ISSN (E): 2583 – 0821

Sun. Agri.:e- Newsletter, (2025) *5*(9), 66-70

Article ID: 440

Use of Nanotechnology in Post-Harvest Management of Fruits

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Open Access

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Available online at
www.sunshineagriculture.vitalbiotech.org

Article History
Received: 1. 09.2025
Revised: 5. 09.2025
Accepted: 10. 09.2025

INTRODUCTION

Fruit post-harvest management is an important horticultural production aspect, as fruits are a highly perishable product that experiences quick physiological, biochemical, and microbial transition once they are harvested. Such transitions tend to result in massive quantitative and qualitative losses if not coupled with appropriate handling and preservation practices. Post-harvest losses of fruits during storage, transport, distribution, and marketing in developing nations have been reported to be between 20–40%, representing a significant threat to food security, farmer incomes, and sustainable supply chains.

Conventional methods like cold storage, chemical treatment, irradiation, and modified atmosphere packaging have been extensively used to ensure fruit quality and shelf life extension. These conventional methods are also often limited by their high cost, energy consumption, environmental implications, and health risks associated with chemical residues. The methods may also fail to achieve good protection from microbial infection, oxidative spoilage, and high-rate ripening, all of which contribute to the deterioration of fruit quality during post-harvest handling.

In this regard, nanotechnology has become a groundbreaking strategy in post-harvest management. Through manipulation of materials at the nanolevel (1–100 nm), it is feasible to leverage distinctive properties like increased surface area, high reactivity, increased barrier strength, and controlled release of active ingredients. These properties enable nanotechnology to be extremely efficient in resolving the limitations of traditional methods. Applications are nanocoatings as edible protective films, nano-enabled antimicrobial and freshness-sensing packaging, real-time quality monitoring nanosensors, and nanocarriers for controlled release of natural preservatives.

Therefore, nanotechnology presents a novel, safe, and sustainable route to minimize post-harvest losses, increase shelf life of fruit, and provide a guarantee for the availability of high-quality produce from farm to table. Its incorporation into horticultural supply chains not only solves food security issues but also supports environmental sustainability and public health.

ISSN (E): 2583 – 0821

Role of Nanotechnology in Post-Harvest Management

Nanotechnology is the design, characterization, and application of materials at the nanolevel (1–100 nm). Materials at this level display novel physical, chemical, and biological properties distinct from the properties of their bulk equivalent. In the post-harvest management of fruits, nanotechnology brings advanced solutions to the problems of spoilage, microbial contamination, and quality loss. Its key roles can be emphasized as below:

Nanopackaging for Extended Shelf Life

Active Packaging: Addition of nanoparticles like silver, zinc oxide, and titanium dioxide to packaging materials provides antimicrobial and antioxidant functionality. It inhibits microbial growth and retards ripening.

Smart Packaging: Nanotechnology makes it possible to create smart packaging that can track fruit freshness through pH, temperature, or gas emission (e.g., ethylene release) indicators. Smart packaging can inform consumers and retailers regarding spoilage.

Barrier Properties: Nanoclays and biodegradable nanocomposites enhance packaging through increased gas, moisture, and UV light resistance, thus preserving fruit quality during transportation and storage.

Nano-Coatings for Preservation

Edible nano-coatings consisting of natural polymers (chitosan, alginate, starch, proteins) with enhanced nanoparticles can create a barrier film on the surface of fruit. These coatings limit water loss, slow oxidation, and give antimicrobial protection while being safe to eat. For instance, chitosan nanoparticles infused with essential oils were used effectively on mangoes and bananas to enhance shelf life without affecting taste or appearance.

Controlled Release Systems

Nanomaterials can be used as a carrier system for controlled release of bioactive agents like antioxidants, antimicrobials, and ethylene inhibitors. It provides for a slow and targeted release of the preservative, minimizing the use of too much chemical application while keeping the fruit fresh for extended periods.

Detection of Spoilage and Contamination

Nanosensors embedded in packaging or storage conditions may respond to shifts in gases such as CO_2, O_2, or ethylene that signal ripening or spoilage. They may also determine the presence of dangerous pathogens (such as E. coli, Salmonella) in real-time food safety and quality assurance across the supply chain.

Enhanced Cold Chain Efficiency

Nano-refrigerants and phase-change nanomaterials increase cold storage facility efficiency and energy efficiency in cooling. This reduces post-harvest losses through maintaining a low-temperature, stable environment and minimizing reliance on costly refrigeration equipment.

Sustainability and Eco-Friendliness

Biodegradable nanocomposite packaging lowers the use of plastic, being in harmony with the aims of environmental sustainability. The nanotechnology approaches tend to employ small amounts of active substances, reducing chemical residues and making the processes safer for consumers and the environment.

2. Nano-Coatings to Enhance Shelf-Life

Edible coatings supplemented with nanomaterials are among the most promising methods to increase the shelf life of fruits. Nano-coatings create an ultra-thin, imperceptible, and safe barrier over the surface of the fruit that serves as a physical and biochemical barrier.

- ✓ **Water Loss and Respiration Regulation:** Through the reduction of moisture evaporation and respiration rate, nano-coatings contribute towards wilting delay and weight loss, thus ensuring fruit firmness.
- ✓ **Ripening Retardation:** Certain coatings include nano-encapsulated ethylene inhibitors, which retard fruit softening and color change through the regulation of ethylene biosynthesis and activity.
- ✓ **Antimicrobial and Antioxidant Activity:** Chitosan nanonparticles, nano-silver, and nanocapsules of essential oils (e.g., thyme oil, oregano oil) are extensively researched for their potential to inhibit malollthmic growth and oxidative browning.

Examples

Chitosan–silver nanoparticle coatings on papayas and bananas have been shown to increase shelf life by over 10 days.

Nano-encapsulated cinnamon oil coating inhibited fungal infection in strawberries and enhanced freshness during storage.

3. Nano-Sensors in Quality Monitoring

Nano-sensors and nano-biosensors are of central importance in real-time tracking of fruit quality parameters during storage, transportation, and retailing. These intelligent sensing systems are extremely sensitive, fast, and inexpensive.

- ✓ **Ethylene Detection:** Gold nanoparticle-based, carbon nanotube-based, or graphene-based nanosensors can identify the presence of ethylene gas at extremely low concentrations with precise evaluation of fruit ripening stages.
- ✓ **Pathogen Detection:** Fungal spores or bacterial contamination can be detected early by nano-biosensors to prevent mass spoilage. Nanosensors based on silver nanoparticles, for instance, detect Botrytis cinerea infection in grapes before symptoms become visible.
- ✓ **Environmental Monitoring:** Packaging with nanosensors incorporated enables continuous monitoring of storage conditions such as temperature, relative humidity, and oxygen levels to ensure optimal conditions during the supply chain.
- ✓ **Practical Application:** "Smart labels" with nanosensors can be color-changing when spoilage starts, providing both shoppers and retailers with immediate visual cues of fruit freshness.

4. Nano-Formulations for Pest and Disease Management

Fungal and bacterial infections of post-harvest fruits, like anthracnose in mango or gray mold in strawberry, are principal reasons for fruit loss. Formulations based on nanotechnology have superior disease management options.

- ✓ **Controlled Release of Fungicides:** Fungicide nano-encapsulation provides slow, continuous release, minimizing the necessity for repeated chemical application.
- ✓ **Lower Residues:** Nano-formulations reduce excess pesticide application, keeping fruits within acceptable chemical residue levels for consumers.
- ✓ **Improved Bioefficacy:** Nanoparticles enhance solubility and penetration of active ingredients, enhancing their effectiveness against resistant pathogens.
- ✓ **Application of Natural Bioagents:** Nanocarrier-encapsulated essential oils (clove, neem, lemongrass) exhibit remarkable antifungal efficiency, presenting a green alternative to chemical fungicides.
- ✓ **Example:** Nano-encapsulated thyme oil was highly active against Aspergillus niger in grapes and preserved market quality of the stored grapes.

5. Nanotechnology in Cold Storage and Transport

Proper cold chain management is necessary for minimizing post-harvest loss of fruits, and nanotechnology is being adopted more and more in storage and transport systems.

- ✓ **Controlled Atmosphere Storage:** Nano-membranes are used to selectively control gas exchange (O_2, CO_2, and ethylene), thus retarding ripening and senescence.
- ✓ **Nano-Refrigerants:** Nanoparticles of Al_2O_3, TiO_2, or CuO are incorporated into refrigerants for more efficient transfer of heat. This results in quicker cooling, lesser energy usage, and less operational cost in cold stores.
- ✓ **Prevention of Chilling Injury:** Fruits such as bananas, mangoes, and papayas are extremely sensitive to low temperature. Nano-coatings containing antioxidants and protective chemicals prevent oxidative stress and hence chilling injury.
- ✓ **Logistics Monitoring:** Nanotechnology-based RFID tags and nanosensors enable accurate monitoring of temperature fluctuations during transportation so that fruits arrive at the consumer's end in a best-possible state.

Benefits of Nanotechnology in Post-Harvest Management

Extension of shelf life is one of the greatest benefits of nanotechnology in post-harvest management. Nanocoatings, nano-enabled packaging, and controlled-release preservatives substantially retard fruit ripening, slow down respiration rates, and inhibit microbial decay. Storage duration increases, post-harvest losses decrease, and fruits are transported to remote or export markets without the loss of quality. For instance, chitosan-silver nanoparticle-coated strawberries were found to retain freshness for a period of up to 12 days longer than untreated fruits.

Another significant advantage is enhanced food safety. Nanomaterials like nano-silver, zinc oxide, and titanium dioxide show significant antimicrobial activity, thus preventing the contamination due to bacteria and fungi. Further, nanoencapsulation of pesticides and natural antimicrobials facilitates targeted delivery with very little residues, thus boosting consumer protection from health hazards. The use of nanosensors adds further robustness to the safety aspect by facilitating early spoilage and contamination detection, thereby providing chances for timely interventions.

Nanotechnology also makes post-harvest management more sustainable and eco-friendly. Biodegradable nanocomposite films of starch, cellulose, or chitosan minimize the use of petroleum-based plastics, and the reduced usage of synthetic chemicals minimizes the impact on the environment. Moreover, the use of essential oils and plant extracts in nano-formulations is an eco-friendly method of fruit preservation, ensuring a greener and safer food system.

On the cost front, nanotechnology minimizes wastage at the stage of storage, transportation, and retaling, thus increasing profitability for manufacturers and dealers. While the upfront costs of introducing nanotechnology-based infrastructure could be high, long-term gains from lower spoilage and optimal use of cold chain facilities offset the expenses. Besides, intelligent packaging infused with nanosensors minimizes the requirement for regular manual checks of quality, which in turn decreases labor expenses.

Lastly, nanotechnology boosts consumer trust and market confidence. Smart packaging with nanosensors offers openness regarding product freshness, ripeness, and general safety. Color-shifting indicators and freshness labels provide consumers and retailers with surefire information on fruit quality, eliminating guesswork and enhancing faith. Not only does this enhance marketability of fruits, but it enhances brand reputation in competitive markets as well.

Challenges and Concerns in Nanotechnology Applications

Although promising, nanotechnology in post-harvest fruit management has its challenges. Top among these is toxicity and food safety hazards. Some nanoparticles, like silver and titanium dioxide, have the potential to accumulate in human tissues with unknown long-term health implications. In dealing with such concerns, thorough toxicological experiments must be carried out to certify that nano-coatings and residues on fruits consumed by humans are within permissible levels. Nevertheless, consumer safety testing procedures continue to develop, leading to uncertainty in risk evaluation. Another significant hindrance is the existence of policy and regulatory gaps. Numerous nations lack uniform regulations or approval systems for food applications based on nanotechnology. Unclear labeling requirements also complicate consumer comprehension and can lower trust in products based on nano. Harmonized global standards are necessary to safeguard commercialization and facilitate international trade while ensuring safe commercialization.

High adoption costs also constrain mass use of nanotechnology, especially for small-scale farmers. Production and utilization of nanomaterials call for sophisticated infrastructure and professional expertise, making it costly. Restricted accessibility in developing countries causes disparity in technology usage, limiting its advantage to large-scale producers and exporters. Increasing the scale of nano-packaging and coating manufacturing to make them affordable is a key challenge.

Lastly, public perception and awareness contribute significantly to the role played by nanotechnology in the food industry. Most consumers are still hesitant, linking nanotechnology to a possible threat to their health or to artificial interventions. Mistrust is also enhanced by a lack of marketing campaigns and a lack of transparency on safety evaluations. Public acceptance of nano-packaged fruits will thus rely heavily on open communication, scientific assurance, and overt consumer advantage.

Future Prospects

As the world increasingly demands fresh, healthy, and safe fruits, nanotechnology will play a revolutionary role in reducing post-harvest losses in the future. Future studies should emphasize the construction of biodegradable nanomaterials that are suitable replacements for the current plastics and help to minimize environmental pollution. Another critical trend is the construction of multi-functional nano-coatings that offer antimicrobial, antioxidant, and ripening-control activities simultaneously, thus providing holistic protection for fruits during storage and transportation.

Just as important is the development of strong regulatory mechanisms and safety test protocols that guarantee consumer safety while enabling mega-scale commercialization of nanotechnology-based technologies.

Additionally, coupling nanotechnology with advanced ICT technologies like Artificial Intelligence (AI), Internet of Things (IoT), and blockchain can open the doors to smart post-harvest management systems. These systems may include real-time tracking, predictive insights, and traceability, eventually making food supply chains more resilient and enhancing consumer confidence.

CONCLUSION

Nanotechnology offers a promising horizon for post-harvest management of fruits by proposing novel solutions to the long-standing issues of perishability, safety in food, and sustainability. Utilizations such as nano-packaging, nano-coatings, and nanosensors not only increase the shelf life of fruits but also provide better quality assurance and consumer protection. In the process, they help decrease food losses, lower environmental footprints, and enhance profitability in the supply chain.

Nevertheless, the universal application of nanotechnology hinges on the surmounting of major challenges, mainly toxicological safety, regulatory definition, implementation cost, and consumer acceptance. Resolution of these issues through scientific verification, policy endorsement, and communication will be essential for public acceptability. With further research, innovation, and integration into intelligent supply chains, nanotechnology could transform fruit post-harvest management to become more efficient, sustainable, and more robust in the context of global food security threats.