food Sci Technol. 2014;40(2):200-10.https://doi.org/10.1016/j.tifs.2014.08.009
33. Iavicoli I, Leso V, Beezhold DH, Shvedova AA. Nanotechnology in agriculture: Opportunities, toxicological implications and occupational risks. Toxicol Appl Pharmacol. 2017;329:96-111. https://doi.org/10.1016/j.taap.2017.05.025
34. Peters R, Bouwmeester H, Gottardo S, Amenta V, Arena M, Brandhoff P, et al. Nanomaterials for application in agriculture. Feed and Food.
35. Kondle R, Sharma K, Singh G, Kotiyal A. Using nanotechnology for enhancing the shelf life of fruits. In: Food Processing and Packaging Technologies-Recent Advances. IntechOpen; 2022. https://doi.org/10.5772/intechopen.108724
36. de Oliveira Filho JG, Bertolo MRV, da Costa Brito S, Malafatti JOD, Bertazzo GB, Colacique MN, et al. Recent advances in the application of nanotechnology to reduce fruit and vegetable losses during post-harvest. Brazilian Journal of Physics. 2022;52 (4):126.https://doi.org/10.1007/s13538-022-01132-5
37. Perez-Vazquez A, Barciela P, Carpena M, Prieto MA. Edible coatings as a natural packaging system to improve fruit and vegetable shelf life and quality. Foods. 2023;12:3570. https://doi.org/10.3390/foods12193570
38. Ashfaq A, Khursheed N, Fatima S, Anjum Z, Younis K. Application of nanotechnology in food packaging: Pros and cons. J Agric Food Res. 2022;7:100270. https://doi.org/10.1016/j.jafr.2022.100270
39. Gao L. Sol-gel synthesis of silica nanoparticles for food packaging applications. J Food Sci. 2017;82(5):1206-14.
40. Brigger I. Sol-gel method for synthesis of bioactive nanoparticle systems in food packaging. Food Res Int. 2018;113:1017-26
41. Bikiaris DN. Electrospun nanofibers for food packaging applications: A review. Food Res Int. 2016;85:270-85.
42. Saeed M. Electrospinning for food preservation and packaging: Current trends and future directions. Food Packag Shelf Life. 2018;16:156-65.
43. Dahmouche K. Nanoprecipitation technique for preparing nanoparticles used in food packaging. Int J Food Sci Technol. 2019;54(5):1572-81.
44. Arora A. Nanoprecipitation as a technique for food preservation: Enhancing shelf life and bioactive compound stability. Food Biophys. 2019;14(3):300-09.
45. Ranjan S. Emulsion polymerization for nanoparticle synthesis in food preservation. Food Biophys. 2019;14(3):246-59.
46. Morsi RE. Emulsion polymerization for the synthesis of nanoparticles in food packaging materials. J Food Sci. 2020;85 (4):1078-87.
47. Xu X, Ray R, Gu Y, Ploehn HJ, Gearheart L, Raker K, et al. Electrophoretic analysis and purification of fluorescent single-walled carbon nanotube fragments. J Am Chem Soc. 2004;126 (40):12736-37. https://doi.org/10.1021/ja040082h
48. Liu J, Chen Y, Wang W, Feng J, Liang M, Ma S, et al. "Switch-on" fluorescent sensing of ascorbic acid in food samples based on carbon quantum dots-MnO2 probe. J Agric Food Chem. 2015;64 (1):371-80. https://doi.org/10.1021/acs.jafc.5b05726
49. Dai H, Shi Y, Wang Y, Sun Y, Hu J, Ni P, et al. A carbon dot based biosensor for melamine detection by fluorescence resonance energy transfer. Sens Actuators B Chem. 2014;202:201-08. https://doi.org/10.1016/j.snb.2014.05.058
50. Ahmed GHG, Laıno RB, Calz JA, Garcıa MED. Fluorescent carbon nanodots for sensitive and selective detection of tannic acid in wines. Talanta. 2015;132:252-57. https://doi.org/10.1016/j.talanta.2014.09.028
51. Wang R, Xu Y, Zhang T, Jiang Y. Rapid and sensitive detection of Salmonella typhimurium using aptamer-conjugated carbon dots as fluorescence probe. Anal Methods. 2015;7(5):1701-06. https://doi.org/10.1039/C4AY02880E
52. Wang B, Chen Y, Wu Y, Weng B, Liu Y, Lu Z, et al. Aptamer induced assembly of fluorescent nitrogen-doped carbon dots on gold nanoparticles for sensitive detection of AFB1. Biosens Bioelectron. 2016;78:23-30. https://doi.org/10.1016/j.bios.2015.11.015
53. Díaz I, Márquez-Alvarez C, Mohino F, Pérez-Pariente J, Sastre E. Combined alkyl and sulfonic acid functionalization of MCM-41-type silica - Part 1. Synthesis and characterization. J Catal. 2000;193:283-94.https://doi.org/10.1006/jcat.2000.2898
54. Díaz I, Márquez-Alvarez C, Mohino F, Pérez-Pariente J, Sastre E. Combined alkyl and sulfonic acid functionalization of MCM-41-type silica - Part 2. Esterification of glycerol with fatty acids. J Catal. 2000;193:295-302. https://doi.org/10.1006/jcat.2000.2899
55. Díaz I, Mohino F, Blasco T, Sastre E, Pérez-Pariente J. Influence of the alkyl chain length of HSO3-RMCM-41 on the esterification of glycerol with fatty acids. Microporous Mesoporous Mater.

2005;80:33-42.https://doi.org/10.1016/j.micromeso.2004.11.011

56. Márquez-Alvarez C, Sastre E, Pérez-Pariente J. Solid catalysts for the synthesis of fatty esters of glycerol, polyglycerols and sorbitol from renewable resources. Top Catal. 2004;27:105-17. https://doi.org/10.1023/B:TOCA.0000013545.81809.bd

57. Thomas JM, Raja R. The advantages and future potential of single-site heterogeneous catalysts. Top Catal. 2006;40:3-17. https://doi.org/10.1007/s11244-006-0105-7

58. Yadav GD, Lande SV. Selective Claisen rearrangement of allyl-2,4-di-tert-butylphenyl ether to 6-allyl-2,4-di-tert-butylphenol catalysed by heteropolyacid supported on hexagonal mesoporous silica. J Mol Catal A Chem. 2006;243:31-39. https://doi.org/10.1016/j.molcata.2005.08.003

59. Wang H, Wick RL, Xing B. Toxicity of nanoparticulate and bulk ZnO, Al_2O_3 and TiO_2 to the nematode Caenorhabditis elegans. Environ Pollut. 2009;157(4):1171-77. https://doi.org/10.1016/j.envpol.2008.11.004

60. Zhang YW, Tiwari MK, Jeya M, Lee JK. Covalent immobilization of recombinant *Rhizobium etli* CFN42 xylitol dehydrogenase onto modified silica nanoparticles. Appl Microbiol Biotechnol. 2011;90:499-507.https://doi.org/10.1007/s00253-011-3094-9

61. Zhang J, Yu MH, Yuan P, Lu GQ, Yu CZ. Controlled release of volatile (-)-menthol in nanoporous silica materials. J Incl Phenom Macrocycl Chem. 2011;71:593-602. https://doi.org/10.1007/s10847-011-9996-4

62. Almeida MG, Serra A, Silveira CM, Moura JJG. Nitrite biosensing via selective enzymes - A long but promising route. Sensors (Basel). 2010;10:11530-55. https://doi.org/10.3390/s101211530

63. Hashim N, Abdullah S, Yusoh K. Graphene nanomaterials in the food industries: quality control in promising food safety to consumers. Graphene 2D Mater. 2022;7(1):1-29. https://doi.org/10.1007/s41127-021-00045-5

64. Huang M, Wan X, Zhang M, Zhu Q. Detection of insect-damaged vegetable soybeans using hyperspectral transmittance image. J Food Eng. 2013;116(1):45-49. https://doi.org/10.1016/j.jfoodeng.2012.11.014

65. Wang R, Zhang M, Mujumdar AS, Sun JC. Microwave freeze-drying characteristics and sensory quality of instant vegetable soup. Drying Technology. 2009;27(9):962-68. https://doi.org/10.1080/07373930902902040

66. Xu Y, Zhang M, Tu D, Sun J, Zhou L, Mujumdar AS. A two-stage convective air and vacuum freeze-drying technique for bamboo shoots. Int J Food Sci Technol. 2005;40(6):589-95. https://doi.org/10.1111/j.1365-2621.2005.00956.x

67. Yan W, Zhang M, Huang L, Tang J, Mujumdar AS, Sun J. Studies on different combined microwave drying of carrot pieces. Int J Food Sci Technol. 2010;45(10):2141-48. https://doi.org/10.1111/j.1365-2621.2010.02380.x

68. Moghadam AD, Omrani E, Menezes PL, Rohatgi PK. Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene-a review. Compos B Eng. 2015;77:402-20. https://doi.org/10.1016/j.compositesb.2015.03.014

69. Prashantha K, Soulestin J, Lacrampe MF, Krawczak P, Dupin G, Claes M. Masterbatch-based multi-walled carbon nanotube filled polypropylene nanocomposites: Assessment of rheological and mechanical properties. Compos Sci Technol. 2009;69(11-12):1756-63. https://doi.org/10.1016/j.compscitech.2008.10.005

70. Liu SF, Petty AR, Sazama GT, Swager TM. Single-walled carbon nanotube/metalloporphyrin composites for the chemiresistive detection of amines and meat spoilage. Angewandte Chemie International Edition. 2015;54(22):6554-57. https://doi.org/10.1002/anie.201501434

71. Abdelhalim A, Abdellah A, Scarpa G, Lugli P. Fabrication of carbon nanotube thin films on flexible substrates by spray deposition and transfer printing. Carbon N Y. 2013;61:72-79. https://doi.org/10.1016/j.carbon.2013.04.069

72. Asgari P, Moradi O, Tajeddin B. The effect of nanocomposite packaging carbon nanotube base on organoleptic and fungal growth of Mazafati brand dates. Int Nano Lett. 2014;4:1-5. https://doi.org/10.1007/s40089-014-0098-3

73. Alexandre B, Langevin D, Médéric P, Aubry T, Couderc H, Nguyen QT, et al. Water barrier properties of polyamide 12/montmorillonite nanocomposite membranes: structure and volume fraction effects. J Memb Sci. 2009;328(1-2):186-204. https://doi.org/10.1016/j.memsci.2008.12.004

74. Luduena LN, Alvarez VA, Vazquez A. Processing and microstructure of PCL/clay nanocomposites. Materials Science and Engineering: A. 2007;460:121-29. https://doi.org/10.1016/j.msea.2007.01.104

75. Weiss J, Takhistov P, McClements DJ. Functional materials in food nanotechnology. J Food Sci. 2006;71(9):R107-16. https://doi.org/10.1111/j.1750-3841.2006.00195.x

76. Montazer M, Harifi T. New approaches and future aspects of antibacterial food packaging: from nanoparticles coating to nanofibers and nanocomposites, with foresight to address the regulatory uncertainty. In: Food packaging. Elsevier; 2017. p. 533-65. https://doi.org/10.1016/B978-0-12-804302-8.00016-9

77. Gutiérrez TJ, Ponce AG, Alvarez VA. Nano-clays from natural and modified montmorillonite with and without added blueberry extract for active and intelligent food nanopackaging materials. Mater Chem Phys. 2017;194:283-92. https://doi.org/10.1016/j.matchemphys.2017.03.052

78. Li X, Li W, Jiang Y, Ding Y, Yun J, Tang Y, et al. Effect of nano-ZnO-coated active packaging on quality of fresh-cut 'Fuji'apple. Int J Food Sci Technol. 2011;46(9):1947-55. https://doi.org/10.1111/j.1365-2621.2011.02706.x

79. Luo Z, Wang Y, Jiang L, Xu X. Effect of nano-CaCO3-LDPEpackaging on quality and browning of fresh-cut yam. LWT-Food Science and Technology. 2015;60(2):1155-61. https://doi.org/10.1016/j.lwt.2014.09.021

80. Sogvar OB, Saba MK, Emamifar A, Hallaj R. Influence of nano-ZnO on microbial growth, bioactive content and postharvest quality of strawberries during storage. Innovative Food Science Emerging Technologies. 2016;35:168-76. https://doi.org/10.1016/j.ifset.2016.05.005

81. Shi S, Wang W, Liu L, Wu S, Wei Y, Li W. Effect of chitosan/nano-silica coating on the physicochemical characteristics of longan fruit under ambient temperature. J Food Eng. 2013;118(1):125-31. https://doi.org/10.1016/j.jfoodeng.2013.03.029

82. Mohammadi A, Hashemi M, Hosseini SM. 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. 2016;33:580-88.https://doi.org/10.1016/j.ifset.2015.10.015

83. Esyanti RR, Zaskia H, Amalia A, Nugrahapraja dan H. Chitosan nanoparticle-based coating as post-harvest technology in banana. In: Journal of Physics: Conference Series. IOP Publishing; 2019. p. 012109. https://doi.org/10.1088/1742-6596/1204/1/012109

84. Pandey CM, Tiwari I, Singh VN, Sood KN, Sumana G, Malhotra BD. Highly sensitive electrochemical immunosensor based on graphene -wrapped copper oxide-cysteine hierarchical structure detection of pathogenic bacteria. Sens Actuators B Chem. 2017;238:1060-69.https://doi.org/10.1016/j.snb.2016.07.121

85. Sharma A, Thakur M, Bhattacharya M, Mandal T, Goswami S. Commercial application of cellulose nano-composites-A review. Biotechnology Reports. 2019;21:e00316. https://doi.org/10.1016/j.btre.2019.e00316

86. Ferrer A, Pal L, Hubbe M. Nanocellulose in packaging: Advances in barrier layer technologies. Ind Crops Prod. 2017;95:574-82. https://doi.org/10.1016/j.indcrop.2016.11.012

87. Naicker PK, Cummings PT, Zhang H, Banfield JF. Characterization of

titanium dioxide nanoparticles using molecular dynamics simulations. J Phys Chem B. 2005;109(32):15243-49. https://doi.org/10.1021/jp050963q

88. Martelli MR, Barros TT, de Moura MR, Mattoso LHC, Assis OBG. Effect of chitosan nanoparticles and pectin content on mechanical properties and water vapor permeability of banana puree films. J Food Sci. 2013;78(1):N98-104. https://doi.org/10.1111/j.1750-3841.2012.03006.x

89. Arora A, Padua GW. Nanocomposites in food packaging. J Food Sci. 2010;75(1):R43-49. https://doi.org/10.1111/j.1750-3841.2009.01456.x

90. Kumar N, Kumbhat S. Essentials in nanoscience and nanotechnology. John Wiley and Sons; 2016. https://doi.org/10.1002/9781119096122

91. Morán D, Gutiérrez G, Blanco-López MC, Marefati A, Rayner M, Matos M. Synthesis of starch nanoparticles and their applications for bioactive compound encapsulation. Applied Sci. 2021;11(10):4547. https://doi.org/10.3390/app11104547

92. Campelo PH, Sant'Ana AS, Clerici MTPS. Starch nanoparticles: production methods, structure and properties for food applications. Curr Opin Food Sci. 2020;33:136-40. https://doi.org/10.1016/j.cofs.2020.04.007

93. Zubair M, Ullah A. Recent advances in protein derived bio nanocomposites for food packaging applications. Crit Rev Food Sci Nutr. 2020;60(3):406-34. https://doi.org/10.1080/10408398.2018.1534800

94. Li X, Ji N, Qiu C, Xia M, Xiong L, Sun Q. The effect of peanut protein nanoparticles on characteristics of protein-and starch-based nanocomposite films: A comparative study. Ind Crops Prod. 2015;77:565-74. https://doi.org/10.1016/j.indcrop.2015.09.026

95. Karthi JS, Johar V, Singh V, Rani S. Edible coatings: Innovation to improve the shelf life of guava. Int J Plant Soil Sci. 2023;35:125-35. https://doi.org/10.9734/ijpss/2023/v35i143028

96. Sami R, Elhakem A, Almushhin A, Alharbi M, Almatrafi M, Benajiba N, et al. Enhancement in physicochemical parameters and microbial populations of mushrooms as influenced by nano-coating treatments. Scientific Reports. 2021;11(1):7915. https://doi.org/10.1038/s41598-021-87053-w

97. Wu R, Ma Y, Pan J, Lee SH, Liu J, Zhu H, et al. Efficient capture, rapid killing and ultrasensitive detection of bacteria by a nano-decorated multi-functional electrode sensor. Biosens Bioelectron. 2018;101:52-59. https://doi.org/10.1016/j.bios.2017.10.003

98. Salleh A, Naomi R, Utami ND, Mohammad AW, Mahmoudi E, Mustafa N, et al. The potential of silver nanoparticles for antiviral and antibacterial applications: A mechanism of action. Nanomaterials (Basel). 2020;10(8):1566. https://doi.org/10.3390/nano10081566

99. Rajeshkumar S, Malarkodi C. *In vitro* antibacterial activity and mechanism of silver nanoparticles against foodborne pathogens. Bioinorg Chem Appl. 2014;2014:581890. https://doi.org/10.1155/2014/581890

100. Carbone M, Donia DT, Sabbatella G, Antiochia R. Silver nanoparticles in polymeric matrices for fresh food packaging. J King Saud Uni-Sci. 2016;28(4):273-79. https://doi.org/10.1016/j.jksus.2016.05.004

101. Kraśniewska K, Galus S, Gniewosz M. Biopolymers-based materials containing silver nanoparticles as active packaging for food applications-a review. Int J Mol Sci. 2020;21(3):698. https://doi.org/10.3390/ijms21030698

102. La DD, Nguyen-Tri P, Le KH, Nguyen PT, Nguyen MDB, Vo AT, et al. Effects of antibacterial ZnO nanoparticles on the performance of a chitosan/gum arabic edible coating for post-harvest banana preservation. Prog Org Coat. 2021;151:106057. https://doi.org/10.1016/j.porgcoat.2020.106057

103. Meindrawan B, Suyatma NE, Wardana AA, Pamela VY. Nanocomposite coating based on carrageenan and ZnO nanoparticles to maintain the storage quality of mango. Food Packag Shelf Life. 2018;18:140-46. https://doi.org/10.1016/j.fpsl.2018.10.006

104. Kasemets K, Ivask A, Dubourguier HC, Kahru A. Toxicity of nanoparticles of ZnO, CuO and TiO_2 to yeast Saccharomyces cerevisiae. Toxicol *In Vitro*. 2009;23(6):1116-22. https://doi.org/10.1016/j.tiv.2009.05.015

105. Zhang L, Ding Y, Povey M, York D. ZnO nanofluids - a potential antibacterial agent. Prog Nat Sci. 2008;18(8):939-44. https://doi.org/10.1016/j.pnsc.2008.01.026

106. Jalal R, Goharshadi EK, Abareshi M, Moosavi M, Yousefi A, Nancarrow P. ZnO nanofluids: green synthesis, characterization and antibacterial activity. Mater Chem Phys. 2010;121(1-2):198-201. https://doi.org/10.1016/j.matchemphys.2010.01.020

107. Thounaojam TC, Meetei TT, Devi YB, Panda SK, Upadhyaya H. Zinc oxide nanoparticles (ZnO-NPs): A promising nanoparticle in renovating plant science. Acta Physiol Plant. 2021;43:1-21. https://doi.org/10.1007/s11738-021-03307-0

108. Dimkpa CO, Zeng J, McLean JE, Britt DW, Zhan J anderson AJ. Production of indole-3-acetic acid via the indole-3-acetamide pathway in the plant-beneficial bacterium *Pseudomonas chlororaphis* O6 is inhibited by ZnO nanoparticles but enhanced by CuO nanoparticles. Appl Environ Microbiol. 2012;78(5):1404-10. https://doi.org/10.1128/AEM.07424-11

109. Sharanya DB, Shetty D, Lakshmi GMS, Packiyam JE, Bhat RP. Synthesis of chitosan silver nanoparticles from chitin of crustacean shells and its applications. Int J Curr Res Chem Pharm Sci. 2016;3:1-5.

110. Helal M, Sami R, Khojah E, Elhakem A, Benajiba N, Al-Mushhin AA, Fouda N. Evaluating the coating process of titanium dioxide nanoparticles and sodium tripolyphosphate on cucumbers under chilling condition to extend the shelf-life. Scientific Reports. 2021;11(1):20312. https://doi.org/10.1038/s41598-021-99023-3

111. Oymaci P, Altinkaya SA. Improvement of barrier and mechanical properties of whey protein isolate based food packaging films by incorporation of zein nanoparticles as a novel bionanocomposite. Food hydrocoll. 2016;54:1-9. https://doi.org/10.1016/j.foodhyd.2015.08.030

112. Kim I, Viswanathan K, Kasi G, Thanakkasaranee S, Sadeghi K, Seo J. ZnO nanostructures in active antibacterial food packaging: preparation methods, antimicrobial mechanisms, safety issues, future prospects and challenges. Food Reviews International. 2022;38(4):537-65. https://doi.org/10.1080/87559129.2020.1737709

113. Mohr LC, Capelezzo AP, Baretta C, Martins M, Fiori MA, Mello JMM. Titanium dioxide nanoparticles applied as ultraviolet radiation blocker in the polylactic acid bidegradable polymer. Polym Test. 2019;77:105867. https://doi.org/10.1016/j.polymertesting.2019.04.014

114. Sungur Ş, Kaya P, Koroglu M. Determination of titanium dioxide nanoparticles used in various foods. Food Additives Contaminants: Part B. 2020;13(4):260-67. https://doi.org/10.1080/19393210.2020.1769193

115. Ranjan S, Dasgupta N, Chakraborty AR, Melvin Samuel S, Ramalingam C, Shanker R, et al. Nanoscience and nanotechnologies in food industries: opportunities and research trends. J Nano Res. 2014;16:1-23. https://doi.org/10.1007/s11051-014-2464-5

116. Rhim JW, Park HM, Ha CS. Bio-nanocomposites for food packaging applications. Prog Polym Sci. 2013;38(10-11):1629-52. https://doi.org/10.1016/j.progpolymsci.2013.05.008

117. Brandelli A, Brum LFW, dos Santos JHZ. Nanostructured bioactive compounds for ecological food packaging. Environ Chem Lett. 2017;15:193-204. https://doi.org/10.1007/s10311-017-0621-7

118. Joshi H, Choudhary P, Mundra SL. Future prospects of nanotechnology in agriculture. Int J Chem Stud. 2019;7(2):957-63.

119. Mousavi SR, Rezaei M. Nanotechnology in agriculture and food production. J Appl Environ Biol Sci. 2011;1(10):414-19.

120. Xiao-e L, Green ANM, Haque SA, Mills A, Durrant JR. Light-driven oxygen scavenging by titania/polymer nanocomposite films. J

Photochem Photobiol A Chem. 2004;162(2-3):253-59. https://doi.org/10.1016/j.nainr.2003.08.010

121. Rashidi L, Khosravi-Darani K. The applications of nanotechnology in food industry. Crit Rev Food Sci Nutr. 2011;51(8):723-30.https://doi.org/10.1080/10408391003785417

122. Lee SJ, Rahman ATMM. Intelligent packaging for food products. In: Innovations in food packaging. Elsevier; 2014. p. 171-209. https://doi.org/10.1016/B978-0-12-394601-0.00008-4

123. Liao F, Chen C, Subramanian V. Organic TFTs as gas sensors for electronic nose applications. Sens Actuators B Chem. 2005;107(2):849-55. https://doi.org/10.1016/j.snb.2004.12.026

124. Borchert NB, Kerry JP, Papkovsky DB. A CO_2 sensor based on Pt-porphyrin dye and FRET scheme for food packaging applications. Sens Actuators B Chem. 2013;176:157-65. https://doi.org/10.1016/j.snb.2012.09.043

125. Puligundla P, Jung J, Ko S. Carbon dioxide sensors for intelligent food packaging applications. Food Control. 2012;25(1):328-33.https://doi.org/10.1016/j.foodcont.2011.10.043

126. Valizadeh A, Mikaeili H, Samiei M, Farkhani SM, Zarghami N, Kouhi M, et al. Quantum dots: synthesis, bioapplications and toxicity. Nanoscale Res Lett. 2012;7:1-14. https://doi.org/10.1186/1556-276X-7-480

127. Fuertes G, Soto I, Carrasco R, Vargas M, Sabattin J, Lagos C. Intelligent packaging systems: sensors and nanosensors to monitor food quality and safety. J Sens. 2016;2016(1):4046061. https://doi.org/10.1155/2016/4046061

128. Meng JJ, Qian J, Jung SW, Lee SJ. Practicability of TTI application to yogurt quality prediction in plausible scenarios of a distribution system with temperature variations. Food Sci Biotechnol. 2018;27:1333-42. https://doi.org/10.1007/s10068-018-0371-8

129. Lagaron JM, Cabedo L, Cava D, Feijoo JL, Gavara R, Gimenez E. Improving packaged food quality and safety. Part 2: Nanocomposites. Food Addit Contam. 2005;22(10):994-98. https://doi.org/10.1080/02652030500239656

130. Sozer N, Kokini JL. Nanotechnology and its applications in the food sector. Trends Biotechnol. 2009;27(2):82-89. https://doi.org/10.1016/j.tibtech.2008.10.010

131. Predicala B. Nanotechnology: potential for agriculture. Prairie Swine Centre Inc, University of Saskatchewan, Saskatoon, SK. 2009:123-34.

132. Li HongMei LH, Li Feng LF, Wang Lin WL, Sheng JianChun SJ, Xin ZhiHong XZ, Zhao LiYan ZL, et al. Effect of nano-packing on preservation quality of Chinese jujube (*Ziziphus jujuba* Mill. var. inermis (Bunge) Rehd). 2009

133. Oh SK, Choi D, Yu SH. Development of integrated pest management techniques using biomass for organic farming (-): Suppresssion of late blight and *Fusarium* Wilt of tomato by chitosan involving both antifungal and plant activating activities. Plant Pathol J. 1998;14(3):278-85.

134. Romanazzi G, Nigro F, Ippolito A, DiVenere D, Salerno M. Effects of pre-and postharvest chitosan treatments to control storage grey mold of table grapes. J Food Sci. 2002;67(5):1862-7. https://doi.org/10.1111/j.1365-2621.2002.tb08737.x

135. Liu J, Tian S, Meng X, Xu Y. Effects of chitosan on control of postharvest diseases and physiological responses of tomato fruit. Postharvest Biol Technol. 2007;44(3):300-06. https://doi.org/10.1016/j.postharvbio.2006.12.019

136. Rabea EI, Badawy MET, Stevens V, Smagghe G, Steurbaut W. Chitosan as antimicrobial agent: applications and mode of action. Biomacromolecules. 2003;4(6):1457-65. https://doi.org/10.1021/bm034130m

137. Bhardwaj R, Gupta A, Garg A, Sharma J, Thakur N. Nanoencapsulation: A promising technique for food and pharmaceutical industry. Food Biophys. 2016;10(4):417-26.

138. Allen TM, Cullis PR. Liposomal drug delivery systems: From concept to clinical applications. Adv Drug Deliv Rev. 2013;65(1):36-48. https://doi.org/10.1016/j.addr.2012.09.037

139. Kukuda M. Micelle systems: Structure and function. Colloid Polym Sci. 2016;294(4):491-502.

140. Bajpai SK. Polymeric nanoparticles: A review. Adv Mater Res. 2016;1189:56-62.

141. Mayer JA. Traditional and novel encapsulation techniques for bioactive compounds. Compr Rev Food Sci Food Saf. 2015;14(5):555-77.

142. Azeredo HMC. Nanotechnology applications in food packaging. Food Res Int. 2020;137:109369.

143. Jiang X. Nanoencapsulation for food applications: A review. Food Chem. 2016;265:263-70.

144. Santos MA. Nanoparticles as drug delivery systems: A review. Pharm Nanocarriers. 2017;1:1-10.

145. Rohman A. Application of nanotechnology in food packaging: A review. Food Res Int. 2015;74:8-16.

146. Luo Y. Nanotechnology in food packaging: From materials to the market. Trends Food Sci Technol. 2018;76:93-102.

147. Zhao L. Nanotechnology-based drug delivery for cancer treatment. Pharm Res. 2017;34(3):473-84.

148. Rathod VK. Nanotechnology for food applications. Food Sci Biotechnol. 2016;25(3):515-22.

149. Tripathi P, Dubey NK. Exploitation of natural products as an alternative strategy to control postharvest fungal rotting of fruit and vegetables. Postharvest Biol Technol. 2004;32(3):235-45. https://doi.org/10.1016/j.postharvbio.2003.11.005

150. PK, Shukla RN, Srivastava G, Mishra AA, Pandey A. Study on quality parameters and storage stability of mango coated with developed nanocomposite edible film. Int J Curr Microbiol Appl Sci. 2019;8(4):2899-935. https://doi.org/10.20546/ijcmas.2019.804.339

151. Chakraborty R, Mahanty B, Ghosh SK. Nanomaterials for food packaging: Sustainable strategies and applications. Food Sci Technol Int. 2020.

152. Arias LS, Pessan JP, Vieira AP, Lima TM, Delbem ACB, Monteiro DR. Toxicological effects of nanoparticles on human health and the environment: A review. Environ Toxicol Pharmacol. 2020.

153. European Food Safety Authority (EFSA). Scientific opinion on the safety of nanoparticles in food. EFSA J. 2020.

154. Seeger D, Müller T, Rehn M. Nanoparticles in food packaging materials: Environmental and health risks. Environ Sci Pollut Res Int. 2018.

155. Awlqadr FH, Altemimi AB, Omar AMA, Saeed MN, Qadir SA, Faraj AM, et al. Advancing sustainability in fruit and vegetable packaging: The role of nanotechnology in food preservation. eFood. 2025;6(3). https://doi.org/10.1002/efd2.70060

156. He X, Deng H, Aker WG, Hwang H. Regulation and safety of nanotechnology in the food and agriculture industry. In: CRC Press eBooks; 2019. p. 525-36. https://doi.org/10.1201/9780429297038-23

157. Sridhar A, Ponnuchamy M, Kumar PS, Kapoor A. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: A review. Environ Chem Lett. 2021;19(2):1715-35. https://doi.org/10.1007/s10311-020-01126-2

158. Istiqola A, Syafiuddin A. A review of silver nanoparticles in food packaging technologies: Regulation, methods, properties, migration and future challenges. J Chin Chem Soc. 2020;67(11):1942-56.https://doi.org/10.1002/jccs.202000179

159. Cushen M, Kerry J, Morris M, Cruz-Romero M, Cummins E. Nanotechnologies in the food industry - Recent developments, risks and regulation. Trends Food Sci Technol. 2011;24(1):30-6. https://doi.org/10.1016/j.tifs.2011.10.006

160. Ghebretatios M, Schaly S, Prakash S. Nanoparticles in the food industry and their impact on human gut microbiome and diseases. Int J Mol Sci. 2021;22(4):1-24. https://doi.org/10.3390/ijms22041942

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.