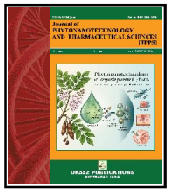
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Nanotechnology enabled fruit preservation: Advances in nanoedible coatings, nanoencapsulation and intelligent packaging

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Abstract

Fruit preservation after harvest remains a major challenge because fresh fruits are highly susceptible to physiological deterioration, moisture loss, ripening, senescence and microbial spoilage. Conventional preservation methods can effectively reduce quality losses; however, limitations associated with chemical residues, environmental sustainability, consumer safety and packaging waste have accelerated the search for innovative and eco-friendly technologies. Nanotechnology has emerged as a promising approach for improving the postharvest quality and shelf life of fresh fruits through the development of nanoenabled preservation and packaging systems. This review critically discusses recent advances in nanoedible coatings, nanoemulsions, nanoencapsulation, nanocellulose based materials, nanocomposite films, active packaging and intelligent packaging for fruit preservation. Particular attention is given to the role of nanomaterials in regulating gas and moisture exchange, reducing microbial growth, controlling ripening, protecting antioxidants and other bioactive compounds, and enabling controlled delivery of functional agents. The potential of nanosensors for monitoring fruit freshness, ripening and spoilage is also highlighted. In addition, the review examines the emerging integration of green nanotechnology with biodegradable and bio-based materials to develop sustainable postharvest systems. Despite their considerable potential, challenges related to nanoparticle migration, toxicological safety, regulatory approval, production cost, standardization and large-scale application remain important barriers to commercialization. Future research should therefore focus on safe-by-design nanomaterials, renewable feedstocks, multifunctional coatings, intelligent sensing technologies and field-scale validation. Overall, nanotechnology offers significant opportunities to develop sustainable, efficient and next-generation preservation strategies capable of reducing postharvest fruit losses while maintaining quality, nutritional value and consumer acceptability.

1. Introduction

Fresh fruits are highly perishable horticultural commodities that remain metabolically active even after harvest. Unlike processed foods, fruits continue to respire, lose water, undergo biochemical changes and respond to environmental conditions during handling, storage, transportation and marketing. Consequently, maintaining fruit quality between harvest and consumption is a major challenge for the postharvest sector. Physiological deterioration, microbial decay, mechanical injury, moisture loss, ripening and senescence are among the major factors responsible for deterioration of fresh fruits (Liu *et al*. (2020); Yousuf *et al*. (2018); Valencia-Chamorro *et al*. (2011)). Postharvest deterioration affects important quality characteristics such as firmness, colour, flavour, nutritional value and visual appearance. Water loss can cause wilting, shrivelling and loss of marketable weight, whereas excessive respiration and ethylene activity can accelerate ripening and senescence. Mechanical injuries occurring during harvesting, grading, packing and transportation further increase susceptibility to microbial infection. Fungal and bacterial pathogens can rapidly colonize damaged tissues, resulting in decay and making fruits unsuitable for consumption. These interacting factors create substantial economic losses throughout the fruit supply chain. (Shapii (2020); Sapper and Chiralt (2018); Cazón *et al*. (2017)). Conventional postharvest technologies, including refrigeration, controlled or modified atmospheres, chemical fungicides, waxing and synthetic packaging, have contributed substantially to maintaining fruit quality. However, their effectiveness may vary according to fruit type, cultivar, storage conditions and distribution period. Increasing consumer demand for minimally processed, residue-free and environmentally sustainable foods has encouraged the development of safer alternatives. In parallel, concerns regarding conventional plastic packaging and the environmental burden associated with persistent packaging materials have stimulated research into biodegradable films and coatings. (Chang *et al*. (2025); Chavan *et al*. (2023))

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In this context, nanotechnology has emerged as an advanced approach for postharvest fruit preservation. Nanomaterials possess unique physicochemical properties arising from their nanoscale dimensions and can be incorporated into edible coatings, packaging materials and controlled delivery systems. Nanoenabled coatings can improve barrier properties, reduce moisture transfer, regulate gas exchange and provide antimicrobial or antioxidant functions. Nanoemulsions are particularly promising as carriers for essential oils and other poorly water-soluble bioactive compounds, while their controlled release characteristics may maintain protective activity during storage.

2. Fundamentals of nanotechnology in postharvest fruit management

Nanotechnology refers to the design, manipulation and application of materials at the nanoscale, generally within the range of approximately 1-100 nm. At this scale, materials can exhibit distinctive physicochemical characteristics, including increased surface area, altered optical behaviour, improved reactivity and enhanced interaction with biological systems. These properties have created new opportunities for the development of advanced food preservation technologies. In postharvest fruit management, nanotechnology is increasingly being explored to control the physiological, biochemical and microbiological processes responsible for quality deterioration and to improve the efficiency of conventional preservation systems. (Das *et al*. (2021); Hassanzadeh (2025); Acevedo-Fani *et al*. (2017)). Nanoencapsulation represents another important principle in postharvest nanotechnology. Bioactive substances such as essential oils, phenolic compounds, antioxidants, vitamins and antimicrobial agents can be enclosed within nanoscale delivery systems. Encapsulation can protect sensitive compounds from oxidation and degradation and may facilitate their gradual or controlled release during storage. This approach is particularly relevant to fruit preservation because the protective activity can potentially be maintained for a longer period than with direct application of free compounds. Nanoemulsions, nanoliposomes, polymeric nanoparticles and other nanoscale carriers have consequently attracted increasing research attention as delivery platforms. (Palanisamy *et al*. (2024); Zhang *et al*. (2024); Nasra *et al*. (2025))

Biopolymer-based nanomaterials are especially important for sustainable postharvest applications. Chitosan, starch, cellulose and other renewable polymers can be combined with nanoscale components to produce films and coatings with improved mechanical, barrier and functional properties. Nanocellulose, including cellulose nanocrystals and cellulose nanofibres, is particularly promising because it can be produced from renewable biomass and horticultural residues. Its incorporation into packaging systems may improve structural strength and barrier performance while supporting the development of biodegradable alternatives to conventional petroleum-based plastics. Nanotechnology also provides a foundation for active and intelligent packaging. Active nano-packaging systems can incorporate antimicrobial, antioxidant or gas-regulating components, whereas intelligent systems can incorporate nanosensors capable of detecting changes associated with ripening, microbial spoilage or environmental conditions. Such technologies could support real-time assessment of fruit quality and facilitate better decisions during storage, transportation and marketing. Recent research has consequently moved from simple preservation toward multifunctional systems combining protection, controlled release and quality monitoring. (Omeroviæ *et al*. (2021); Rout and Pradhan (2024); Zhang *et al*. (2020); Shankar *et al*. (2019); Rhim *et al*. (2013); Espitia *et al*. (2012)). Despite these advantages, the successful application of nanotechnology in postharvest fruit management requires careful evaluation of nanomaterial toxicity, migration into food, environmental fate, consumer exposure, regulatory compliance and economic feasibility. The behaviour of nanomaterials can differ according to particle size, shape, concentration, surface chemistry and interaction with the fruit matrix. Therefore, laboratory-scale evidence must be complemented by standardized safety assessment and large-scale validation before widespread commercial adoption. Overall, nanotechnology provides a versatile platform for designing next-generation fruit preservation systems that combine shelf-life extension, quality retention, reduced chemical inputs and sustainable packaging.

3. Nanomaterials used in fruit preservation

Nanotechnology has emerged as a promising approach for improving the postharvest life, quality and safety of fresh fruits. Nanomaterials possess unique physicochemical properties arising from their very small particle size, large surface area and enhanced reactivity. These characteristics allow them to function as antimicrobial agents, antioxidant carriers, gas and moisture barriers, and delivery systems for bioactive compounds. Recent research indicates that nanotechnology can complement conventional postharvest practices by reducing microbial spoilage, delaying ripening and maintaining physicochemical quality during storage. Zinc oxide (ZnO), titanium dioxide (TiO_2), calcium-based nanoparticles and other metal or metal-oxide nanomaterials have also been investigated for fruit preservation. Depending on their composition and formulation, these materials can provide antimicrobial activity and improve the barrier characteristics of coating or packaging systems. Their effectiveness is influenced by particle concentration, particle size, coating composition, fruit type and storage conditions. Therefore, optimization is necessary to achieve preservation benefits without adversely affecting fruit sensory quality or food safety.

Nanoemulsions and nanocomposites represent another important class of preservation technologies. Nanoemulsions can encapsulate essential oils, antioxidants and other poorly water-soluble bioactive compounds and facilitate their controlled release on fruit surfaces. Chitosan nanoemulsions, for example, have been explored as multifunctional edible coatings for fresh horticultural produce. Cellulose nanomaterials are also gaining interest, particularly as stabilizers of pickering emulsions, where they can improve coating stability, interfacial properties and barrier performance. Recent advances further emphasize nanoedible coatings and active nanocomposite packaging. Incorporating nanomaterials into polysaccharide, protein or lipid matrices can improve mechanical strength, oxygen and moisture barrier properties, antimicrobial performance and controlled release of active compounds. Such systems may help maintain firmness, colour, nutritional constituents and overall acceptability while extending storage life. Nevertheless, commercialization remains dependent on establishing appropriate nanoparticle concentrations, migration limits, toxicological profiles, regulatory standards and consumer acceptance. Future research should therefore focus on food-grade and biodegradable nanomaterials, green synthesis, standardized safety evaluation and scalable processing

technologies. Overall, nanomaterials offer considerable potential for sustainable fruit preservation, but their successful adoption requires a balance between preservation efficiency, environmental sustainability and food safety.

4. Green synthesis of nanoparticles for food applications

Green synthesis of nanoparticles has emerged as an environmentally responsible alternative to conventional physical and chemical approaches for producing functional nanomaterials for the food sector. Conventional nanoparticle synthesis may require toxic reducing agents, hazardous solvents, high energy input and multiple purification steps. In contrast, green synthesis uses biological resources such as plant extracts, microorganisms, algae, enzymes and agro-industrial residues as reducing, stabilizing and capping agents. This approach can reduce the environmental burden associated with nanoparticle production while providing materials with useful biological properties. Recent reviews have highlighted plant-based and waste derived synthesis as particularly promising routes for sustainable nanotechnology (Khan *et al*. (2025); Shafiq (2025)). Another emerging application is the development of nano-enabled sensors for monitoring food quality and safety. Green nanoparticles can contribute to sensing platforms capable of detecting microbial contamination, toxins, allergens and other indicators of food deterioration. Their integration with smart packaging may provide real-time or visual information about changes occurring during storage. Consequently, green nanotechnology is moving beyond simple preservation toward multifunctional food systems that combine protection, monitoring and controlled delivery (Arslantürk *et al*. (2026); Anand *et al*. (2026)).

Despite these advantages, several challenges must be addressed before large-scale food applications become routine. Variations in plant species, extraction conditions and phytochemical composition can affect nanoparticle reproducibility. Precise control over particle size, shape, surface characteristics, stability and concentration is therefore essential. In addition, nanoparticle migration, bioavailability, toxicity, environmental fate and long-term exposure require systematic evaluation. Regulatory frameworks and standardized analytical methods are also necessary to ensure that green-synthesized nanomaterials used in food-contact applications are safe for consumers. Overall, green synthesis provides a promising pathway for developing safer, more sustainable and potentially cost-effective nanomaterials for food applications. Future research should emphasize reproducible synthesis, utilization of agricultural waste, biodegradable nanocomposites, food-grade materials, controlled-release systems and comprehensive toxicological evaluation. Integration of green nanoparticles with edible coatings, active packaging and smart food-sensing technologies could contribute substantially to reducing food losses while supporting sustainable food-processing systems.

5. Nanoedible coatings for fruit shelf-life extension

Nanoedible coatings have emerged as an advanced postharvest technology for extending the shelf life of fresh fruits while maintaining their nutritional, physicochemical and sensory quality. Conventional edible coatings based on polysaccharides, proteins, lipids and waxes can provide a protective barrier, but their performance may be limited by weak mechanical properties, poor moisture resistance or insufficient antimicrobial activity. Incorporation of nanoscale materials can improve these characteristics by increasing surface area, modifying barrier properties and enabling more controlled delivery of functional compounds. Thus, nanoedible coatings are increasingly being investigated as multifunctional systems for reducing postharvest losses (Zhang (2024); Wang *et al*. (2023); Abdalla (2023)). A nanoedible coating generally consists of a food-compatible biopolymer matrix combined with nanoparticles, nanoemulsions or encapsulated bioactive compounds. Chitosan, alginate, starch, cellulose derivatives, pectin, gelatin and other biodegradable polymers are commonly considered coating materials. Chitosan is particularly attractive because it possesses inherent antimicrobial properties and film-forming ability. At the nanoscale, chitosan-based systems can provide improved dispersion of active compounds and enhanced interaction with the fruit surface. Nanoemulsions containing essential oils or plant-derived compounds can further increase the stability and effectiveness of hydrophobic bioactive ingredients (Das *et al*. (2021); Hassanzadeh (2025)).

Nanoedible coatings can also act as delivery systems for antioxidants and other bioactive compounds. Nanoencapsulation may protect sensitive compounds from oxidation and improve their dispersion, stability and controlled release. Essential oils, phenolic compounds, organic acids and plant extracts have therefore been incorporated into nanoscale coating systems. Such approaches may help preserve antioxidant activity and nutritional quality while simultaneously providing antimicrobial protection. Recent research has particularly emphasized multifunctional coatings that combine preservation, antioxidant protection and controlled release within a single biodegradable system. Despite their considerable potential, several challenges remain before nanoedible coatings can be widely commercialized. Particle size, concentration, coating thickness, surface properties, release behaviour and interaction with fruit tissues can strongly influence preservation efficiency. Large-scale production must also provide consistent coating characteristics and acceptable cost. Most importantly, comprehensive studies are required to evaluate nanoparticle migration, dietary exposure, toxicological effects, environmental fate and consumer acceptance. Standardized protocols and clear regulatory frameworks will be essential for translating laboratory-scale findings into practical food applications. Overall, nanoedible coatings represent a promising next-generation postharvest technology for extending fruit shelf life. Their ability to combine moisture and gas regulation, antimicrobial activity and controlled delivery of bioactive compounds makes them particularly attractive for sustainable fruit preservation. Future research should prioritize food-grade and biodegradable nanomaterials, green synthesis approaches, low-dose formulations and commodity-specific coating systems. Integration of nanoedible coatings with modified-atmosphere packaging, cold storage and intelligent packaging could provide an effective strategy for reducing postharvest fruit losses while maintaining quality and food safety.

7. Nanoemulsions as carriers of bioactive compounds

Nanoemulsions have gained considerable attention as advanced delivery systems for improving the stability, dispersibility and functional performance of bioactive compounds in food and postharvest applications. A nanoemulsion is a colloidal dispersion in which one immiscible phase is distributed within another as very small droplets, generally in the nanometre range. Their small droplet size provides a large interfacial area and can improve the physical stability, dispersion and bioavailability of poorly water-soluble

compounds. Consequently, nanoemulsions are increasingly being explored for incorporating natural antioxidants, antimicrobial agents, essential oils, vitamins, pigments and other functional phytochemicals into food systems and edible coatings (Acevedo-Fani *et al*. (2017); Sharma *et al*. (2024)). Many important plant-derived bioactive compounds have limited water solubility, chemical instability or susceptibility to oxidation. Phenolic compounds, carotenoids, essential oils and certain vitamins can readily undergo degradation when exposed to oxygen, light, heat or unfavourable pH conditions. Nanoemulsion-based encapsulation can provide a protective environment around these compounds and reduce their exposure to adverse environmental conditions. The interfacial layer formed by emulsifiers or biopolymers can further influence the release and stability of the encapsulated compounds. This makes nanoemulsions particularly useful for delivering sensitive phytochemicals without substantially altering their functional properties (Panwar *et al*. (2024); Abdalla (2023)). In fruit preservation, nanoemulsions can serve as carriers for essential oils and plant extracts with antimicrobial and antioxidant activity. Essential oils from sources such as thyme, cinnamon, clove, oregano and citrus possess compounds capable of inhibiting microorganisms responsible for postharvest deterioration. However, direct application of essential oils may be restricted by their strong aroma, volatility, poor water dispersibility and rapid loss from the fruit surface. Incorporating these compounds into nanoemulsions can improve their dispersion in aqueous coating formulations and facilitate more uniform distribution over fruit surfaces. Controlled release from the nanoemulsion may also prolong their protective activity during storage.

Nanoemulsions can additionally improve the performance of edible coatings and active packaging systems. When incorporated into matrices based on chitosan, alginate, pectin, starch, cellulose derivatives or other biodegradable polymers, they can contribute to the development of multifunctional coatings. Such systems may simultaneously provide moisture regulation, antioxidant protection and antimicrobial activity. The interaction between the nanoemulsion droplets and the polymer matrix can influence coating thickness, surface characteristics, mechanical properties and permeability to gases and water vapour. Therefore, the formulation of the carrier system is an important determinant of preservation efficiency. Overall, nanoemulsions represent a promising platform for the efficient delivery of natural bioactive compounds in fruit preservation and functional food systems. Their ability to improve the dispersibility, stability and controlled release of poorly soluble compounds provides opportunities for reducing postharvest deterioration while maintaining fruit quality. Future research should focus on green and food-grade emulsification methods, utilization of plant-derived emulsifiers, integration with nanoedible coatings, synergistic combinations of antioxidants and antimicrobials, and scale-up of stable formulations. Such developments could facilitate the transition of nanoemulsion-based preservation from laboratory research to commercially viable and sustainable postharvest technologies.

8. Nanoencapsulation of antioxidants, essential oils and nutraceuticals

Nanoencapsulation has emerged as an important nanotechnology-based strategy for improving the stability, dispersibility, bioaccessibility and functional performance of sensitive food bioactive compounds. Many naturally occurring compounds, including polyphenols, carotenoids, flavonoids, vitamins, essential oils and other nutraceuticals, possess considerable health-promoting potential but are often limited by poor water solubility, oxidation, volatility, sensitivity to light and heat, and degradation during food processing and storage. Nanoencapsulation addresses these limitations by entrapping the active compound within a nanoscale carrier, thereby providing protection and facilitating controlled release (Das *et al*. (2021); Acevedo-Fani *et al*. (2017)). Antioxidants such as curcumin, quercetin, resveratrol, catechins, anthocyanins and carotenoids are important targets for nanoencapsulation. Although, these compounds exhibit antioxidant and other biological activities, their practical application can be restricted by low aqueous solubility and chemical instability. Lipid nanoparticles, nanoemulsions, liposomes and biopolymer-based nanocarriers can improve their dispersion and protect them from oxidation and environmental stress. The small size of the carrier system can also increase the surface area available for interaction with the surrounding food matrix and gastrointestinal environment, potentially improving bioaccessibility (Odetayo *et al*. (2022); Hassanzadeh (2025)).

Essential oils are another important group of bioactive compounds suitable for nanoencapsulation. Oils obtained from cinnamon, clove, oregano, thyme, lemongrass and other aromatic plants contain compounds with antimicrobial, antioxidant and antifungal properties. However, their high volatility, strong flavour, poor water solubility and sensitivity to environmental conditions can limit direct incorporation into foods. Nanoemulsions, liposomes and solid lipid nanoparticles can protect essential oils from premature evaporation and degradation while improving their dispersion in aqueous food systems. Nanoencapsulated essential oils may therefore provide prolonged antimicrobial activity at lower effective concentrations, which is particularly relevant for food preservation and active packaging.

For fruit preservation, nanoencapsulated antioxidants and essential oils can be incorporated into edible coatings and active packaging. Such systems can provide a protective layer on the fruit surface and simultaneously deliver antimicrobial and antioxidant compounds. This approach may help reduce microbial growth, oxidative deterioration, moisture loss and quality deterioration during storage. The use of biodegradable materials such as chitosan, alginate, pectin, starch, cellulose derivatives and plant proteins is particularly attractive for developing sustainable delivery systems. Recent research is also emphasizing food-waste-derived and plant-based carrier materials as alternatives to conventional synthetic components. Despite these advantages, safety, stability, regulatory acceptance and scalability remain important challenges. The physicochemical properties of nanoparticles can influence their behaviour within different food matrices, and interactions between nanocarriers and food components may affect bioavailability and functionality. Therefore, comprehensive assessment of particle characteristics, digestion behaviour, nanoparticle migration, toxicity and long-term exposure is necessary. Future research should focus on food-grade materials, green production methods, sustainable carriers, controlled-release systems and validation in real food products rather than relying solely on laboratory models.

9. Nanocellulose-based coatings and packaging materials

Nanocellulose has emerged as a promising bio-based nanomaterial for sustainable food and fruit packaging because of its renewability, biodegradability, high specific surface area, excellent mechanical strength and tunable surface chemistry. It can be obtained from lignocellulosic biomass and is generally classified into cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs) and bacterial cellulose (BC). Agricultural residues such as fruit peels, straw, bagasse, shells and other plant-derived wastes are increasingly being explored as inexpensive feedstocks for nanocellulose production, creating opportunities to integrate waste valorization with sustainable packaging development (Palanisamy *et al*. (2024); Wardana *et al*. (2025)). The distinctive structure of nanocellulose makes it particularly suitable for developing thin films, edible coatings and nanocomposite packaging materials. Nanocellulose possesses a strong hydrogen-bonded network that can improve the mechanical strength and structural integrity of polymeric packaging matrices. When incorporated into biopolymers such as starch, chitosan, alginate, pectin, cellulose derivatives, gelatin and other natural polymers, it can act as a reinforcing nanofiller and produce stronger and more functional composite films. Recent studies have demonstrated improvements in mechanical, thermal, oxygen-barrier and ultraviolet-barrier properties of nanocellulose-based packaging systems. An important application is the development of nanocellulose-based coatings for fresh fruits and vegetables. A thin coating deposited on the produce surface can provide a semi-permeable barrier that influences moisture transfer and respiratory gas exchange. Appropriate regulation of oxygen and carbon dioxide movement can help slow metabolic processes, while reduced water loss may assist in maintaining firmness and fresh appearance. The performance of such coatings depends on nanocellulose type, concentration, coating thickness, polymer composition and storage conditions. Consequently, formulation optimization is necessary to obtain sufficient protection without causing undesirable anaerobic conditions or sensory changes (Palanisamy *et al*. (2024); Nasra *et al*. (2025)).

The use of agricultural waste for nanocellulose production further strengthens its sustainability potential. Converting fruit residues, crop straw, bagasse and other lignocellulosic wastes into CNC or CNF can generate value-added materials while reducing dependence on petroleum-derived plastics. However, challenges related to extraction chemicals, energy consumption, scale-up, reproducibility, cost, moisture sensitivity, nanoparticle migration and food-contact safety must be addressed. Appropriate toxicological assessment and standardized regulatory approaches are particularly important before widespread commercial implementation. Overall, nanocellulose-based coatings and packaging materials represent an important direction in next-generation sustainable food preservation. Their combination of biodegradability, mechanical reinforcement, barrier enhancement and compatibility with active compounds provides opportunities for extending the shelf life of fruits and other perishable foods. Future research should focus on low-energy and green production methods, agricultural-waste-derived nanocellulose, moisture-resistant formulations, controlled release of bioactives, intelligent packaging and validation under real commercial storage conditions.

10. Chitosan-based nanocomposites for fruit preservation

Chitosan-based nanocomposites have emerged as promising bio-based materials for postharvest fruit preservation, combining the natural functionality of chitosan with the enhanced properties of nanoscale fillers and bioactive compounds. Chitosan is obtained mainly by deacetylation of chitin and is attractive for food applications because of its biodegradability, film-forming capacity, biocompatibility and intrinsic antimicrobial activity. However, conventional chitosan films may have limitations in mechanical strength and barrier performance. Incorporation of nanoparticles, nanocellulose, essential oils and other functional ingredients can overcome some of these limitations and generate multifunctional preservation systems (Wang *et al*. (2023); Abdalla (2023)). Chitosan nanoparticles (ChiNPs) are particularly important because reducing chitosan to the nanoscale can modify its surface characteristics and functional performance. Research has shown that chitosan nanoparticles can improve postharvest antioxidant capacity, nutritional quality and storage life while reducing the incidence of postharvest pathogens. Smaller particles may provide greater surface area and improved interaction with fruit tissues, although, their effectiveness depends strongly on particle characteristics, formulation and fruit species. Chitosan nanoparticles can be applied directly as dispersions or incorporated into films and coatings (Omeroviæ *et al*. (2021); Rout and Pradhan (2024))

The incorporation of essential oils and plant-derived bioactive compounds provides another route for developing multifunctional chitosan nanocomposites. Essential oils from clove, cinnamon, oregano, thyme and other plants possess antimicrobial and antioxidant properties but may be volatile, poorly water-dispersible and susceptible to rapid loss. Encapsulation within chitosan nanoparticles or their incorporation into chitosan nanocomposite coatings can improve their distribution and potentially provide a more sustained release. Such combinations may enhance protection against fungal pathogens while also reducing oxidative deterioration of fruit tissues. Nanocomposites can also contain metal and metal-oxide nanoparticles, nanocellulose and other reinforcing nanomaterials. These components can contribute antimicrobial activity, mechanical reinforcement, improved barrier characteristics or UV protection. Nanocellulose, for example, can strengthen the polymer network, whereas selected inorganic nanoparticles may provide additional antimicrobial functionality. However, the choice and concentration of nanoparticles require careful optimization because excessive loading may affect coating transparency, fruit appearance, sensory properties or food-contact safety.

11. Metal and metal oxide nanoparticles for antimicrobial protection

Metal and metal oxide nanoparticles have attracted considerable interest as advanced antimicrobial agents for food preservation and postharvest management. Their incorporation into edible coatings, active packaging films and nanocomposite materials provides an opportunity to control microbial deterioration while reducing dependence on conventional chemical preservatives. Among the extensively investigated materials, silver (Ag), zinc oxide (ZnO), copper oxide (CuO), titanium dioxide (TiO_2) and magnesium oxide (MgO) nanoparticles have demonstrated antimicrobial activity against a broad range of food-associated bacteria and fungi. Their effectiveness is generally related to their nanoscale dimensions, high surface-to-volume ratio and ability to interact closely with microbial cells. (Omeroviæ *et al*. (2021)) Silver nanoparticles (AgNPs) are among the most studied antimicrobial nanomaterials. They can inhibit

microorganisms through several simultaneous mechanisms, including interaction with cell membranes, disruption of membrane permeability, generation of reactive oxygen species and interference with essential cellular processes. AgNPs can also release silver ions, which contribute to antimicrobial activity. When incorporated into biodegradable polymer matrices such as chitosan, cellulose, starch and other biopolymers, they can produce active packaging materials with improved microbial protection. For fruit preservation, such systems have potential to suppress spoilage microorganisms and thereby delay deterioration during storage (Omeroviæ *et al*. (2021)).

Zinc oxide nanoparticles (ZnO-NPs) have received particular attention because zinc is an essential micronutrient and ZnO possesses antimicrobial and ultraviolet-screening properties. Their antimicrobial activity has been associated with reactive oxygen species generation, membrane damage and release of $Zn^{2}z$ ions. ZnO nanoparticles can be incorporated into edible coatings and polymeric films to improve their functional performance. Studies involving fresh produce have reported reductions in microbial populations and improvements in selected quality attributes following application of ZnO-containing formulations. However, concentration, particle characteristics and coating composition must be carefully optimized to avoid undesirable effects on fruit quality (Omeroviæ *et al*. (2021)). Copper oxide nanoparticles (CuO-NPs) provide another promising antimicrobial platform. Copper-based nanoparticles can interact with microbial membranes and promote oxidative stress, ultimately impairing cellular metabolism. Their relatively strong antimicrobial properties make them candidates for active packaging and surface-coating applications. Nevertheless, excessive copper exposure may raise food-safety and toxicity concerns. Therefore, the use of CuO nanoparticles in food-contact systems requires appropriate control of particle concentration, migration and consumer exposure.

Titanium dioxide nanoparticles (TiO_2 – NPs) have also been investigated because of their photocatalytic activity. Under appropriate light conditions, TiO_2 can generate reactive oxygen species capable of damaging microbial cells. This property has encouraged its investigation in antimicrobial packaging and surface treatments. However, the dependence of photocatalytic activity on light conditions and concerns regarding nanoparticle migration and safety need to be considered when developing food-contact applications. Consequently, immobilization within polymer matrices and careful assessment of exposure are important research areas.

12. Nanotechnology for controlling fruit ripening and ethylene action

Fruit ripening is a genetically regulated physiological process involving coordinated changes in ethylene production, respiration, cell-wall degradation, pigment metabolism, sugar accumulation and aroma formation. Although, ripening is essential for developing desirable eating quality, excessive or uncontrolled ripening after harvest can result in rapid softening, senescence, microbial deterioration and substantial postharvest losses. Nanotechnology offers new possibilities for regulating these processes through nanoscale delivery systems, active packaging, gas-management materials and nanostructured coatings. Unlike conventional postharvest treatments, nano-enabled approaches can provide more controlled interactions between the fruit surface and its surrounding atmosphere, potentially allowing gradual regulation of ripening-related processes (Liu *et al*. (2020))

Another promising strategy involves the use of nano-enabled delivery systems for ripening regulators. Nanocarriers can encapsulate compounds such as 1-methylcyclopropene (1-MCP), plant-derived bioactive compounds, antioxidants and other postharvest regulators. Encapsulation can improve stability and provide gradual release, potentially maintaining an effective concentration for a longer period. In the case of 1-MCP, which interferes with ethylene perception by binding to ethylene receptors, nanoformulations could potentially provide more controlled delivery than conventional application methods. Such approaches may be especially useful when prolonged ethylene inhibition is required during transportation and storage (Chang *et al*. (2025))

Nanoedible coatings can regulate ripening through a different mechanism. A coating containing chitosan, alginate, cellulose nanomaterials, starch or other biodegradable polymers can form a thin semi-permeable layer over the fruit surface. Appropriate modification of oxygen and carbon dioxide diffusion may reduce respiration intensity and metabolic activity. Simultaneously, reduced water loss can help maintain firmness and appearance. Incorporating nanoparticles or nanoemulsions containing antioxidants and antimicrobial compounds can provide additional protection against oxidative stress and microbial deterioration. The coating must nevertheless permit sufficient gas exchange because excessive restriction can induce anaerobic respiration and off-flavour development. Nanotechnology also provides opportunities for ethylene-responsive and intelligent packaging. Nanostructured sensors containing functional nanomaterials can potentially detect changes in ethylene concentration and provide information about fruit maturity. Such systems could be integrated into smart packages that indicate ripening status and storage conditions. In the future, combining sensing with active ethylene removal may produce packaging capable of monitoring and responding to changes in the fruit microenvironment. This concept represents a transition from passive packaging toward responsive postharvest management.

13. Nanoenabled delivery systems for controlled release of preservatives

Nanoenabled delivery systems are increasingly being investigated as advanced approaches for improving the effectiveness and controlled application of preservatives in food and postharvest fruit systems. Conventional preservatives may undergo rapid degradation, evaporation, oxidation or diffusion after application, resulting in a short period of protection and, in some cases, the need for repeated treatments. Nanotechnology can address these limitations by incorporating preservatives into nanoscale carriers that protect the active compounds and regulate their movement into the surrounding food matrix. Such systems can improve the stability, dispersion, retention and functional activity of antimicrobial and antioxidant substances while potentially reducing the quantity required for effective preservation (Hassanzadeh (2025); Rout and Pradhan (2024)). The release of a preservative from a nanocarrier is governed by several factors, including **particle size, surface characteristics, carrier composition, diffusion properties, temperature, pH, moisture and interactions with the food matrix.** By modifying these parameters, researchers can design systems that provide rapid initial protection or prolonged release according to the requirements of a particular food. Stimuli-responsive nanocarriers offer an additional level of control, with release potentially triggered by changes in pH,

temperature, enzymes or other environmental conditions. Such systems could minimize unnecessary release while providing preservatives when deterioration conditions become favourable (Omeroviæ *et al*. (2021)).

For fruit preservation, nano-enabled delivery systems can be incorporated into edible coatings, films and active packaging. A coating containing nanoencapsulated antimicrobial compounds can form a protective barrier while gradually releasing the active ingredient onto the fruit surface. Simultaneously, the coating may reduce moisture loss and regulate respiratory gas exchange. Combining antimicrobial preservatives with antioxidants can provide dual protection against microbial growth and oxidative deterioration. Nano-enabled systems can therefore contribute to maintaining fruit firmness, colour, nutritional compounds and overall sensory quality during storage. Another important advantage is the possibility of reducing preservative dosage. Because nanoscale carriers can improve the dispersion and surface availability of active substances, effective antimicrobial activity may be achieved using lower concentrations than those required for direct application. This could help reduce strong sensory effects associated with some essential oils and minimize unnecessary exposure to preservatives. Nevertheless, lower dosage should not be assumed to guarantee safety; the biological activity, migration behaviour and toxicity of both the active compound and nanocarrier must be independently evaluated.

Despite their potential, several challenges limit the transition of nanoenabled delivery systems from laboratory research to commercial applications. Long-term physical stability, controlled-release reproducibility, nanoparticle migration, gastrointestinal behaviour, toxicological effects, regulatory acceptance and consumer perception require systematic investigation. Food composition can also alter the release behaviour of nanocarriers, making results obtained in simplified laboratory systems difficult to extrapolate to real foods. Standardized methods for characterizing particle size, encapsulation efficiency, release kinetics and food-contact migration are therefore essential. Future research should emphasize food-grade and biodegradable nanocarriers, green production techniques, natural preservatives and sustainable packaging materials. Combining nanoencapsulation with chitosan coatings, nanocellulose films, modified-atmosphere packaging and cold storage could create integrated preservation systems with complementary mechanisms. Overall, nanoenabled controlled-release technology offers considerable potential for improving preservative efficiency, extending fruit shelf life and reducing postharvest losses. However, successful commercialization will depend on achieving an appropriate balance between controlled preservation, material safety, environmental sustainability, cost and consumer acceptance.

14. Nanotechnology for prevention of microbial spoilage and postharvest diseases

Microbial spoilage is one of the major causes of postharvest losses in fresh fruits, particularly because harvested produce remains physiologically active and is highly susceptible to invasion by bacteria, yeasts and filamentous fungi. Mechanical injuries, physiological disorders, high relative humidity and unsuitable storage temperatures can create favourable conditions for microbial colonization. Important postharvest pathogens such as *Botrytis cinerea*, *Penicillium* spp., *Monilinia* spp., *Colletotrichum* spp. and *Rhizopus* spp. can rapidly develop on damaged fruit surfaces, resulting in softening, tissue discoloration, off-flavours, nutrient deterioration and reduced marketability. Conventional chemical fungicides can provide effective disease control, but repeated application may raise concerns related to chemical residues, pathogen resistance, environmental contamination and consumer acceptance. Consequently, nanotechnology has emerged as an innovative approach for developing efficient, low-dose and multifunctional antimicrobial systems for postharvest disease management (Wang *et al*. (2023); Rout and Pradhan (2024)).

Nanotechnology also facilitates the development of nano-enabled edible coatings. Incorporating nanoparticles into edible polymer matrices such as chitosan, alginate, cellulose derivatives, starch and protein-based materials can improve coating integrity and antimicrobial performance. Such coatings form a protective layer on the fruit surface, reducing direct contact between pathogens and host tissues while modifying oxygen and carbon dioxide transfer and reducing moisture loss. Nanoparticles can additionally act as reservoirs for antimicrobial compounds, allowing their gradual release during storage. Recent research has highlighted the potential of chitosan nanoparticle-stabilized Pickering emulsions to provide antimicrobial activity together with improved barrier properties, thereby delaying microbial growth and fruit deterioration (Das *et al*. (2021); Odetayo *et al*. (2022)). Nanoencapsulation of natural antimicrobial agents represents another important strategy. Essential oils and plant-derived phenolic compounds possess strong antifungal and antibacterial properties but may suffer from volatility, oxidation, poor water dispersibility and instability during storage. Encapsulation within nanoemulsions, nanoliposomes, polymeric nanoparticles or other nanoscale carriers can improve their stability and dispersion while facilitating controlled delivery. This approach may permit effective antimicrobial concentrations to be maintained at the fruit surface for longer periods while reducing the quantity of active compound required. Combining nanocarriers with natural antimicrobials therefore offers a potential alternative to intensive synthetic fungicide use (Wang *et al*. (2023)).

15. Nanotechnology for maintaining fruit quality and nutritional attributes

Maintaining the physicochemical, sensory and nutritional quality of fruits after harvest is a major challenge because harvested fruits continue to undergo respiration, transpiration, ripening and biochemical transformations. These processes can lead to loss of firmness, colour deterioration, depletion of vitamins and phenolic compounds, reduction in antioxidant activity and development of undesirable flavours. Conventional cold storage and packaging can slow these changes, but their effectiveness is often influenced by fruit type, storage conditions and duration. Nanotechnology has emerged as an advanced postharvest approach capable of simultaneously controlling physiological deterioration, microbial growth and the loss of nutritionally important compounds. Recent reviews indicate that nanoenabled coatings, nanoemulsions, nanocomposites and controlled-release systems can improve the quality retention and storage stability of fresh produce (Zhang (2024); Wang et al. (2023)). One of the principal mechanisms through which nanotechnology maintains fruit quality is the formation of nanoengineered edible coatings. Nanoparticles incorporated into biodegradable polymers such as chitosan, alginate, starch, cellulose derivatives and proteins can modify the barrier characteristics of the

coating. These systems regulate the movement of oxygen, carbon dioxide and water vapour between the fruit and surrounding atmosphere, thereby reducing excessive respiration and moisture loss. The resulting modification of the internal atmosphere can delay ripening, maintain firmness and reduce shrivelling. Nanoedible coatings have therefore attracted considerable attention as multifunctional systems for maintaining freshness while extending marketable shelf life (Yousuf *et al*. (2018); Chavan *et al*. (2023))

Fruit firmness and texture are important indicators of consumer acceptance and are closely associated with cell-wall degradation during ripening. Nanotechnology can delay softening by reducing respiration and water loss and, in some formulations, by maintaining the structural integrity of pectic and hemicellulosic components. Chitosan nanoparticles and nanocomposite coatings have shown potential for preserving tissue firmness by creating a semi-permeable protective barrier. In addition, nanoemulsion based coatings can improve the uniformity and stability of active compounds on fruit surfaces, supporting more effective preservation during storage (Das *et al*. (2021); Panwar *et al*. (2024)).

Nanotechnology also contributes to the preservation of vitamins and bioactive compounds. Fruits contain valuable nutritional components such as ascorbic acid, carotenoids, phenolic acids, flavonoids and anthocyanins, but many of these compounds are susceptible to oxidation and degradation. Nanoencapsulation can protect sensitive bioactive substances from oxygen, light and other environmental stresses and may provide gradual release of active compounds. Nanoemulsions are particularly useful for dispersing poorly water-soluble phytochemicals and essential oils, potentially improving their stability and functional effectiveness. Recent research describes nanoemulsion based coatings as promising systems for retaining functional attributes while reducing postharvest losses. Antioxidant capacity is closely associated with nutritional quality and postharvest stress tolerance. Harvesting and storage can generate reactive oxygen species, which accelerate membrane damage and degradation of cellular components. Certain nanoenabled treatments may reduce oxidative stress by limiting exposure to oxygen and by incorporating antioxidant compounds into protective coatings. Chitosan-based nanoparticles, plant-derived nanoparticles and nanoencapsulated phytochemicals may additionally interact with fruit defense mechanisms and antioxidant metabolism. Thus, nanotechnology can contribute not only to the physical preservation of fruit but also to the maintenance of its biochemical quality.

16. Future prospects

The future of nanotechnology-enabled fruit preservation lies in developing multifunctional, affordable, safe, and environmentally sustainable systems that can be integrated into commercial postharvest operations. Future research should prioritize biodegradable nanoedible coatings derived from chitosan, alginate, cellulose, starch, pectin, and other renewable biopolymers. Incorporating essential oils, plant extracts, and natural antioxidants into these coatings may improve antimicrobial activity, reduce oxidative deterioration, and maintain fruit firmness, colour, and nutritional quality. Optimization of coating composition, thickness, permeability, and sensory characteristics will be essential for their successful application across diverse fruit commodities. Advanced nanoencapsulation systems offer opportunities to protect sensitive bioactive compounds from oxidation, volatilization, and degradation while enabling controlled release during storage. Future investigations should explore biopolymer-based nanoparticles, nanoemulsions, and other suitable delivery systems for improving the stability and effectiveness of natural preservatives. Simultaneously, intelligent packaging incorporating nanosensors and responsive indicators could facilitate real-time monitoring of ethylene, temperature, humidity, gases, and spoilage-associated metabolites. Integration with the Internet of Things, artificial intelligence, and predictive modelling may enable more accurate shelf-life estimation, early spoilage detection, and improved cold-chain management. Food safety and regulatory compliance will remain critical research priorities. Comprehensive investigations into nanoparticle migration, toxicological effects, environmental fate, and interactions with fruit tissues are necessary to establish safe application limits. Standardized testing procedures and harmonized regulatory frameworks should support responsible commercialization. Furthermore, pilot-scale trials, cost-benefit analyses, and life-cycle assessments are needed to determine economic feasibility, industrial scalability, and environmental performance.

Future innovations should also emphasize agricultural waste valorization by utilizing fruit peels, seeds, and other processing residues as sources of biopolymers and bioactive compounds. Developing fruit-specific preservation strategies and affordable technologies for smallholder farmers could improve accessibility, particularly in developing countries. Consumer acceptance should be strengthened through transparent communication and scientifically supported safety assessments. Ultimately, integrating nanoedible coatings, nanoencapsulation, and intelligent packaging with sustainable postharvest practices could reduce food losses, preserve nutritional quality, improve supply-chain efficiency, and contribute to global food security.

17. Conclusion

Nanotechnology-enabled fruit preservation represents a promising advancement in postharvest management, offering innovative approaches to extending shelf life, maintaining nutritional quality, and minimizing postharvest losses. The integration of nanoedible coatings, nanoencapsulation, and intelligent packaging technologies provides multifunctional solutions for preserving fruit quality throughout storage, transportation, and marketing. Future developments should prioritize biodegradable and biocompatible materials, plant-derived bioactive compounds, cost-effective manufacturing processes, and environmentally sustainable packaging solutions. Integration with artificial intelligence, digital sensing, and predictive modelling could further improve shelf-life estimation and quality management. Life-cycle assessment and economic feasibility studies will also be important for evaluating their long-term benefits. Overall, nanotechnology offers considerable potential to transform fruit preservation by combining improved quality retention, food safety, and reduced wastage. However, successful implementation will depend on balancing technological innovation with scientific validation, regulatory compliance, environmental responsibility, and consumer acceptance. Responsible development and commercialization of these technologies could contribute significantly to sustainable food systems and global food security.

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Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

M. Kabilan and K. Sundharaiya: Supervision, academic oversight and overall monitoring of the research work; **R.V. Sundarrajan and T. Anitha:** Conceptualization, supervision, critical review and overall guidance of the manuscript; **Adnan A. Khan:** Critical review, validation of scientific content and final approval of the manuscript.

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