PLANT SCIENCE TODAY
Vol 12(sp1): 1-11
https://doi.org/10.14719/pst.7492

eISSN 2348-1900

REVIEW ARTICLE

Nano-preservation- A revolutionary approach to improve the shelf-life of fruits: A comprehensive review

Vidthyaa A[1], Irene Vethamoni P[2]*, Ashokkumar G[3], Sivakumar U[4], Sumithra A[5]

[1]Department of Vegetable science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[2]Department of Horticulture, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[3]Department of Vegetable Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[4]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, India
[5]Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Aruppukottai 626 107, India

*Correspondence email - irenevetha17@gmail.com

Received: 29 January 2025; Accepted: 24 April 2025; Available online: Version 1.0: 24 July 2025; Version 2.0: 01 August 2025

Cite this article: Vidthyaa A, Irene VP, Ashokkumar G, Sivakumar U, Sumithra A. Nano-preservation- A revolutionary approach to improve the shelf-life of fruits: A comprehensive review. Plant Science Today. 2025; 12(sp1): 1-11. https://doi.org/10.14719/pst.7492

Abstract

Fruits and vegetables can lose their freshness after harvesting due to various factors, including physical damage during harvesting, moisture loss, unfavorable weather conditions and microbial infestations by pests, molds and bacteria. Fruits, particularly, are more prone to spoilage and loss than vegetables. Several preservation techniques are used to enhance the postharvest quality and extend the shelf life of produce. A key emerging method is nano-preservation, which involves advanced technologies such as nano-edible coatings, active packaging, innovative packaging, nanocomposites, nanofilms and nano-biosensors. These techniques aim to improve the preservation of fruits and vegetables, ensuring they stay fresh longer. One of the significant benefits of nanotechnology in food preservation is the design of functional packaging materials that offer superior mechanical properties, better gas permeability and lower bioactive component levels. These materials help extend shelf life while having minimal impact on the sensory attributes like taste, texture and colour of the produce. Compared to traditional preservation methods, nano-preservation provides a more controlled environment around the produce, preventing spoilage, reducing waste and maintaining nutritional value. Additionally, these technologies help reduce the use of chemical preservatives. This review focuses on various nano-preservation techniques and their applications, indicating that nanotechnology is revolutionizing food preservation, offering sustainable development.

Keywords: bioactive compounds; nanobiosensors; nano-edible coating; nanofilms; nano-preservation

Introduction

The leading causes of postharvest losses are due to microbial and pathogenic attack. Fruits are sensitive to fungal attacks because of their low pH, increased moisture content and highly nutritious nature. As per the NABARD Consultancy Services (NABCONS) study (2022), the postharvest losses of fruits constitute about 6.02-15.05 %. The insufficient practices in postharvest management can lead to softening, wilting, production of off-flavour, browning and quality deterioration. Fruits are generally classified as climacteric and non-climacteric based on their ripening character. After being harvested, climacteric fruits hasten ripening and synthesize ethylene, which increases respiration rate and increases perishability. Inhibiting ethylene production is a useful approach for delaying ripening and increasing the shelf life of climacteric fruits. Non-climacteric fruits, on the other hand, do not increase in ethylene, but should be harvested at proper maturity. Time of harvesting, method of harvesting and maturity indices play a significant role in the postharvest quality of fruits. Fruit preservation, which includes a variety of techniques and procedures aimed at preserving fruit quality, improving shelf life and limiting losses, is a vital component of postharvest technology. The temperature and relative humidity during storage play a crucial role in maintaining the quality because they are positively correlated with transpiration and respiration of the fruits. Preservation technologies such as fermentation, dehydration, canning, refrigeration, edible coating and use of different packaging materials are involved. Novel preservation techniques include irradiation, electron beam acceleration, pulsed electric field, ozone technology and nano-preservation. The materials in which at least one dimension of the structure is nanoscale are referred to as nanomaterials (1). They can be prepared in two ways: "bottom-up," which involves assembling atoms or molecules to form nanostructures, or 'top-down,' which refers to breaking down bulk materials into nanoscale structures using mechanical, chemical, or lithographic techniques. Studies have indicated that nanomaterials can increase animal feed digestibility and are suggested as a potential substitute for antibiotics to enhance feed safety (2). Owing to its advantageous characteristics, which include a larger surface area per volume, broad-spectrum antibacterial capabilities and high barrier to efficiency qualities, nanoparticles can be viewed as an effective means to get around the drawbacks of conventional preservation methods.

Principles of nano-preservation

Although each preservation technique has a unique focus, they all control three essential elements that are crucial to the preservation of quality: 1) managing the senescence process, which is typically accomplished by regulating respiration; 2) managing microorganisms, which is primarily accomplished by keeping of spoilage bacteria; and 3) controlling the evaporation of water within, which is primarily accomplished by managing the environment's relative humidity (3). Novel preservation techniques should be emphasized to ensure food security among consumers. Fruit preservation has generated an enormous amount of interest in nano-level detection techniques. The sections below provide extensive detail about the fundamental concepts behind shelf-life extension techniques related to nanotechnology.

Properties of nanomaterials used for nano-preservation

Nanomaterials used in nano-preservation possess unique properties conducive to preserving materials at the nanoscale. These properties include mechanical, barrier, thermal, photocatalytic and antimicrobial properties.

Mechanical properties

The primary causes of the improved mechanical properties of nanocomposite materials are: 1) the positive interactions, such as hydrogen bonds and ionic interactions, between nanoparticles and matrix, as well as 2) the stress transfer's impact at the nanoparticle-matrix contact (4). Guar gum-nanocrystalline cellulose film's hardness and elastic modulus may be strengthened by nanocrystalline cellulose (5). A detailed study on the effects of niobium carbide (NbC) addition to AlCrFeNi medium-entropy alloy (MEA) was performed. Hardness and wear resistance of the AlCrFeNi MEA are increased by the addition of NbC (6).

Barrier properties

Nanocrystalline cellulose increased the tensile strength of chitosan films by approximately 26 %, as measured by tensile testing methods such as ASTM D882 (7). Particulate nanomaterial-infused composites often offer superior "quantum mechanics" qualities, such as improved barrier properties, then the standard preservation materials (8). Nanocrystalline cellulose and guar gum were used to construct a degradable nanocomposite film. As more nanocrystalline cellulose (NCC) was added, the pore shape changed, improving the oxygen barrier and reducing oxygen transmission (5). Highly processed clay nanoparticles had a greater effect on the moisture and oxygen barriers of carboxymethylated CFRs (9).

Thermal properties

Thermal characteristics of the nanomaterial, which have a direct impact on its usage. Because of their intrinsic atomic structure and interatomic interaction, nanomaterials, which include materials doped to produce point defect scattering and nano-grain-sized materials, have poor heat conductivity. Gelatin-based nanocomposite films (ZnoCEo) were created by (10). Two and three weight loss phases were visible in the TGA curves for the thermal stability of the control film and the nanocomposite films. Reduced glycerol hydrated and hydrated water related to heat. Additionally, the thermal breakdown of larger proteins was linked to the second step, the primary stage of thermal degradation. The assertion was that adding ZnO nanoparticles to the gelatin matrix may serve as a thermal insulator for the volatile compounds generated during thermal degradation. Consequently, the thermal stability of the gelatin films was significantly enhanced by the ZnO reinforcement (11).

Photocatalytic properties

The most popular photocatalyst material for maintaining the freshness of fruits and vegetables is nano-TiO_2 (12). Nanomaterials can postpone the deterioration of harvested fruits and vegetables and speed up the oxidative breakdown of ethylene and other gases produced during fruit and vegetable storage (13). Zinc oxide, both pure and doped, as well as ZnO-containing composite materials, are well recognized as effective photocatalysts with widespread applications (11, 14).

Anti-microbial properties

Nano antibacterial materials may be divided into two categories based on the antibacterial active ingredients: oxide photocatalytic type and metal ion type (15, 16). Adding a metal ion with an antibacterial property, such as Ag, Zn, Ni and Al, to different natural or artificial mineral nano-carriers is known as metal ionic nano-antimicrobial particles (17). According to the theory of metal ion dissolution, when nano-antimicrobial materials are applied to protect fruits and vegetables from spoiling, antibacterial metal ions gradually disappear from the germifuga. These dissolved metallic ions prevent microbes from reproducing and prevent bacteria cells from metabolizing energy (18).

Nanoparticles used in nano-preservation

Chitosan

A potential biopolymer, chitosan (CS), is a biodegradable, biocompatible and has antibacterial properties (19). Chitosan nanoparticles (CHNPs) have the same characteristics as chitosan biopolymer, including quantum size effects. They are used as antibacterial agents in various applications (20). It possesses malleable chemical and physical characteristics, is easily altered and is harmless to people. The chitosan coating improves gas exchange and preserves the quality of the fruit by reducing transpiration losses and delaying senescence and maturation (21). The grapes retained their sensory qualities and effectively extended the oxidation of vitamin C because of the edible chitosan nanoparticles. The chitosan nanoparticles act as a semi-permeable film on the grapes that reduces the oxidation and the microbial growth. A CS derivative with superior physicochemical characteristics, chitosan nanoparticles (CS-NPs) have more antioxidant and antibacterial activity than traditional chitosan. The enhanced biological activity of CS-NPs is attributed to their higher contact area and smaller particle size. For the same reasons, they can penetrate biofilms and eliminate harmful microorganisms (22).

Silver nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) are currently the most researched antibacterial nanoparticle due to their biocidal activity against a wide range of Gram-positive and Gram-negative microorganisms, yeast, molds and viruses. The antibacterial action of silver nanoparticles is primarily attributed to Ag^{+} ion release, oxidative stress induction and disruption of bacterial cell membranes by reactive oxygen species (ROS) generation (23). Silver has been adopted as an antioxidant and antimicrobial material. The most recent innovation in the use and development of edible coatings for fresh fruit is the use of silver nanoparticles, which contain a wide range of chemicals that may be employed in forming edible coatings. Food processors were more interested in silver nanoparticles because of their potential as preservatives. The production of AgNPs by green synthesis is less complicated and requires fewer expensive and sometimes less dangerous ingredients. There are several benefits and drawbacks of using different bio-sources, including fungus, bacteria, algae and plants, for the environmentally friendly synthesis of AgNPs (24).

Zinc oxide nanoparticles

The US Food and Drug Administration (FDA) has properly approved the food safety of zinc oxide nanoparticles, which are classified as GRAS (Generally Recognized as Safe). These nanoparticles are used in many cutting-edge applications, including electronic devices, communications, sensors, personal care products, environmental protection, life sciences and the medical industry (25). Scientists have been interested in zinc oxide nanoparticles (ZnONPs) because of their exceptional mechanical qualities, barrier capabilities, biocompatibility and broad-spectrum antibacterial activities (26). Zinc oxide nanoparticles (ZnONPs) have strong antibacterial properties and hence are being explored as a potential addition to replace dangerous chemicals and physical antibacterial materials (27).

Nano-edible coating

The fruit's edible coating acts as a barrier to regulate loss of moisture and exchange of gases among the fruit and its surrounding environment, slows down respiration, delays physiological ripening and keeps naturally occurring volatile flavour compounds from being lost (28). The physical and chemical properties of their constituents significantly impact the mechanical and barrier qualities of these coatings. Edible coverings made of biopolymers have emerged as a new packaging technique to extend the shelf life of freshly cut fruits (29). The impact of coating on the quality and shelf life of minimally processed pomegranate arils at 5 °C storage (30). The best covering for increasing the shelf life and preventing unfavourable microbiological, physicochemical and sensory changes to pomegranate arils was CHNPs. When adding nanoparticles to an edible coating, fruit shelf life is significantly increased compared to when using a pure polymer. An experiment compared the effects of xanthan gum in combination with 0.2 % and 0.4 % chitosan nanoparticles to those of xanthan gum alone and uncoated. Combined with 0.2 % Nano chitosan, xanthan gum and a substantial amount of chitosan nanoparticles (0.4 %), the combination prevented fruit deterioration, colour change and loss of firmness, vitamin C and flavour. The recent use of nanoparticles has encouraged the application of a lower amount of coating given in the form of nanoparticles to improve fruit quality and prolong fruit shelf life (31). Table 1 describes different nano edible coatings in fruits and their functions. Fig. 1 elucidates the nano-edible coating in strawberry.

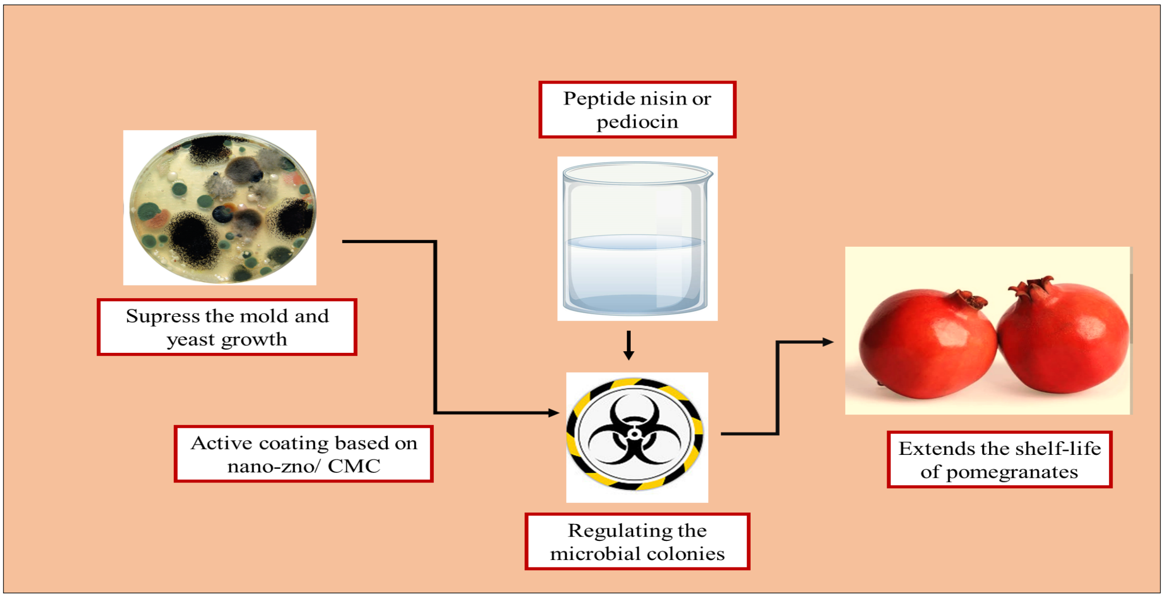

Fig. 1. Antimicrobial film based active packaging of pomegranate.

Table 1. Nanoedible coatings in fruits and their functions

Nano-edible coating	Fruit	Function	Reference
Chitosan	Strawberry	Increased the shelf-life and colour of the fruit (Fig. 3).	(32)
Copper oxide nanoparticles improved guava	Papaya	Increased shelf-life and freshness, imparting high quality fruit.	(33)
Chitosan	Apricot	Maintenance of colour and quality, control of decay.	(34)
Beeswax solid lipid nanoparticles (BSLN)	Strawberry	Increased shelf-life and anti-microbial	(35)
Aluminium	Dates	Increases the quality	(36)

Nano emulsion

A mixture of more than two difficult-to-combine liquids is called an emulsion. Nano emulsions, or nano-sized emulsions, are made to improve the distribution of active medicinal substances. They are in the spectrum of nanoscale emulsions. These are thermodynamically resistant isotropic systems when an emulsifying agent, such as a surfactant and co-surfactant, combines two immiscible liquids to create a single phase (51). Excellent antibacterial properties make essential oils (EOs) widely accepted as safe for use as food preservatives. According to the study, kiwifruit soft rot pathogens were successfully suppressed by lemon essential oil (LEO) nano emulsions, which also increased reactive oxygen species production, antioxidant enzyme activity and cell death (52). According to the study, kiwifruit postharvest degradation may be reduced using LEO-based nano emulsions as green preservatives. To identify the most effective inhibitory components, further investigation is required. Compared to shellac, the carnauba nano emulsion coating produced reduced ethanol, gloss and water loss in coated "Nova" mandarins (Citrus reticulata) and "Unique" tangors (Citrus sinensis). Compared to traditional carnauba wax emulsion and commercial shellac, carnauba nano emulsion coating showed reduced alterations in the fruit's internal environment and volatile profile and as a result, improved flavour (53). Fig. 2 elucidates the process of nano emulsion dipping in mango. A pullulan covering with a nano emulsion of cinnamon essential oil was developed to preserve strawberries (54). When it came to lowering acidity, the loss of weight, its texture and regulating bacterial and fungal development during fruit storage, the nano emulsion-based coating outperformed conventional coatings. Table 2 describes about different nano emulsions used in fruits.

Active packaging

Active packaging is classified into two categories: active scavenging and active releasing systems. Active scavenging systems maintain quality and increase shelf life by eliminating unneeded substances like ethylene, moisture and oxygen. To stop microbial development and softening, moisture management techniques regulate the moisture level of packaged horticulture goods (37). Active packaging aims to guarantee superior food quality and a longer shelf life. Several instances of this dynamic use in food packaging consist of microbiological, temperature, quality, absorbance/scavenging qualities and features removal and release/emission (38). Freshly cut "Fuji" apples were effectively preserved for 12 days at 4 °C using a new nano-ZnO packaging film. The outcomes demonstrated that, comparison to standard packaging, the nano-ZnO coating was more advantageous in maintaining the preservation quality of fresh-cut items. Thus, fresh-cut fruits may be able to retain their freshness using nano-ZnO packaging, except refrigeration. Synthesizing polyethylene with nano-powder like nano silver, kaolin and titanium dioxide improved the preservation of fruits during storage at 40 °C, resulting in a new technology of nano-packing materials with lower oxygen transmission rate and relative humidity (39). Comparing strawberry fruits packed in polythene bags with nano-packaging, the former may more effectively preserve the fruit’s chemical, physiological and sensory attributes. The anthocyanin and malondialdehyde degradation rates are reduced more quickly by nano packing than by standard polythene packaging. According to a study, fresh blueberries can have their shelf life increased by using active packaging (40). It is composed of polyethylene along with salicylate nano-carrier and modified atmospheric packing, which efficiently prevents the formation of mold

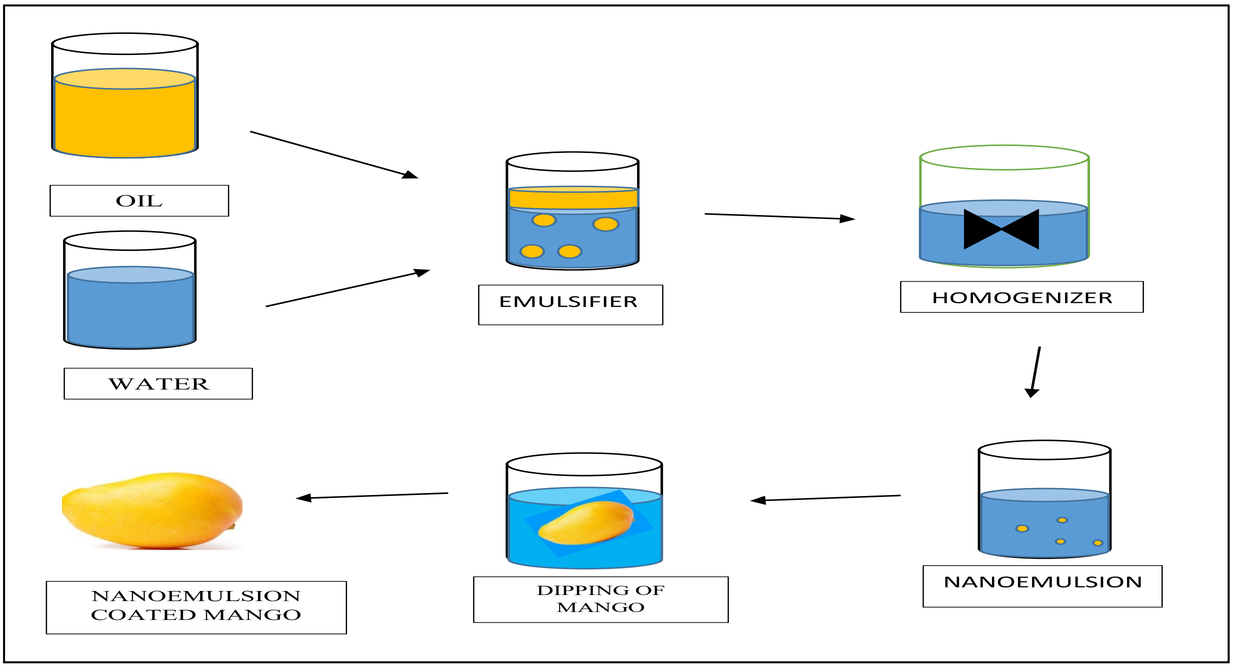

Fig. 2. Process of nanoemulsion dipping in mango.

Table 2. Nanoemulsions used in fruits

Fruit	Nanoemulsion	Uses	References
Avocado	Orange essential oil	Encapsulation	(55)
Pineapple	Sodium alginate and citral	Antimicrobial.	(56, 57)
Red Delicious-Apple	Tocopherol	Encapsulant	(58)

while preserving the firmness, texture and nutritional content of the fruit. In addition to demonstrating adherence to food safety regulations, the active packaging displayed controlled salicylate dispersion, enhancing its antibacterial qualities. This offers a possible way to increase the quality and marketability of blueberries after harvest.

Antioxidant films based on active packaging

Recent studies have concentrated on nano-active antioxidant packaging; for example, a nano-biofilm was developed in which thymol served as the primary active ingredient (41). They looked at the nano-biofilm's mechanical, optical and thermal characteristics as well as how nanomaterials affected its antioxidant function. The investigation revealed that including thymol and montmorillonite (MMT) did not significantly alter the thermal degradation profile and that thymol may still function as an active component of the nano-biofilm. Although the nano-mixtures' mechanical characteristics and oxygen resistance rate were improved, a 15 % reduction in elastic modulus was noted. The activity of polyphenol oxidase and peroxidase linked to the deterioration of storage product quality might be inhibited by chitosan/nano -silica coating (42). A previous work introduces a novel litchi peel extract, chitosan matrix and nano-TiO_2-based antioxidant packaging material and also used as a coating in water cored apples (43). The CS film's mechanical strength, thermal stability and water vapor barrier capacity are all improved by adding nano TiO_2 and/or LPE. It is verified that interactions exist between molecules among nano TiO_2, litchi peel extract and chitosan matrix. The overall phenolic content and antioxidant capacity of the CS film are increased by the identification of 64 phenolic compounds in LPE by the LC-MS/MS analysis. The respiration rate, weight reduction, softening and decay of fruits, PPO activity, loss of electrolytes and MDA build-up are all markedly inhibited by these coatings. Fruit preservation coatings and food packaging films show good prospective uses for the incorporation of nano-TiO_2 and/or LPE into chitosan.

Antimicrobial film-based active packaging

An active coating based on nano-ZnO/carboxymethyl cellulose could suppress the mold and yeast growth while regulating the overall pomegranate microbial colonies to a manageable level, greatly extending the shelf life of fresh pomegranates represented in Fig. 3 (44). By combining peptide nisin or pediocin, they created a new starch-halloysite packaging film that has antibacterial properties (45). When compared to starch film alone, they discovered that the Young's modulus values of both starch-halloysite film adsorbed with bacteriocins were all at the most significant level and did not significantly differ. It was proposed that halloysite might improve the active film's mechanical characteristics.

Intelligent and smart packaging

Fruit quality is monitored via intelligent packaging using indicators such as time-temperature, RFID indications, microbiological growth, product authenticity and pack integrity. These methods can be used to preserve commercially processed and packaged meals and fresh, minimally processed fruits with further development. Manufacturers of food and beverages employ clever packaging for their final products. This enables them to give information on the product's quality and storage life. Smart sensors play a crucial role in regulating and observing several factors, including food freshness, oxygen content, temperature and moisture (37). Electronic sensors can be used in innovative packaging. A software solution, which is smart barcode packaging has been created that allows brand owners to use the GS1 IDs included in universal product codes (UPCs) to build digital identities for their products was described (46). This creates a standardized data format, enabling marketers to embed these IDs into other codes, such as NFC tags and QR codes. This strategy promises more smartphone interactions between businesses and customers and streamlined container design. Every product that has a barcode on it has an online address.

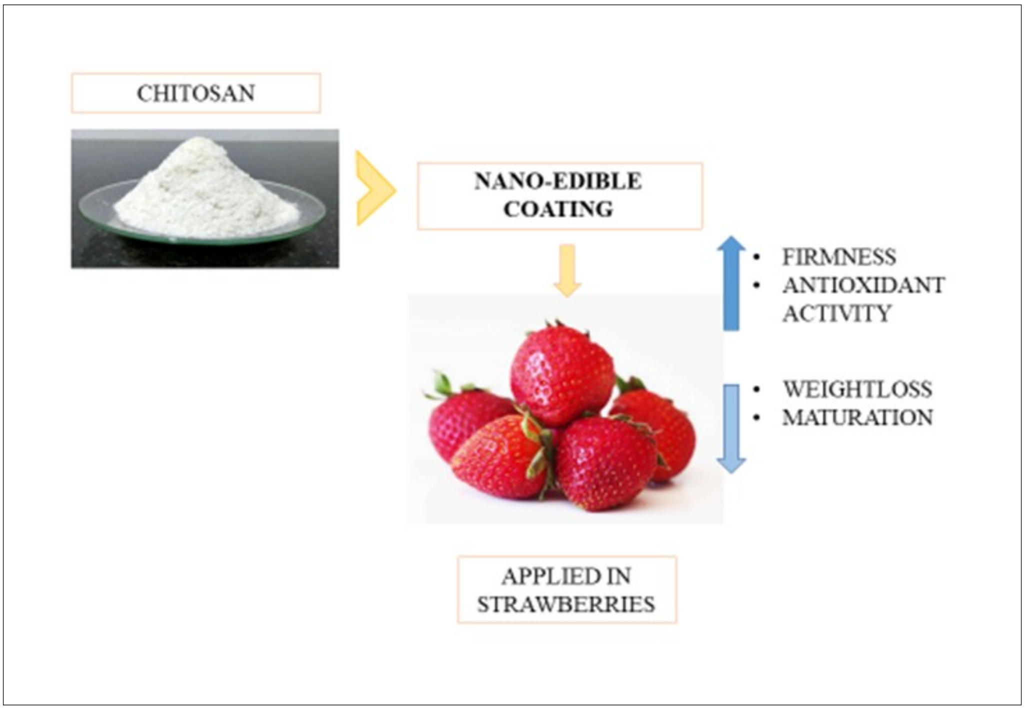

Fig. 3. Nano-edible coating in strawberry.

There are four types of intelligent systems: (i) data carriers, which include barcode, RFID, electronic article surveillance (EAS) and digital watermark; (ii) quality indicators, which include freshness and time-temperature indicators; (iii) sensors; and (iv) other devices, which include holograms and organic light-emitting diodes (OLED) (47). Intelligent packaging monitors and gives consumers high-quality information on packed items using the packaging as a smart system. Temperature, microbiological attack, product legitimacy and packaging integrity are important markers. Indicators for freshness and leakage are also provided (48). Microbial growth and irreversible metabolic processes are two reasons why food might deteriorate at high temperatures. Time-Temperature Indicators (TTIs) are intelligent sensors that monitor cumulative temperature exposure and provide a colorimetric or electronic response based on threshold exceedance. If the fruits have been stored under unfavourable temperature circumstances, they offer an optical or electronic indicator that may indicate a risk of microbial development or quality degradation. This facilitates informed decision-making by suppliers and customers about the food's safety and freshness (49). Hydrogels can provide a certification enabling their integration into the packaging system to regulate the moisture produced by the meal items. Furthermore, adding nanomaterials can impart antibacterial activity to the hydrogels (50).

Nano biosensors

Recently, food items have been using many nanotechnology-related biodegradable sensors in the form of microchips known as electronic tongue technology sensors. When a product's pH fluctuates due to spoiling, it changes colour. Three parts make up a nano biosensor: a transducer that transforms biological vibrations into digital ones, a biological sensor that uses affinity-based material to study interactions between antibodies and antigens, enzymes and substrates, nucleic acids and cells and a data-capturing unit that stores and transfers the information (59). Since agricultural wastes are abundant in the environment and a cheap alternative, they may be employed as an innovative material for nanobiosensors. Nanocellulose fibers have been produced and have many uses (60). One development in nano biosensor technology is multiplex sensing, which enables the simultaneous detection of several analytes. A nanobiosensor can detect and measure the concentrations of several sweets, such as saccharin, glucose, sucrose and cyclamate (61). By identifying degradation markers like volatile organic compounds (VOCs) and the growth of microbes, nano biosensors also aid in quality assurance. Early identification reduces the possibility of faulty or dangerous items and allows for quick decision-making. Nano biosensors provide accurate and timely information on packaging conditions for shelf-life extension. It is necessary to create manufacturing-machinable processes, optimize material prices and streamline production to guarantee that manufacturing becomes economically viable on a broad scale (62). By integrating nano biosensors, fruit preservation and monitoring systems, these initiatives will make them accessible and financially feasible (63).

Nanocomposites

Nanocomposites are multi-layered structures made of different polymers with unique characteristics that are employed to provide the right physical, barrier and sealing capabilities. The employment of additional chemicals and adhesives (in the case of laminates) adds to the expense of these complicated constructions (64). Nanocomposites generally have low mechanical properties. Layer-by-layer (LBL) assembly was the method suggested employing to increase the barrier characteristics (65). In their study, they produced undetectable and highly organized oxygen transmission rates. Additionally, the number of deposited layers may be changed and different layers can be chosen appropriately to provide the required permeabilities. The electrostatic interaction of the charged nanoclay platelets with the polymer surface is the main factor involved in developing these formations. Even in 95 % relative humidity settings, a very low oxygen transfer rate may be maintained when paired with a strong moisture barrier. Antioxidants can prevent food products from oxidizing by slowing the development of off-flavours and enhancing the food's colour stability. Examples of ways to limit or eliminate oxygen in food products include using high-barrier packaging materials, creating an anaerobic environment and using oxygen scavengers in addition to active packaging (66).

Cellulose nanocomposite

Because of its huge specific surface area, plenty of hydroxyl groups on the surface to create hydrogen bonding, high aspect ratio and crystallinity and ecologically favourable cellulose nanostructures, or cellulose nanofibers (CNF), have gathered increasing attention recently as organic nano-reinforcement or nano-fillers. Many research on biopolymer-based nanocomposite films reinforced with carbon nanofibers (CNF) has been published recently and they have demonstrated that the inclusion of CNF enhances the films' mechanical, barrier and thermal characteristics (67). A soy protein isolate-based nanocomposite film incorporating CNF was created and the produced films showed improvements in their tensile strength, water resistance, oxygen and water vapour barrier qualities and thermal stability (68). Similarly, a previous work showed better mechanical and barrier characteristics for a nanocomposite film incorporating CNF that was built on polydextrose and whey protein isolate (69).

Agar nanocomposite

Agar nanocomposites, an elastic polysaccharide made up of agarose and agaropectin, are potential polysaccharides for food packaging due to their transparency and limited hydrophilicity, good film-forming capabilities, widespread availability and inexpensive price. Yet, their restricted utilization has been caused by inadequate mechanical qualities, thermal stability and antibacterial abilities. With the addition of nano-fillers such as metallic, bimetallic, nano clay and nanocellulose, agar films have been strengthened in recent studies to improve these characteristics (70).

Zein and wheat gluten nanocomposite

Zein nanocomposites are a naturally occurring protein derived from maize kernels that exhibit hydrophobic, biodegradable, biocompatible and film-forming characteristics (71). Zein often contains plasticizers such as ethers, aldehydes, long-chain fatty acids and glycerol. It is possible to improve functions, including water solubility, foaming and emulsifying qualities, using physical, chemical, or enzymatic techniques. Zein can be processed to create glossy, oil-resistant, greasy films and coatings for food packaging. It can preserve food quality by functioning as an oxygen barrier and reducing oxidative damage since it naturally possesses antioxidant activity (72).

Coloured composite conducting sheets using a nanocomposite of polypyrrole (PP), wheat gluten and chlorophyll (CH) was made (73). According to their findings, WG film's physico-mechanical and antibacterial properties can be enhanced by adding polypyrrole and chlorophyll, which suggests using the film as an active and antibacterial packaging material.

Active nanocomposite films

By inhibiting enzymatic, oxidative and microbiological deterioration, the shelf lives of food items may be increased by nanocomposites with antifungal and antioxidant qualities. For antimicrobial packaging applications, metal oxide and metal nanoparticles, including titanium, silver, copper, zinc, MgO, ZnO and TiO_2, have been described (74). Antioxidants may prevent some substances from oxidizing, such as lipids and proteins. Antioxidants enhance the food's colour stability and slow the emergence of off-flavours. In addition to active packaging, using an oxygen scavenger, the oxidation of food items can be minimized by eliminating or restricting the presence of oxygen (66). Table 3 describes the other nanocomposite films and their function in fruits.

Biopolymers are a new category of polymer materials that are biodegradable and sourced from renewable resources. Examples of biopolymers are agar nanocomposite, zinc oxide nanocomposite, etc. Table 4 describes different biopolymer nanocomposites and their functions. The development of polymer nanocomposites using biopolymers as the main element has attracted a lot of attention due to their numerous uses and minimal environmental impact.

Future perspectives of nano-preservation

Nano-preservation offers an extended shelf life for perishable goods by inhibiting microbial growth and enzymatic reactions. Foods with bioactive chemicals are protected via nanoencapsulation, resulting in functional foods with improved nutritional benefits. To ensure consumers' acceptance of fruits, intelligent packaging materials such as time-temperature indicators (TTIs) can be used to address issues with food hygiene and losses. The safety and functionality of the entire packaging system in contact with food must be evaluated in subsequent research, with a preference for naturally occurring biopolymers. Regulations are required for intelligent food packaging to be both high-quality and safe. Creating bioplastics and their functional alterations may help intelligent food packaging, but further research, testing and evaluation are needed. Customer confidence will increase due to technological advancements in safety, structure, connections and regulations.

Table 3. Other types of nanocomposites and their function

Types of nanocomposite	Function	Reference
Starch nanocomposite with glatin	Enhancement of shelf-life and appearance in red-crimson grapes.	(75)
Wheat gluten nanocomposite with chlorophyll and polypyrrole (PP)	Improves the antibacterial or an active packaging film.	(73)
Alginate/Thyme oil/Oregano oil.	Coating increased antibacterial activity, decreased weight loss and respiration rate considerably.	(76)
Chitosan and MMT nanocomposite	Enhanced the oxygen barrier properties and decreased the water susceptibility in tangerine fruits.	(77)
Carnauba wax	Minimizing Indian jujube (plum) weight loss, rate of respiration, ethylene generation and softening at postharvest storage.	(78)
Caesin nanocomposite with starch and gelatin	Improved shelf-life and reduces moisture in guava.	(79)
Caseinate-Whey protein isolate nanocomposite	Significant antibacterial effects when storing strawberries.	(80)
Bacterial cellulose based nanocomposites	Enhances the water vapor permeability, thermal conductivity and tensile strength of fresh fruits .	(81)
Beewax based nanocomposite with tapioca starch	Decreased the gas exchange and moisture loss in blackberries.	(82)
Xanthan gum based coating with a-tocopherol nanocapsules	Coated apple slices retained more of the fruit's firmness and had a lower browning index.	(83)

Table 4. Biopolymer nanocomposite

Biopolymer-nanocomposites	Method of Coating	Observation on quality of fruits	Reference
Denatured protein/ $CaCl_2$	Dip-coating	Fresh-cut mangoes retained firmness, color variations, sensory appeal and microbiological quality	(84)
Gellan/ Pomegranate extract	Dip-coating	Did not alter sensory quality and greatly decreased the bacteria population during the period of storage.	(85)
Sodium alginate/ CMC	Dip-coating	After 14 days of storage, the coated mango slices had the lowest microbiological count.	(86)
Soy protein isolate	Dip-coating	Coating prolongs the shelf life of fresh cut pineapple by up to 14 days and prevents microbiological development and ripening.	(87)
Agar/ZnO	Dip-coating	Extended shelf-life of Green Grapes up to 21days	(88)

Conclusion

It should be stated that there are still many obstacles to be solved before widespread industrial applications for nanotechnology-related preservation techniques for extending the shelf-life of fruits. These techniques are now in the laboratory research stage. For example, it is feasible that nanoparticles might inadvertently enter fruits through absorption, dissolution and diffusion during fruit and vegetable contact; yet, the safety characteristics of nanomaterials remain incompletely known. Thus, future studies must include safety issues as well as legal considerations. Moreover, modelling studies might be useful in forecasting how nanotechnology would affect fruit and vegetable shelf life and product quality. Thus, more relevant research has to be done. Furthermore, because the mass manufacturing of nano-packaging materials is a complicated process requiring high levels of technological input, it will be necessary to refine the processing techniques and advance existing processing technologies. Furthermore, because the mass manufacturing of nano-packaging materials is a complicated process requiring high levels of technological input, it will be necessary to refine the processing techniques and advance existing processing technologies.

Acknowledgements

The authors would like to express their sincere gratitude to the Horticultural College and Research Institute faculty members, Tamil Nadu Agricultural University, Coimbatore, for their valuable discussions and feedback, which significantly enhanced this review article.

Authors' contributions

VA and IVP contributed to the original draft preparation and conceptualization. AG and SU were involved in revising the draft, adding tables and figures and proofreading. All the authors collectively participated in revision, formatting and supervision. All authors reviewed and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

References

1. Peters RJ, Bouwmeester H, Gottardo S, Amenta V, Arena M, Brandhoff P, et al. Nanomaterials for products and application in agriculture, feed and food. Trends Food Sci Technol. 2016;54:155–64. https://doi.org/10.1016/j.tifs.2016.06.008
2. Gholami-Ahangaran M, Zia-Jahromi N. Nanosilver effects on growth parameters in experimental aflatoxicosis in broiler chickens. Toxicol Ind Health. 2013;29(2):121–25. https://doi.org/10.1177/0748233711425078
3. Song X-j, Zhang M, Mujumdar AS, Fan L. Drying characteristics and kinetics of vacuum microwave-dried potato slices. Dry Technol. 2009;27(9):969–74. https://doi.org/10.1080/07373930902902099
4. Abdollahi M, Alboofetileh M, Rezaei M, Behrooz R. Comparing physico-mechanical and thermal properties of alginate nanocomposite films reinforced with organic and/or inorganic nanofillers. Food Hydrocoll. 2013;32(2):416–24. https://doi.org/10.1016/j.foodhyd.2013.02.006
5. Cheng S, Zhang Y, Cha R, Yang J, Jiang X. Water-soluble nanocrystalline cellulose films with highly transparent and oxygen barrier properties. Nanoscale. 2016;8(2):973–78. https://doi.org/10.1039/C5NR07647A
6. Xu Z, Li D, Diao G, Wu M, Fraser D, Li J, et al. Effects of Nb C addition on mechanical and tribological properties of AlCrFeNi medium-entropy alloy. Tribol Int. 2024;194:109486. https://doi.org/10.1016/j.triboint.2024.109486
7. Khan A, Khan RA, Salmieri S, Le Tien C, Riedl B, Bouchard J, et al. Mechanical and barrier properties of nanocrystalline cellulose reinforced chitosan-based nanocomposite films. Carbohydrate polymers. 2012;90(4):1601–08. https://doi.org/10.1016/j.carbpol.2012.07.037
8. Sanchez-Garcia MD, Lopez-Rubio A, Lagaron JM. Natural micro and nanobiocomposites with enhanced barrier properties and novel functionalities for food biopackaging applications. Trends Food Sci Technol. 2010;21(11):528–36. https://doi.org/10.1016/j.tifs.2010.07.008
9. Aulin C, Salazar-Alvarez G, Lindström T. High strength, flexible and transparent nanofibrillated cellulose-nanoclay biohybrid films with tunable oxygen and water vapour permeability. Nanoscale. 2012;4(20):6622–28. https://doi.org/10.1039/c2nr31726e
10. Seifi H, Gholami T, Seifi S, Ghoreishi SM, Salavati-Niasari M. A review on current trends in thermal analysis and hyphenated techniques in the investigation of physical, mechanical and chemical properties of nanomaterials. J Anal Appl Pyrolysis. 2020;149:104840. https://doi.org/10.1016/j.jaap.2020.104840
11. Mehmood Z, Sadiq MB, Khan MR. Gelatin nanocomposite films incorporated with magnetic iron oxide nanoparticles for shelf life extension of grapes. J Food Saf. 2020;40(4):e12814. https://doi.org/10.1111/jfs.12814
12. Brody AL, Zhuang H, Han JH. Modified atmosphere packaging for fresh-cut fruits and vegetables. Hoboken (NJ): John Wiley & Sons; 2010. https://doi.org/10.1002/9780470959145
13. Mihindukulasuriya S, Lim L-T. Nanotechnology development in food packaging: A review. Trends Food Sci Technol. 2014;40(2):149–67. https://doi.org/10.1016/j.tifs.2014.09.009
14. Omri K, Alonizan N. Effects of ZnO/Mn concentration on the micro-structure and optical properties of ZnO/Mn-TiO 2 nano-composite for applications in photo-catalysis. J Inorg Organomet Polym Mater. 2019;29:203–12. https://doi.org/10.1007/s10904-018-0979-4
15. Liu D, Gu N. Nanomaterials for fresh-keeping and sterilization in food preservation. Recent Pat Food Nutr Agric. 2009;1(2):149–54. https://doi.org/10.2174/1876142910901020149
16. Rossi M, Cubadda F, Dini L, Terranova M, Aureli F, Sorbo A, et al. Scientific basis of nanotechnology, implications for the food sector and future trends. Trends Food Sci Technol. 2014;40(2):127–48. https://doi.org/10.1016/j.tifs.2014.09.004
17. Brody A, Zhuang H, Han J. Nanostructure packaging technologies. Modified atmosphere packaging for fresh-cut fruits and vegetables. 2011. https://doi.org/10.1002/9780470959145
18. Montazer M, Keshvari A, Kahali P. Tragacanth gum/nano silver hydrogel on cotton fabric: In-situ synthesis and antibacterial properties. Carbohydr Polym. 2016;154:257–66. https://doi.org/10.1016/j.carbpol.2016.06.084
19. Divya K, Jisha M. Chitosan nanoparticles preparation and applications. Environ Chem Lett. 2018;16:101–12. https://doi.org/10.1007/s10311-017-0670-y

20. Kalaivani R, Maruthupandy M, Muneeswaran T, Singh M, Sureshkumar S, Anand M, et al. Chitosan-mediated gold nanoparticles against pathogenic bacteria, fungal strains and MCF-7 cancer cells. Int J Biol Macromol. 2020;146:560–68. https://doi.org/10.1016/j.ijbiomac.2020.01.037

21. Wantat A, Seraypheap K, Rojsitthisak P. Effect of chitosan coatings supplemented with chitosan-montmorillonite nanocomposites on postharvest quality of 'Hom Thong' banana fruit. Food Chem. 2022;374:131731. https://doi.org/10.1016/j.foodchem.2021.131731

22. Melo NFCB, de MendonçaSoares BL, Diniz KM, Leal CF, Canto D, Flores MA, et al. Effects of fungal chitosan nanoparticles as eco-friendly edible coatings on the quality of postharvest table grapes. Postharvest Biol Technol. 2018;139:56–66. https://doi.org/10.1016/j.postharvbio.2018.01.014

23. Aadil KR, Mussatto SI, Jha H. Synthesis and characterization of silver nanoparticles loaded poly (vinyl alcohol)-lignin electrospun nanofibers and their antimicrobial activity. Int J Biol Macromol. 2018;120:763–67. https://doi.org/10.1016/j.ijbiomac.2018.08.109

24. Moradi F, Sedaghat S, Moradi O, Arab Salmanabadi S. Review on green nano-biosynthesis of silver nanoparticles and their biological activities: With an emphasis on medicinal plants. Inorganic and nano-metal chem. 2021;51(1):133–42. https://doi.org/10.1080/24701556.2020.1769662

25. Noshirvani N, Ghanbarzadeh B, Mokarram RR, Hashemi M, Coma V. Preparation and characterization of active emulsified films based on chitosan-carboxymethyl cellulose containing zinc oxide nanoparticles. Int J Biol Macromol. 2017;99:530–38. https://doi.org/10.1016/j.ijbiomac.2017.03.007

26. Yusof NAA, Zain NM. The effect of ZnO nanoparticles on the physical, mechanical and antibacterial properties of chitosan/gelatin hydrogel films. J Teknological. 2019;81(2):21–26. https://doi.org/10.11113/jt.v81.12605

27. Awwad AM, Amer MW, Salem NM, Abdeen AO. Green synthesis of zinc oxide nanoparticles (ZnO-NPs) using Ailanthus altissima fruit extracts and antibacterial activity. Chem Int. 2020;6(3):151–59.

28. Khatri D, Panigrahi J, Prajapati A, Bariya H. Attributes of Aloe vera gel and chitosan treatments on the quality and biochemical traits of post-harvest tomatoes. Sci Hortic. 2020;259:108837. https://doi.org/10.1016/j.scienta.2019.108837

29. Maringgal B, Hashim N, Tawakkal ISMA, Mohamed MTM. Recent advances in edible coating and its effect on fresh/fresh-cut fruits quality. Trends Food Sci Technol. 2020;96:253–67. https://doi.org/10.1016/j.tifs.2019.12.024

30. Hasheminejad N, Khodaiyan F. The effect of clove essential oil-loaded chitosan nanoparticles on the shelf life and quality of pomegranate arils. Food Chem. 2020;309:125520. https://doi.org/10.1016/j.foodchem.2019.125520

31. Gad MM, Zagzog OA. Mixing xanthan gum and chitosan nanoparticles to form a new coating for maintaining the storage life and quality of Elmamoura guava fruits. Int J Curr Microbiol Appl Sci. 2017;6(11):1582–91. https://doi.org/10.20546/ijcmas.2017.611.190

32. Taha I, Shahat M, Mohamed M, Osheba A. Improving the quality and shelf-life of strawberries coated with nano-edible films during storage. Al-Azhar J Agri Res. 2020;45(2):1–14. https://doi.org/10.21608/ajar.2020.149403

33. Sharma B, Nigam S, Verma A, Garg M, Mittal A, Sadhu SD. A Biogenic Approach to Develop Guava-Derived Edible Copper and Zinc Oxide Nanocoating to Extend Shelf Life and Efficiency for Food Preservation. J Polym Environ. 2024;32(1):331–44. https://doi.org/10.1007/s10924-023-02972-1

34. Algarni EH, Elnaggar IA, Abd El-wahed AE-wN, Taha IM, Al-Jumayi HA, et al. Effect of chitosan nanoparticles as edible coating on the storability and quality of apricot fruits. Polymers. 2022;14(11):2227. https://doi.org/10.3390/polym14112227

35. 35. Zambrano-Zaragoza ML, Quintanar-Guerrero D, Del Real A, González-Reza RM, Cornejo-Villegas MA, Gutiérrez-Cortez E. Effect of nano-edible coating based on beeswax solid lipid nanoparticles on strawberry's preservation. Coatings. 2020;10(3):253. https://doi.org/10.3390/coatings10030253

36. Anean HEDA. Noval in Nano-Edible Films Applications in the Production of High-Quality Dates Al Hulwah and Soukari for Export. EC Nutrition. 2023;18:04–24. https://doi.org/10.21203/rs.3.rs-2474837/v1

37. Pudake RN, Chauhan N, Kole C. Nanoscience for sustainable agriculture: Springer; 2019. https://doi.org/10.1007/978-3-319-97852-9

38. Nile SH, Baskar V, Selvaraj D, Nile A, Xiao J, Kai G. Nanotechnologies in food science: Applications, recent trends and future perspectives. Nano-micro letters. 2020;12:134. https://doi.org/10.1007/s40820-020-0383-9

39. Sujithra S, Manikkandan T. Application of nanotechnology in packaging of foods: A review. Int J Chemtech Res. 2019;12(4):07–14. https://doi.org/10.20902/IJCTR.2019.120402

40. Bugatti V, Cefola M, Montemurro N, Palumbo M, Quintieri L, Pace B, et al. Combined effect of active packaging of polyethene filled with a nano-carrier of salicylate and modified atmosphere to improve the shelf life of fresh blueberries. Nanomaterials. 2020;10(12):2513. https://doi.org/10.3390/nano10122513

41. Ramos M, Jiménez A, Peltzer M, Garrigós MC. Development of novel nano-biocomposite antioxidant films based on poly (lactic acid) and thymol for active packaging. Food Chem. 2014;162:149–55. https://doi.org/10.1016/j.foodchem.2014.04.026

42. 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

43. Liu Z, Du M, Liu H, Zhang K, Xu X, Liu K, et al. Chitosan films incorporating litchi peel extract and titanium dioxide nanoparticles and their application as coatings on watercored apples. Prog Org Coat. 2021;151:106103. https://doi.org/10.1016/j.porgcoat.2020.106103

44. Saba MK, Amini R. Nano-ZnO/carboxymethyl cellulose-based active coating impact on ready-to-use pomegranate during cold storage. Food Chem. 2017;232:721–26. https://doi.org/10.1016/j.foodchem.2017.04.076

45. Meira SMM, Zehetmeyer G, Werner JO, Brandelli A. A novel active packaging material based on starch-halloysite nanocomposites incorporating antimicrobial peptides. Food Hydrocoll. 2017;63:561–70. https://doi.org/10.1016/j.foodhyd.2016.10.013

46. Vigneshwaran N, Kadam DM, Patil S. Nanomaterials for active and smart packaging of food. Nanoscience for Sustainable Agriculture. 2019:581–600. https://doi.org/10.1007/978-3-319-97852-9_22

47. Mlalila N, Kadam DM, Swai H, Hilonga A. Transformation of food packaging from passive to innovative via nanotechnology: concepts and critiques. J Food Sci Technol. 2016;53:3395–407. https://doi.org/10.1007/s13197-016-2325-6

48. Kruijf ND, Beest MV, Rijk R, Sipiläinen-Malm T, Losada PP, Meulenaer BD. Active and intelligent packaging: Applications and regulatory aspects. Food Addit Contam. 2002;19(S1):144–62. https://doi.org/10.1080/02652030110072722

49. Altaf U, Kanojia V, Rouf A. Novel packaging technology for the food industry. J Pharmacogn Phytochem. 2018;7(1):1618–25.

50. Batista RA, Espitia PJP, Quintans JdSS, Freitas MM, Cerqueira MÂ, Teixeira JA, et al. Hydrogel as an alternative structure for food packaging systems. Carbohydr Polym. 2019;205:106–16. https://doi.org/10.1016/j.carbpol.2018.10.006

51. de Oliveira Filho JG, Miranda M, Ferreira MD, Plotto A. Nanoemulsions as edible coatings: A potential strategy for fresh fruits and vegetables preservation. Foods. 2021;10(10):2438. https://doi.org/10.3390/foods10102438

52. Meng F-B, Gou Z-Z, Li Y-C, Zou L-H, Chen W-J, Liu D-Y. The efficiency of lemon essential oil-based nanoemulsions on the inhibition of Phomopsis sp. and reduction of postharvest decay of kiwifruit. Foods. 2022;11(10):1510. https://doi.org/10.3390/foods11101510

53. Miranda M, Sun X, Ference C, Plotto A, Bai J, Wood D, et al. Nano- and micro-carnauba wax emulsions versus shellac protective coatings on postharvest citrus quality. J Am Soc Hortic Sci. 2021;146(1):40–49. https://doi.org/10.21273/JASHS04972-20

54. Chu Y, Gao C, Liu X, Zhang N, Xu T, Feng X, et al. Improvement of storage quality of strawberries by pullulan coatings incorporated with cinnamon essential oil nanoemulsion. LWT. 2020;122:109054. https://doi.org/10.1016/j.lwt.2020.109054

55. Yang R, Miao J, Shen Y, Cai N, Wan C, Zou L, et al. Antifungal effect of cinnamaldehyde, eugenol and carvacrol nanoemulsion against Penicillium digitatum and application in postharvest preservation of citrus fruit. LWT. 2021;141:110924. https://doi.org/10.1016/j.lwt.2021.110924

56. Ali A, Muhammad MTM, Sijam K, Siddiqui Y. Potential of chitosan coating in delaying the postharvest anthracnose (*Colletotrichum gloeosporioides* Penz.) of Eksotika II papaya. Int J Food Sci Technol. 2010;45(10):2134–40. https://doi.org/10.1111/j.1365-2621.2010.02389.x

57. Prakash A, Baskaran R, Vadivel V. Citral nanoemulsion incorporated edible coating to extend the shelf life of fresh cut pineapples. LWT. 2020;118:108851. https://doi.org/10.1016/j.lwt.2019.108851

58. Gardesh ASK, Badii F, Hashemi M, Ardakani AY, Maftoonazad N, Gorji AM. Effect of nanochitosan-based coating on climacteric behaviour and postharvest shelf-life extension of apple cv. Golab Kohanz. LWT. 2016;70:33–40. https://doi.org/10.1016/j.lwt.2016.02.002

59. Verma ML, Rani V. Biosensors for toxic metals, polychlorinated biphenyls, biological oxygen demand, endocrine disruptors, hormones, dioxin, phenolic and organophosphorus compounds: a review. Environ Chem Lett. 2021;19(2):1657–66. https://doi.org/10.1007/s10311-020-01116-4

60. Shen Y. Rice husk silica derived nanomaterials for sustainable applications. Renew Sustain Energy Rev. 2017;80:453–66. https://doi.org/10.1016/j.rser.2017.05.115

61. Zhang F, Zhang Q, Zhang D, Lu Y, Liu Q, Wang P. Biosensor analysis of natural and artificial sweeteners in intact taste epithelium. Biosens Bioelectron. 2014;54:385–92. https://doi.org/10.1016/j.bios.2013.11.020

62. Kakimova Z, Orynbekov D, Zharykbasova K, Kakimov A, Zharykbasov Y, Mirasheva G, et al. Advancements in nano-bio sensors for food quality and safety assurance review. Potr S J Food Sci. 2023;17(1). https://doi.org/10.5219/1903

63. Feng L, Song S, Li H, He R, Chen S, Wang J, et al. Nano-biosensors based on noble metal and semiconductor materials: emerging trends and future prospects. Metals. 2023;13(4):792. https://doi.org/10.3390/met13040792

64. Sarfraz J, Gulin-Sarfraz T, Nilsen-Nygaard J, Pettersen MK. Nanocomposites for food packaging applications: An overview. Nanomaterials. 2020;11(1):10. https://doi.org/10.3390/nano11010010

65. Jang W-S, Rawson I, Grunlan JC. Layer-by-layer assembly of a thin film oxygen barrier. Thin Solid Films. 2008;516(15):4819–25. https://doi.org/10.1016/j.tsf.2007.08.141

66. Yildirim S, Röcker B, Pettersen MK, Nilsen-Nygaard J, Ayhan Z, Rutkaite R, et al. Active packaging applications for food. ComprRev Food Sci Food Saf. 2018;17(1):165–99. https://doi.org/10.1111/1541-4337.12322

67. Pelissari FM, Andrade-Mahecha MM, do Amaral Sobral PJ, Menegalli FC. Nanocomposites based on banana starch reinforced with cellulose nanofibers isolated from banana peels. J Colloid Interface Sci. 2017;505:154–67. https://doi.org/10.1016/j.jcis.2017.05.106

68. Xiao Y, Liu Y, Kang S, Wang K, Xu H. Development and evaluation of soy protein isolate-based antibacterial nanocomposite films containing cellulose nanocrystals and zinc oxide nanoparticles. Food Hydrocoll. 2020;106:105898. https://doi.org/10.1016/j.foodhyd.2020.105898

69. Karimi N, Alizadeh A, Almasi H, Hanifian S. Preparation and characterization of whey protein isolate/polydextrose-based nanocomposite film incorporated with cellulose nanofiber and L. plantarum: A new probiotic active packaging system. LWT. 2020;121:108978. https://doi.org/10.1016/j.lwt.2019.108978

70. Basumatary K, Daimary P, Das SK, Thapa M, Singh M, Mukherjee A, et al. *Lagerstroemia speciosa* fruit-mediated synthesis of silver nanoparticles and its application as filler in agar-based nanocomposite films for antimicrobial food packaging. Food Packag Shelf Life. 2018;17:99–106. https://doi.org/10.1016/j.fpsl.2018.06.003

71. Vimala Bharathi S, Maria Leena M, Moses J, Anandharamakrishnan C. Zein-based anti-browning cling wraps for fresh-cut apple slices. Int J Food Sci Technol. 2020;55(3):1238–45. https://doi.org/10.1111/ijfs.14401

72. Basumatary IB, Mukherjee A, Katiyar V, Kumar S. Biopolymer-based nanocomposite films and coatings: Recent advances in shelf-life improvement of fruits and vegetables. Crit Rev Food Sci Nutr. 2022;62(7):1912–35. https://doi.org/10.1080/10408398.2020.1848789

73. Chavoshizadeh S, Pirsa S, Mohtarami F. Conducting/smart color film based on wheat gluten/chlorophyll/polypyrrole nanocomposite. Food Packag Shelf Life. 2020;24:100501. https://doi.org/10.1016/j.fpsl.2020.100501

74. Noorbakhsh-Soltani S, Zerafat M, Sabbaghi S. A comparative study of gelatin and starch-based nano-composite films modified by nano-cellulose and chitosan for food packaging applications. Carbohydr Polym. 2018;189:48–55. https://doi.org/10.1016/j.carbpol.2018.02.012

75. Fakhouri FM, Martelli SM, Caon T, Velasco JI, Mei LHI. Edible films and coatings based on starch/gelatin: Film properties and effect of coatings on quality of refrigerated Red Crimson grapes. Postharvest Biol Technol. 2015;109:57–64. https://doi.org/10.1016/j.postharvbio.2015.05.015

76. Tabassum N, Khan MA. Modified atmosphere packaging of fresh-cut papaya using alginate-based edible coating: Quality evaluation and shelf life study. Sci Hortic. 2020;259:108853. https://doi.org/10.1016/j.scienta.2019.108853

77. Xu D, Qin H, Ren D. Prolonged preservation of tangerine fruits using chitosan/montmorillonite composite coating. Postharvest Biol Technol. 2018;143:50–57. https://doi.org/10.1016/j.postharvbio.2018.04.013

78. Chen H, Sun Z, Yang H. Effect of carnauba wax-based coating containing glycerol monolaurate on the quality maintenance and shelf-life of Indian jujube (*Zizyphus mauritiana* Lamk.) fruit during storage. Sci Hortic. 2019;244:157–64. https://doi.org/10.1016/j.scienta.2018.09.039

79. Pellá MC, Silva OA, Pellá MG, Beneton AG, Caetano J, Simões MR, et al. Effect of gelatin and casein additions on starch edible biodegradable films for fruit surface coating. Food Chem. 2020;309:125764. https://doi.org/10.1016/j.foodchem.2019.125764

80. 80. Lin D, Zhao Y. Innovations in the development and application of edible coatings for fresh and minimally processed fruits and vegetables. Compr Rev Food Sci Food Saf. 2007;6(3):60–75.

https://doi.org/10.1111/j.1541-4337.2007.00018.x

81. Shabanpour B, Kazemi M, Ojagh SM, Pourashouri P. Bacterial cellulose nanofibers as reinforcement in edible fish myofibrillar protein nanocomposite films. Int J Biol Macromol. 2018;117:742–51. https://doi.org/10.1016/j.ijbiomac.2018.05.038
82. GarcÃa-AlmendÃ B, Regalado C, Pimentel-GonzÃ D, Barbosa-CÃ G, Reyes-GonzÃ L. Effect of starch-beeswax coatings on quality parameters of blackberries (*Rubus* spp.). J Food Biosci Technol. 2015;52(9). https://doi.org/10.1007/s13197-014-1665-3
83. Zambrano-Zaragoza M, Mercado-Silva E, Gutiérrez-Cortez E, Cornejo-Villegas M, Quintanar-Guerrero D. The effect of nano-coatings with α-tocopherol and xanthan gum on shelf-life and browning index of fresh-cut "Red Delicious" apples. Innov Food Sci Emerg Technol. 2014;22:188–96. https://doi.org/10.1016/j.ifset.2013.09.008
84. Tomadoni B, Moreira MdR, Pereda M, Ponce AG. Gellan-based coatings incorporated with natural antimicrobials in fresh-cut strawberries: Microbiological and sensory evaluation through refrigerated storage. LWT. 2018;97:384–89. https://doi.org/10.1016/j.lwt.2018.07.029
85. Sharma B, Malik P, Jain P. Biopolymer reinforced nanocomposites: A comprehensive review. Mater Today Commun. 2018;16:353–63. https://doi.org/10.1016/j.mtcomm.2018.07.004
86. Salinas-Roca B, Guerreiro A, Welti-Chanes J, Antunes MD, Martín-Belloso O. Improving quality of fresh-cut mango using polysaccharide-based edible coatings. Int J Food Sci Technol. 2018;53(4):938–45. https://doi.org/10.1111/ijfs.13666
87. Yousuf B, Srivastava AK. Impact of honey treatments and soy protein isolate-based coating on fresh-cut pineapple during storage at 4 °C. Food Packag Shelf Life. 2019;21:100361. https://doi.org/10.1016/j.fpsl.2019.100361
88. Kumar S, Boro JC, Ray D, Mukherjee A, Dutta J. Bionanocomposite films of agar incorporated with ZnO nanoparticles as an active packaging material for shelf life extension of green grape. Heliyon. 2019;5(6). https://doi.org/10.1016/j.heliyon.2019.e01867

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.