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REVIEW ARTICLE

Application of nanoscience and technology for increasing the shelf life of seeds and fruits of horticulture crops

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Abstract

The use of nanoscience and technology in horticulture has attracted significant attention due to its potential to enhance the shelf life of seeds and fruits. Nanotechnology-based methods, such as nanocoatings, nanoencapsulation, nanoemulsions and nano-packaging, have shown promising results in preserving the freshness of fruits and seeds by minimizing microbial contamination, reducing post-harvest losses and improving seed viability. Nanomaterials such as silver nanoparticles, titanium dioxide, zinc oxide, chitosan and carbon-based nanostructures exhibit antimicrobial, antioxidant and controlled-release properties, which contribute to extending the storage periods. This review examines the recent advancements in nanotechnology for post-harvest preservation, emphasizing the mechanisms, benefits and challenges associated with these innovative techniques. Biodegradable nanoparticles are emerging as environmentally friendly alternatives to chemical preservatives in food preservation. Additionally, advanced nano biosensors are being developed to measure freshness in real time and detect spoilage at an early stage. Research and policy development are necessary to address issues including cost-effectiveness, regulatory concerns and environmental impacts, despite these encouraging benefits. Furthermore, the environmental and safety concerns related to nanomaterial applications in horticultural products are discussed. Integrating nanotechnology in horticulture presents a sustainable and efficient solution to meet global food security demands by minimizing post-harvest losses and improving crop productivity and food security, making it a crucial area for future innovation and investment.

Keywords: horticultural crops; nanoencapsulation; nanomaterials; post-harvest preservation; seed and fruit shelf life

Introduction

Horticultural produce, which includes fruits, vegetables, flowers and ornamental plants, is essential to human nutrition as it contains vital fiber, vitamins and minerals. However, these products are highly perishable, leading to significant post-harvest losses. Among all food categories, fruits and vegetables experience the highest rate of loss. According to the Food and Agriculture Organization (FAO), around one-third of all food produced for human consumption is wasted or lost globally. This perishability contributes to food instability, resulting in economic losses for farmers and retailers, while also posing environmental sustainability challenges.

The short shelf life of horticultural produce is primarily caused by environmental and biological factors such as enzymatic browning, moisture loss, microbial spoilage and physiological disorders. Microbial spoilage, which leads to deterioration and reduced nutritional value, is a major concern and is primarily caused by bacteria, fungi and yeasts. These issues are further aggravated by improper handling, inadequate storage conditions and inefficient transportation methods, all of which reduce the longevity of perishable products. In recent times, nanoscience and nanotechnology-based methods are being applied to extend the shelf life of fruits and seeds in horticultural commodities.

Nanotechnology-driven approaches

Nanotechnology involves developing, manufacturing and applying materials and devices by manipulating their dimensions and form at the nanoscale level. At this level, materials have special qualities that set them apart from their equivalents on a broader scale. These distinctive characteristics arise due to an increased surface area-to-volume ratio and quantum effects, which influence optical, electrical and chemical behaviors (1). Physicist Richard Feynman first proposed the idea of nanotechnology in his 1959 lecture *"There's Plenty of Room at the Bottom,"* in which he discussed the possibility of modifying individual molecules and atoms. The term "nanotechnology" was later used by Professor Norio Taniguchi in

1974. Since then, the field has advanced rapidly, driven by progress in microscopy and fabrication techniques, leading to applications across various industries, including medicine, electronics and agriculture. Nanotechnology, defined as the manipulation and control of matter at the nanoscale (1 to 100 nm), provides promising solutions for increasing the shelf life of horticultural products. This advanced field utilizes nanoparticles, which possess unique physical, chemical and biological properties because of their small size and large surface area. These properties enhance their interaction with biological systems, making them highly effective for agriculture and food industry applications. Nanotechnology can help to extend the shelf life of horticultural produce through various mechanisms, offering innovative solutions to reduce post-harvest losses.

Antimicrobial properties to prevent microbial contamination and extend freshness, nanoparticles (NPs) such as silver, zinc oxide and titanium dioxide are suitable for use in packaging materials or applied as coatings on the surface of fruits and vegetables. These NPs exhibit strong antimicrobial properties, effectively inhibiting the expansion of spoilage-causing microorganisms. Nanotechnology enable the development of controlled-release systems for antioxidants, preservatives and other shelf life enhancing substances. These compounds can be encapsulated in nanocarriers and gradually released over time, providing a long-lasting anti-spoiling effect. Certain nanoparticles, like carbon nanotubes and titanium dioxide, functions as an ethylene scavenger, effectively delaying ripening and prolonging the shelf life of produce. Ethylene is a plant hormone responsible for accelerating the ripening and senescence of fruits and vegetables. Nano-encapsulation involves enclosing bioactive compounds such as vitamins, antioxidants and antimicrobial agents within nanostructures. This process enhances the stability and bioavailability of these substances while providing extended protection against deterioration and spoilage (1).

Application of nanotechnology in horticulture

Nano-coatings/films

Nanofilms act as protective barriers that deliver metal NPs as antibacterial agents. These innovative materials prolong the shelf life of horticultural crops by controlling decomposition, preventing color changes, regulating respiration rates and optimizing storage conditions. Edible nanofilms have been proposed as a practical solution for preserving the quality of horticultural products during storage and shelf life. A recent study formulated a nano-composite edible film by combining aloe vera gel (70 mL), glycerol (1 g) and zinc oxide nanoparticles (ZnO NPs). Among the following edible nanocomposite films, ZnO NPs solutions demonstrated the ability to enhance the shelf life and quality of mango fruits for up to 9 days (at room temp). The films are produced by reducing soluble solids, maintaining fruit thickness and transparency, increasing titratable acidity and ascorbic acid concentration, minimizing mass loss and preserving pH levels (2).

Nanoparticles used as edible coatings

Chitosan

Chitosan, a naturally occurring biopolymer derived from chitin, has gained attention for its ability to enhance fruit quality and prolong the shelf life. Because of its antibacterial, barrier-forming and film-forming qualities, it has positive benefits. When applied to fruit surfaces, chitosan forms a protective layer that reduces gas exchange and water loss, delaying ripening and prolonging freshness. Additionally, its antimicrobial properties help to inhibit the growth of spoilage-causing microbes, ensuring fruit safety and quality (3). Applying chitosan coatings significantly improved the postharvest quality of strawberries by enhancing shelf life, reducing fruit softening and reducing weight loss compared to untreated strawberries. Furthermore, chitosan-treated fruits demonstrated higher antioxidant and vitamin C content while experiencing reduced respiration and degradation rates (4). Similarly, to confirm that chitosan coatings effectively maintain the firmness, color and overall quality of strawberries throughout storage. As chitosan coatings are non-toxic and safe for consumption, they present a promising solution for reducing post-harvest losses while enhancing the quality and longevity of fruits (5).

Zinc oxide nanoparticles (ZnO NPs)

ZnO NPs have been extensively studied for their potential utilization in fruit preservation and quality enhancement due to their antibacterial and UV-blocking properties (6). When applied as coatings or treatments, these nanoparticles can help to maintain fruit quality and extend shelf life. ZnO NPs were used as a coating for postharvest kiwifruits. The ZnO NPs coating effectively inhibited the growth of harmful bacteria and fungi on the fruit's surface, reducing microbial contamination (7). Additionally, kiwifruits coated with ZnO NPs exhibited a significant delay in ripening, improved firmness and prolonged shelf life, without negatively affecting sensory quality. These findings suggest that ZnO NPs could serve as a safe and natural technique for improving the postharvest quality of fruits by reducing microbial deterioration and delaying ripening processes (8). Furthermore, ZnO NPs' UV-blocking properties protect the fruits from harmful radiation, helping to preserve their color, flavor and nutritional content. However, further research is needed to ensure the safety and regulatory compliance of ZnO NPs coatings for food applications. To investigate the impact of ZnO NPs coatings on the postharvest quality of kiwifruits. Their findings demonstrated that ZnO coatings helped to less the weight loss and maintain fruit firmness during storage. Additionally, ZnO-coated kiwifruits showed less deterioration and had a longer shelf life compared to untreated fruits. This protective effect against microbial infections and physical damage is attributed to the antibacterial and barrier properties of ZnO NPs (9).

Silver nanoparticles (Ag NPs)

The impact of various Ag NPs formulations on fruit shelf life has been widely documented. Agriculture-rich nations such as China, India, Brazil and the United States have extensively utilized Ag NPs to prolong the freshness and storage capacity of fruits. India, the world's second-largest producer of fresh produce, employs numerous Ag NPs-based nanostructures to enhance the longevity of fruits and vegetables. For instance, Ag-based NPs have been demonstrated to prolong the shelf life of apples (*Malus domestica)* and limes (*Citrus aurantifolium*) (10). One study found that chitosan-based silver nanoparticle (Ag NPs 1 % + Tween 80) significantly reduced postharvest losses in fresh mangoes and enhanced their quality, owing to their antifungal properties (11). Additionally, Ag NPs combined with biocompatible coating materials such as chitosan and glycol were shown to extend the shelf life of red grapes by up to 14 days, while the integration of Ag nanostructures into organic polymers improved the mechanical strength of coating films (12). In countries like China and India, Ag NPs are widely used to preserve the freshness and prolong the storage duration of fruits and vegetables (13). Due to their strong antibacterial properties, Ag NPs have been reported to extend the shelf life of cherry tomatoes by as much as 15 days. In Brazil, biologically synthesized Ag NPs derived from *Myxobacteria virescens* extracts are also employed to increase the shelf life of fresh apples, either by incorporating these active nanoparticles into packaging materials or by synthesizing them directly on the fruit surface. Ag NPs exhibit strong antibacterial properties and can extend the shelf life of fresh apples by up to 2 weeks (14) (Table 1).

Silver nanotechnology in cut flowers

After cutting the stems and placing flowers in a vase, bacteria begin to grow on the exposed ends of the stems, blocking the water-entry channels. This is the primary reason why expensive flowers, such as roses, freesias and lilies, have a short vase life. Many florists include a small packet of plant food with their bouquets, but this does not address the bacterial blockage in the stems. While adding a drop of household bleach can be a useful tip, not all flower enthusiasts prefer the scent of bleach overpowering their flowers' natural fragrance. Ag NPs, known for their antimicrobial properties, have recently been studied by researchers at the Department of Horticulture at Ferdowsi University of Mashhad, Iran, to extend the cut lily vase life (*Lilium orientalis* cv. "Shocking"). Ag NP suspensions in water at concentrations of 5, 15, 25 and 35 parts per million (ppm) were tested and their effects were compared with untreated vase water as a control. The study found that control flowers maintained their vibrant appearance for less than a week, while flowers treated with lower concentrations of Ag NPs lasted a few days longer. However, at 35 ppm, the flowers remained fresh and colorful for nearly twice as long as the control group (less than 12 days) (as mentioned Fig. 1) (32).

Nanomaterials for Enhancing the Shelf Life of Fruits

Researchers are exploring nanotechnology to enhance the stability and quality of horticultural crops, particularly fruits and vegetables, to extend their shelf life (33, 34). Recently, synthetic and organic coated NPs, like chitosan, Si (silicon), titanium dioxide (TiO_2) and their composite derivatives, have been used to develop protective coatings for fruits with limited shelf life. These nanomaterials have been found to enhance the mechanical and antibacterial properties of fruits such as Chinese bayberries (35), loquats (36) and strawberries (34), significantly prolonging their freshness. Below are

Fig. 1. Comparative ripening of papaya with and without edible coating.

Table 1. Nanoparticle-based coatings and composites for extending the shelf life of horticultural fruits.

Fruit	Nanoparticle	Other compounds	Benefit	References
Strawberry	Chitosan (1 %)	Oleic acid	Less respiration, transpiration and microbial activity due to the combined application	(15)
Strawberry	Methyl Cellulose	Curcumin and limonene	Lesser fungal growth, higher titratable acidity and total phenolic content	(16)
Papaya	Chitosan (1.5 %)	-	1.5 % more respiration was observed in uncoated samples	(17)
Peach	Methyl cellulose (6 g)	Alginate	Decreased transpiration and respiration rates observed	(18)
Orange	Chitosan (1 %)	Locust bean gum and pomegranate peel extract	The incorporation of 0.361 g dry Weather Proof Protective Envelope per mL into both chitosan and locust bean gum coatings led to a significant reduction in disease incidence by 49 % and 28 % respectively.	(19)
Mango	Chitosan	-	Improved shelf life of sliced mango	(20)
Guava	Chitosan (2 %)	Cassava starch and *Lippa gracilis* Schauer	Shelf life grew by 10 days	(21)
Apple	Silver/Zinc oxide	Gelatin/Chitosan	Fruit quality was maintained and the shelf life was prolonged by 42 days.	(22)
Banana	Zinc oxide	Soybean protein isolate and cinnamaldehyde	During the 7-day storage period, it delays banana ripening, maintains nutrient content, minimizes water loss and thereby prolongs the shelf life.	(23)
Banana	Chitosan (1.25 %)	-	Coatings extended the banana shelf life and maintained sensory quality	(24)
Banana	Chitosan (0.2 %)	Acetic acid	The ripening was postponed by displaying a reduced rate of skin browning as compared to the control during 6 days of storage	(25)
Banana	Zinc	Chitosan/gum-Arabica	The bananas remained consistent and had a prolonged shelf life of over 17 days in storage.	(26)
Mango	Silver (1%)	Chitosan and Tween-80	The combination reduced postharvest decay by suppressing anthracnose incidence during 7 days of mango storage	(11)
Mango	Zinc (2 %)	Cassava starch and stearic acid	Fresh-cut mangoes were less likely to lose weight, microbial growth was delayed and shelf life was improved when stored at 8 °C for 12 days.	(27)
Fig	Zinc (175 ppm)	Chitosan and acetic acid	Fruits are coated to delay ripening and maintain quality when being stored.	(28)
Guava	Chitosan (0.2 %)	Xanthan gum and Tween-80	When stored cold and stored for a long time, it enhances the overall quality	(29)
Papaya	Silver	Hydroxypropyl methylcellulose	During storage, silver nanoparticles prolonged shelf life by 14 days, preserved postharvest quality and acted against *Colletotrichum gloeosporioides*.	(30)
Apricot	Silver	Glycerol	A 24 hr period at 6 °C significantly reduced weight loss and decay percentage and the quality was maintained	(31)

some promising nanoparticles and their potential role in prolonging the shelf life of agricultural goods.

Hexanal

Hexanal ($C_6H_{12}O$) is a highly volatile, flavor-producing compound released during fruit ripening. It functions by inhibiting enzymatic activity on the fruit's surface, thereby reducing ethylene production (37). Hexanal is commercially used in pre-harvest sprays or dip treatments to prolong fruit freshness by up to two or 3 weeks without compromising fruit quality. Under ambient conditions (25 ± 0.8 °C and 60 ± 10 % relative humidity) (38). It had demonstrated that applying a 0.02 % hexanal solution as a postharvest dip for 10 min (2 L of solution per kg of fruit) and storing the fruit in a dry shed significantly decreased ethylene production, physiological weight loss and soluble solid content while increasing chlorophyll levels. In mangoes, this treatment delayed ripening by at least 2 days.

Applications of nanomaterials

Nanomaterials in rubber industry

The rubber industry is increasingly recognizing the potential of nanoparticles as substitutes for traditional materials commonly used in the rubber industry due to their unique properties and enhanced performance. Rubber nanocomposites, which incorporate various nanoparticles, have gained significant attention from both industry and research sectors because they require a smaller volume of nanomaterials while improving mechanical and functional properties. A rubber nanocomposite is a novel composite material in which at least one dimension of the dispersed components or particles falls within the nm range (1-100 nm). The Rubber Research Institute of Sri Lanka nanocomposite research group has developed a unique method for producing natural rubber nanocomposites using montmorillonite clay. In this process, stacked silicates and rubber molecules undergo simultaneous modifications during processing. Nanomaterials used in rubber-based seed coatings and packaging increase seed shelf life by reducing moisture and oxygen permeability, providing antimicrobial protection and enabling controlled release of seed protectants.

Rubber nanocomposites offer several advantages over traditional, highly filled rubber composites, including lighter weight due to lower material density, enhanced reinforcement while maintaining natural elasticity, additional functional properties without compromising elasticity and tensile strength, improved flow characteristics, including better viscous and elastic properties, making processing more efficient (39).

Nanomaterials in food processing

Food processing techniques are used to extend the shelf life of food products and enhance their flavor. Traditional conservation methods, such as radiation treatment, high hydrostatic pressure and ohmic heating, often fall short in maintaining food quality (40). Today, the use of various NPs and nanotechnology in the food processing industry is expanding rapidly.

Nanotechnology in spices

Spices, medicinal plants and aromatic crops contain bioactive compounds and secondary metabolites, making them valuable commercial commodities. Nanotechnology-based treatments for these crops can enhance seed protection and promote efficient germination, improving resistance to moisture stress and ensuring better food product quality and traceability. It also plays a vital role in strengthening food security through advanced preservation and packaging techniques. Additionally, nanotechnology contributes to value addition by enabling the development of nano-based drug formulations and facilitates the rapid detection of bio-contaminants, thereby ensuring food safety and quality. The application of NMs such as nano-silicon dioxide (SiO_2), nano-calcium oxalate (Ca_2O_4), nano-sodium aluminum silicate ($AlNa_{12}SiO_5$) and nano-dicalcium phosphate ($CaHPO_4$) can improve the flow properties of ground spices, reducing lump formation. Additionally, advanced electronic nose systems, which use piezo sensors and piezoelectric quartz crystals, can be developed for flavor identification in spices. For example, these systems have been used to distinguish between CO_2 extracts of coriander, musk and black pepper (41, 42).

Nano packaging

Nanotechnology has the potential to revolutionize fruit packaging by enhancing material strength, oxygen transmission rates and moisture control. A new generation of nano-packaging materials has been developed by incorporating nanopowders such as nano-silver (Ag), kaolin, anatase TiO_2 and mineral TiO_2 polyethylene-based films. This innovation improves the packaging material's durability and enhances fruit preservation quality, even at high storage temperatures (e.g., 40 °C) (43). For example, when used for packaging strawberries, nano-packaging materials help to maintain the fruit's sensory qualities, chemical composition and physiological characteristics more effectively than conventional polyethylene bags (44). Additionally, nano-packaging reduces the degradation rates of anthocyanins and malondialdehyde, further preserving the fruit's freshness and quality.

The activities of pyrogallic acid oxidase (POD) and polyphenol oxidase (PPO) were significantly reduced in nano-packaging compared to traditional methods. This suggests that nano-packaging can improve the quality of preservation over prolonged storage periods (45). In the US, apples are commonly sold with a wax coating to prevent moisture loss and drying. Currently, edible coatings for fruits, vegetables and baked goods are as thin as 5 nm. These coatings help with gas exchange, prevent water loss and preserve color, flavor and antioxidants, allowing products to stay fresh even after opening (46). Nano-Silicon Oxide/chitosan composite preservation agents have been shown to improve the quality of Fuji apples compared to uncoated ones (47). As previously mentioned, nano-packaging has various applications in food preservation and storage. The packaging of spices is particularly challenging, as it must maintain their flavor, color and aroma while extending shelf life and reducing microbial contamination risks. Cylindrical nanopores with diameters between 15 and 100 nm were produced on the aluminum (Al) surface of packaging foil through electrochemical anodization. Packaging surfaces with nanopores measuring 15–25 nm significantly reduced biofilm formation and bacterial adhesion, making them highly suitable for spice packaging (48) (Table 2 & 3).

Table 2. Comparison of conventional and nano packaging for fruit quality parameters.

Contents	Conventional packaging	Nano packaging	References
Decay rate	26.8 %	16.7 %	(48)
Anthocyanin	31.9 mg/100 g	26.3 mg/100 g	(48)
Malondialdehyde	75.4 µmol/ g	66.3 µmol/ g	(48)

Table 3. Nanomaterial-based packaging for fruits and vegetables.

Nanomaterial packaging material	Vegetables and fruits used for packaging	Characteristics of packaging	References
Silver (Ag)-cellulose films	Tomato	Inhibits bacterial proliferation and infection	(49)
Titanium dioxide (TiO_2)polyacrylonitrile	Tomato	Lowers the rate of ethylene production	(50)
Titanium dioxide (TiO_2)-chitosan	Grapes	It acts as a preservative and prevents the entry of microbes	(51)
Zinc oxide (ZnO)-chitosan	Apple and mango	Antioxidant and prevents microbial attack	(52)

Nanoencapsulation

Nanoencapsulation involves techniques such as nanocomposites, nanoemulsification and nano-structuration. This technology encases materials in tiny packages, allowing for controlled core release as part of the final product. This method can be used to develop functional foods by delivering bioactive compounds such as vitamins, antioxidants, proteins, lipids and carbohydrates. Once the active ingredients are released, the nanocapsules break down and are absorbed like regular food, enhancing their functionality and stability (53). Zein, a prolamine found in corn endosperm, binds to and encapsulates lipids, preventing their deterioration. Additionally, research has shown that zein can adsorb fatty acids and form repeating nanoscale structures, particularly layered formations of fatty acids and zein. Nanocochleates, which are nanocoiled particles that encase micronutrients, can stabilize and protect a wide range of micronutrients while enhancing the nutritional content of processed foods (54).

Techniques to achieve nanoencapsulation

For the development of nanomaterials, nanoencapsulation techniques employ either top-down or bottom-up techniques. Applying precise tools that enable size reduction and structure sculpting for the intended use of the nanomaterials under development is part of a top-down approach. The self-assembly and self-organization of molecules, which were impacted by a variety of variables such as pH, temperature, concentration and ionic strength, developed the materials in a bottom-up manner (55). The top-down approach employs methods like emulsification and emulsification-solvent evaporation. Conversely, the bottom-up strategy uses the supercritical fluid technique, inclusion complexation, coacervation and nanoprecipitation (56, 57). Some hydrophilic and lipophilic bioactive substances can be encapsulated using these nanoencapsulation processes.

Nanoemulsions

The emulsion is a mixture of 2 or more liquids that are difficult to combine. Nanoemulsions, which fall within the nanoscale emulsion range, are produced to improve the delivery of active medicinal and nutritional components. These systems are isotropic and thermodynamically stable, formed by blending 2 immiscible liquids with an emulsifying agent such as a surfactant or co-surfactant, to produce a single homogeneous phase. A well-known example of nanoemulsion application is the use of a 42 nm-diameter carnauba wax coating, derived from carnauba palm (*Copernicia prunifera*) leaves. A 2.4 % wax emulsion was applied to papaya fruits, which were subsequently stored for 9 days at 22 °C and 60–70 % relative humidity. The treated fruits exhibited reduced weight loss and slower degradation (58) (Fig. 2).

Various nanoemulsions are applied to fruits to protect them from spoilage and microbial contamination. Nanolaminate, an ultra-thin (1–100 nm/layer) food-grade material, is chemically or physically bonded to form protective coatings (59). When used in edible films, nanolaminate offers numerous benefits. These films are commonly applied to horticultural products, as well as chocolate, toffees, baked goods and French fries (60). These protective layers help prevent gas exchange, lipid oxidation and moisture loss. Additionally, they preserve the fruits' color, flavor, antioxidant content and nutritional value while enhancing their textural properties (as mentioned in Table 4 and Fig. 2) (66).

Biosensors

Nanosensors are used to monitor horticultural products in real-time, providing valuable information on factors such as ripeness, spoilage and pathogen exposure. An application is a sensor based on carbon nanotubes or quantum dots that can detect ripening hormones, ethylene gas and changes in temperature and humidity, all of which affect shelf life (1). These technologies enable analysts and farmers to quickly and accurately determine the presence of harmful analytes in horticultural produce. Moreover, they simplify the analysis process, making it faster and more efficient. The development of biosensors is therefore essential for detecting a wide range of analytes, including pesticides, toxins, phytohormones, plant pathogens, flavour compounds, essential minerals and key nutrients

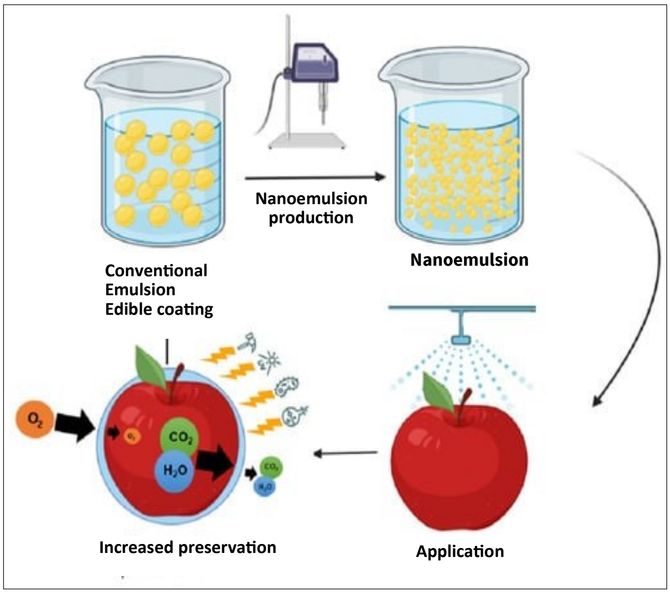

Fig. 2. Nanoemulsion-based edible coatings.

Table 4. Applications of nanoemulsions in fruit preservation.

Fruits	Nanoemulsion	Method of emulsion	References
Red Delicious-Apple	Tocopherol/nopal mucilage nanoemulsion	Encapsulant	(61)
GolabKohanz-Apple	Chitosan-nanoemulsion	Coating	(62)
Banana	Chitosan-nanoemulsion	Coating	(63)
Papaya	Chitosan-nanoemulsion	Coating	(64)
Papaya	Wax-nanoemulsion	Coating	(65)

in horticultural products (67). For example, green tea and clove extracts were analyzed using an optical sensor based on gallic acid as the detection material. In order to detect changes in the appearance of the food products, the sensor used bismuth-based nanoparticles and gold (Au) nanotubes (68).

Role of nanotechnology in horticulture

Nanofertilizers

Nanofertilizers are nutrient carriers with nanoscale dimensions ranging from 1 to 100 nm, used alone or in combination to enhance plant performance, growth and yield. These advanced fertilizers are produced by incorporating nanomaterials into traditional fertilizers derived from various plant sources. Various types of nanofertilizer formulations include nano-carriers, bio-nanofertilizers, nano-enabled fertilizers, controlled-release nanofertilizers, nanoparticle-based nutrients and nano-based micronutrient delivery systems. These formulations ensure precise nutrient release at optimal locations and times (69). Nanofertilizers significantly impact physiological and biochemical processes by increasing nutrient availability, which enhances metabolic functions and meristematic activity. This leads to improved apical growth and expanded photosynthetic areas (70). Such improvements are crucial for promoting vegetative and reproductive growth, including flowering, which ultimately enhances yield and fruit quality.

A key advantage of nanofertilizers is their ability to regulate nutrient release, preventing excessive losses and undesirable interactions with water, air and soil microorganisms. They help to maintain a balanced supply of nitrogen, phosphorus and other macronutrients (71). Additionally, nanofertilizers are adaptable to diverse environmental conditions, including fluctuations in temperature, soil moisture and soil acidity, thereby optimizing plant nutrient absorption. Compared to conventional fertilizers, nanofertilizers offer superior efficiency in nutrient uptake by plant roots and shoots (72). They effectively minimize nitrogen losses caused by emissions, leaching and microbial interactions. Nanofertilizers and nutrient-loaded nanomaterials can be designed with various release mechanisms, including moisture-triggered, pH-triggered, heat-triggered, ultrasonic-triggered, magnetic-triggered, specific-triggered, slow-release and rapid-release. Their use reduces nutrient loss through leaching and enhances soil nutrient availability (73) (Table 5).

Table 5. Effects of nanofertilizers on growth, yield and quality of horticultural crops.

S.No.	Crop	Nano fertilizers	Effects	References
			Fruits	
1.	Apple	Nano zinc oxide (ZnO) (200 ppm, 400 ppm)	Prolonged shelf life and reduced degradation	(74)
		Nano biofertilizer	Increased plant height, plant diameter, leaf area and content of chlorophyll	(75)
		Nano calcium (Ca) (0 %, 1.5%, 2 %)	Enhanced fruit quality, along with increased total antioxidant activity, phenolic content, starch and fiber levels	(76)
2.	Pomegranate	Nano zinc (Zn) and Nano B (34 mg B tree^{-1} or 636 mg Zn tree^{-1})	Increased fruit yield, quality, total soluble solids (TSS) and juice content, while reducing total acidity	(77)
3.	Mango	Nano chitosan and nano potassium silicate	Both fertilizers had a beneficial impact on flowering, chlorophyll content, fruit set and yield. Nano potassium silicate specifically enhanced panicle length, resulting in higher yields and improved fruit characteristics, while also reducing floral malformation	(78)
		Nano B (10 ppm)	Demonstrated a positive impact on increasing fruit yield and improving its chemical attributes, while also boosting chlorophyll levels and the concentrations of essential nutrients such as nitrogen, potassium, phosphorus, magnesium, manganese, Zinc, boron and iron in the leaves	(79)
4.	Citrus	Nano nitrogen phosphorous potassium (NPK)	Highest total leaf area, seedling stem diameter, root and shoot dry weight.	(80)
			Vegetables	
5.	Tomato	Nano potassium (K) (300 kg/ha, 400 kg/ha)	Increased the no. of fruits, weight, diameter of fruit and increased the plant height and stem diameter.	(81)
6.	Potato	Nano nitrogen phosphorous potassium (NPK)	Increased Water use efficiency, Fertilizer use efficiency and Animal unit equivalent.	(82)
7.	Brinjal	Nano zinc oxide (ZnO) (50 ppm, 100 ppm)	Increased the number of fruits and alleviated the impact of water stress on production.	(78)
8.	Cucumber	Nano nitrogen phosphorous potassium (NPK) (6 mL)	Displayed superior growth traits, yield and fruit quality, along with the highest number of leaves and chlorophyll content. Lowest weight loss and decay % in storage conditions.	(83)
			Spices, medicinal and aromatic crop	
9.	Peppermint	Nano iron (Fe), zinc (Zn) and potassium (K)	Recorded the greatest number of branches and leaf height, as well as the highest wet and dry weights of leaves, stems and the entire plant.	(84)
10.	Coriander	Nano silica (Si) (3 mM)	Enhanced morphological traits and elevated the levels of chlorophyll, carotenoids and carbohydrate.	(85)
11.	Black cumin	Nanofertilizer (Pharmks®) (at 2 levels 0 mL/L and 1 mL/L)	Increased seed weight, seed yield and overall biological yield, with a significant positive impact on photosynthetic activity.	(86)
		Nano iron oxide (FeO) (3 g/L water)	Increased aerial dry weight and pigments	(87)
		Nano zinc (Zn) (40 kg/ha), Nano iron (Fe) (50 kg/ha) and Nano manganese (Mn) (40 kg/ha)	Enhanced seed yield, essential oil content and essential oil percentage.	(88)
			Flowers	
12.	Gladiolus	Nano nitrogen phosphorous potassium (NPK) (1g/L)	Increased flower and spike stem diameter, as well as the dry weight of spikes.	(89)
13.	Marigold	Nano chelation	Increased the fresh weight of the shoot, peroxidase activity, proline and glycine content.	(90)
14.	Rosemary	Nano nitrogen phosphorous potassium (NPK) (0 mg/L, 25 mg/L and 75 mg/L)	Enhanced plant height, branch number, oil yield, density and the concentration of active compounds in the flowers.	(91)

Macronutrient nanofertilizers: Macronutrients are essential nutrients required in relatively large quantities for healthy plant growth and productivity. To enhance their efficiency, one or more of these nutrients are typically linked to nanoparticles. This approach ensures the precise delivery of nutrients to target crops while reducing the overall quantity needed and providing additional benefits (92, 93). Macronutrient nanofertilizers consist of specific NPs that encapsulate one or more nutrient components, improving nutrient availability and uptake. By 2020, it was estimated that agricultural production would require up to 265 million tons of nitrogen (N), phosphorus (P) and potassium (K) (94) (Table 5).

Conclusion

Nanotechnology holds significant promise for transforming the horticulture sector by enhancing seed viability and improving post-harvest preservation (95). The application of nanomaterials and nano-based technologies can improve food quality and safety, extend shelf life and reduce microbiological contamination (96). Additionally, the use of biosensors and other biodegradable, intelligent nano solutions enables sustainable practices and supports real-time monitoring of produce. Despite these benefits, further research, comprehensive regulatory frameworks and thorough environmental impact assessments are essential to fully realize the potential of nanotechnology in horticulture. Overall, the integration of nanotechnology into horticultural practices presents a promising strategy to minimize post-harvest losses and contribute to global food security.

Authors' contributions

GKP has written the whole manuscript. KK guided in providing technical support to write the manuscript in a proper format and approved the final manuscript. MS guided in providing technical support to write the manuscript in a proper format and approved the final manuscript. CIR guided to write the manuscript in a proper format and approved the final manuscript. MV guided to write the manuscript in a proper format and approved the final manuscript. GAK guided to write the manuscript in a proper format and approved the final manuscript.

Compliance with ethical standards

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Declaration of generative AI and AI-assisted technologies in the writing process

I used AI tools for editing and paraphrasing, not for writing the manuscript.

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