Review Article

Edible coating with plant extracts and essential oils loaded nanoparticles: Sustaining postharvest quality of fruits and vegetables

Abstract

The fruits and vegetables are affected by postharvest diseases and physiological processes such as transpiration and respiration after harvest, leading to significant quality losses during transportation and storage. Research has demonstrated that edible coatings enriched with plant extracts, essential oils and nanoparticles loaded with plant extracts as an innovative and eco-friendly approach to reduce postharvest losses and extending the shelf life of fresh fruits and vegetables. This edible coating creates a semi-permeable layer around the produce that reduces respiration rates, delays ripening, and inhibits microbial growth, thereby preserving the nutritional and sensory qualities of produce during storage. Recent studies demonstrate that nanoparticle-enriched coatings significantly delay ripening, maintain firmness, and preserve nutritional quality through their enhanced barrier properties and controlled release of active compounds. The synergistic effects of the nano-reinforced matrices show promising results in reducing post-harvest losses while maintaining food safety standards. This review examines the current developments in edible coating technology, focusing on various plant extracts, essential oils, and nanoparticles loaded with plant extracts enriched edible coating for extending shelf life and preserving the quality of fruits and vegetables.

1. Introduction

India is the second largest producer of fruits and vegetables and plays a major role in food, nutritional and economic security of the country. The area under fruit cultivation is 69.3 lakh ha with a production of 102.481 million tons and vegetables production is 200.445 million tons from an area of 102.60 lakh ha (NHB, 2020). However, major problem in fruits and vegetables is their higher perishability leading to postharvest losses and short shelf life. The postharvest loss in India is reported to be around 8-18% (APEDA, 2019) because of high moisture content (75–95%) in fruits and vegetables, leading to dehydration, mechanical injury, environmental stress, pathological breakdown, poor postharvest management, inadequate cold storage, processing facilities etc. (Otoni *et al*., 2017).

Preserving postharvest quality is a critical concern for fruits and vegetables growers to ensure efficient handling, transportation, and marketing of fresh produce (Dave *et al*., 2017). Various chemical compounds are commonly used to control postharvest diseases and to extend the shelf life of fruits and vegetables, some of these substances pose risks to human health. Additionally, the widespread use of fungicides and synthetic chemicals has contributed to the emergence of resistant strains of pathogens, accompanied by the accumulation of harmful residues (Khaliq *et al*., 2019). With growing consumer demand for safe, high-quality produce, minimizing postharvest losses has become increasingly important (Adekunle *et al*., 2021). To address these challenges, the application of edible coatings has been explored as a sustainable solution. These eco-friendly, thin-layer substances are applied to fresh fruits and vegetables to reduce postharvest losses and maintain their quality (Dhall *et al*., 2013).

Edible coatings can serve as carriers for active ingredients that help to extend the postharvest life of fruits and vegetables, reduce the risk of pathogen infestation on food surfaces, and slow down other undesirable changes. Polysaccharide-based edible coatings are widely used to prolong the storage life of fruits (Cazon *et al*., 2017; Liu *et al*., 2021). These coatings provide protection by minimizing moisture loss, regulating respiration and gas exchange, and inhibiting the activity of reactive oxygen species (Aloui, *et al*., 2016). Enhancing these coatings with plant extracts or essential oils increases their effectiveness while making them more environmentally friendly. Additionally, these coatings offer several benefits, such as being cost-effective and readily available. The effectiveness of plant-based edible coatings or those enriched with plant extracts largely depends on the active compounds in the extracts, which are generally recognized as safe for human consumption and possess strong antioxidant and antimicrobial properties (Flores-Lopez *et al*., 2016).

The incorporation of nanoparticles into edible coatings enhances their functional, nutritional, organoleptic, and mechanical properties, presenting a novel approach to maintaining product quality. Research has demonstrated that adding nanoparticles to edible coatings improves their effectiveness in preserving the quality of fresh produce, provides antibacterial properties, and enhances food safety during storage (Martelli *et al*., 2013). The integration of plant-based materials into edible coatings represents a recent and innovative technology. These coatings, being entirely organic, not only preserve the postharvest quality of fruits and vegetables but also ensure consumer safety. This review highlights the potential of edible coatings enriched with plant extracts, essential oils, and nanoparticles loaded with these bioactive compounds. It examines their impact on various physical, biochemical, antioxidant, and enzymatic parameters during the postharvest period of fruits and vegetables.

2. Plant extracts and essential oils for edible coating

The edible coating is a thin layer of edible materials applied on the surface of fruits and vegetables, providing protection to them. An edible coating comprising of protein, lipid, polysaccharide, or resin, alone or in combination, helps to improve the appearance and provide safety to the produce by its environmentally friendly nature. The different structural materials for the development of edible coating are given in Table 1.

Table 1. Summary of diverse structural materials frequently used for edible coating

Material	Main Matrices	References
Polysaccharide	Starch, chitosan, alginate, cellulose and its derivatives and pectin	Mohamed *et al*., 2020
Lipid	Animal, vegetable waxes and resins, vegetable oil, and fatty acids	Miranda *et al*., 2020; Eddin *et al*., 2019
Protein	Gelatin, casein, whey protein, zein, soy protein, myofibrillar protein, and quinoa protein	Arnon-Rips *et al*., 2018
Composite	Combination of polysaccharide and/or protein with lipids	De Oliveira Filho *et al*., 2020

In recent years, there has been growing interest in enhancing the performance of edible coatings for fresh and fresh-cut fruits and vegetables, especially when the coatings fail to achieve all the desired effects. A notable trend involves the incorporation of essential oils and plant extracts into these coatings. Essential oils are naturally occurring volatile compounds with complex structures and strong aromas, produced by aromatic plants as secondary metabolites. These compounds play a crucial role in the plant's defense mechanisms. Essential oils are widely recognized for their antibacterial, antifungal, and insecticidal properties. Classified as GRAS (Generally Recognized as Safe) substances, essential oils derived from plant materials are effective against foodborne pathogens and spoilage-causing bacteria (Hager *et al*., 2019). Among the essential oils, commonly extracted from spices and incorporated into edible coatings are those from the Myrtaceae family (e.g., clove and tea tree) and the Lauraceae family (e.g., cinnamon). The essential oils used in edible coatings from herbs and grasses are typically obtained from the Lamiaceae family (e.g., thyme, peppermint, rosemary, oregano, and savory), the Asteraceae family (e.g., tarragon), and the Poaceae family (e.g., lemongrass). Additionally, citrus-based essential oils have been applied in edible coatings for fresh and fresh-cut fruits and vegetables, with notable examples coming from the Rutaceae family, such as lemon, lime, and bergamot (Yousuf *et al*., 2021).

Plant extracts are complex blends of compounds belonging to various chemical classes that possess bioactive properties. Traditionally, these extracts are obtained from the entire plant or specific parts such as the rhizome, root, stem, leaf, flower, or tissues and cell cultures (Hao *et al*., 2015). The bioactive compounds within these mixtures are extracted from plants or plant materials using different solvents (Sasidharan *et al*., 2011). These bioactive compounds, along with other natural substances like metabolites, volatile compounds, and active enzymes produced by selected microorganisms, serve as valuable sources of antifungal agents, making them promising candidates for fungicides to manage post-harvest fungal diseases (Bhutia, 2015). As noted by Gurjar *et al*. (2012), plant tissues have the capability to produce aromatic secondary metabolites, including phenols, phenolic acids, quinones, flavones, flavonoids, flavonols, tannins, and coumarins.

Moringa extract is a potent source of vitamins, minerals, proteins, β-carotene, phenolic acids, flavonoids, and various other bioactive compounds (Saucedo-Pompa *et al*., 2018). Its high levels of phenolic acids and flavonoids are largely responsible for its strong antioxidant activity, demonstrated in both in vitro and in vivo studies, as reported by Vongsak *et al*. (2013). Research has shown that moringa extract exhibits several beneficial properties, including anti-inflammatory, antifungal (Chung *et al*., 2007), pro-coagulant (Nkurunziza *et al*., 2009), flocculating (Beltran-Heredia *et al*., 2009), and antibacterial activities (Doughari *et al*., 2007). Papaya leaves and seeds are rich in proteolytic enzymes (papain and chymopapain), alkaloids (carpain and carpasemine), sulfur-containing compounds (benzyl isothiocyanate), flavonoids, triterpenes, and organic acids. Extracts derived from various papaya tissues have demonstrated bioactive properties. Aqueous extracts from papaya leaves and seeds exhibit antifungal activity against *Colletotrichum gloeosporioides* (Bautista-Banos *et al*., 2002). Additionally, alcoholic extracts from the epicarp, endocarp, roots, and seeds of ripe and unripe papaya fruits possess antidiarrheal, antidysenteric, and antibacterial properties (Doughari *et al*., 2007).

The application of moringa leaf extract (2%) and a combination of moringa leaf extract with 1% carboxymethyl cellulose on 'Fuerte' and 'Hass' avocado fruits significantly reduced respiration rate, moisture loss, and firmness loss during storage, thereby extending their postharvest shelf life (Tesfaya and Magwazaa, 2017). Similarly, postharvest treatments using 10% moringa leaf extract combined with 10% gum arabic or 1% carboxymethyl cellulose effectively controlled *Colletotrichum gloeosporioides* by up to 33%, minimized weight and firmness loss, and delayed colour changes in 'Maluma' avocados (Kubheka *et al*., 2020). The edible coating of guava (cv. Maamoura) with 10% gum arabic and 10% moringa leaf extract effectively reduced postharvest weight loss, decay, and *Rhizopus* rot infection, while delaying fruit softening under cold storage conditions and improving marketability (El-Gioushy *et al*., 2022). Similarly, the application of 6% moringa leaf extract on strawberry fruits (cv. Chandler) resulted in the lowest respiration rate, ethylene production, malondialdehyde levels, and total soluble solid accumulation compared to untreated fruits during five days of storage at ambient conditions (Shafique *et al*., 2023).

Tabassum *et al*. (2018) studied the effects of guava leaf and lemon extracts on the postharvest quality of Sabri bananas under ambient conditions. A combination of 20% guava leaf extract and 15% lemon extract was most effective in maintaining higher firmness, reducing total soluble solids and microbial infection, and extending shelf life to 8.75 days. Meanwhile, 40% guava leaf extract with 5% lemon extract preserved the highest vitamin C (1.83 mg/100g), titratable acidity (0.11%), and reducing sugar (7.13%) after two weeks of storage. Khaliq *et al*. (2019) examined the effects of aloe vera gel enriched with *Fagonia indica* extract on the quality and antioxidant activity of sapodilla fruit during postharvest storage at 20 °C for 12 days. Aloe vera gel (50% or 100%) combined with 1% *Fagonia indica* extract significantly reduced weight loss, decay, and soluble solids concentration while preserving firmness, titratable acidity, ascorbic acid, total flavonoids, phenolics, and antioxidant activity. Sensory analysis showed no negative impact on fruit attributes, highlighting the potential of this treatment to extend sapodilla fruit shelf life and maintain quality. Moringa leaf extract combined with carboxymethyl cellulose serves as an eco-friendly edible coating to reduce postharvest losses in “Hass” avocados. A coating of 16 % moringa leaf extract with 5% carboxymethyl cellulose effectively preserved phenolics, flavonoids, and antioxidant activity and firmness during storage at 5.5°C and 90% RH (Ngubane *et al*., 2024).

3. Effect of plant extracts/essential oils loaded nanoparticles on quality and shelf life of fruits and vegetables

Nanotechnology has emerged as a powerful tool for developing edible coatings based on emulsions with enhanced properties and functionalities. It represents a novel approach to improving postharvest management of fruits and vegetables. Incorporating nanoparticles into edible coatings significantly extends the shelf life of fruits compared to coatings made solely from pure polymers (Gad and Zog, 2017). The inclusion of nanoparticles enhances the mechanical and barrier properties of the coatings while also increasing their thermal stability (Shankar and Rhim, 2015).

Most successful applications of nanotechnology in the field of packaging concerns the development of “nanocomposites” (Unalan *et al*., 2014). In polymer science, while the term “composites” generally refers to mixtures of polymers with inorganic or organic additives having micron-length scale and certain geometries (fibers, flakes, spheres, and particulates), the use of nano-length-scale entities can be more specifically referred to as “nanocomposites.” A new subclass of nanocomposite materials has recently stemmed from the increasing endeavour to replace oil-based polymers with polymers partially or totally obtained from renewable resources. The term “bionanocomposites” refers to those materials in which the polymer matrix carrying the nanosized fillers is a biopolymer (e.g., polysaccharides, lipids and proteins). Composite materials exhibit stronger physical, chemical, and mechanical properties than their constituent materials. However, conventional composite materials mechanically differ from nanocomposites because of their exceptionally high surface-to-volume ratio and are excellent green technology materials with good biodegradability, biocompatible properties, and the capability to mimic biomaterials.

Table 2. Studies on bionanocomposite edible coatings on different fruits and vegetables

Sl. No.	**Fruit/ vegetable**	**Nanoparticle component**	**Bioactive compound**	**Reference**
1.	Apple	Zein nanofibers	Curcumin	Aytac *et al*., 2017
Result		The surface was inoculated with *Botrytis cineraria* and *Penicillium expansum*; then, apples were coated by electro-spinning with zein nanotubes and stored for 15 days, revealing the inhibition of microbial growth and increase in the shelf life of apples.		
2.	Cucumber	Chitosan	Carvacrol	Tastan *et al*., 2017
Result		The combination of pulsed light (12 J/cm^2) with the edible coating (0.08% carvacrol) resulted in a strong synergistic effect, with *E. coli* reduction reaching >5 log cycles.		
3.	Grape berry	Chitosan	Lemongrass oil	Cordoba and Sobral, 2017
Result		The use of the nanoemulsion effectively reduced the initial growth of *Salmonella typhimurium*, total aerobic mesophiles, yeasts and moulds, and showed retention of antioxidant capacity.		
4.	Green beans	Chitosan	Mandarin essential Oil	Severino *et al*., 2014
Result		The combination of the bioactive coating and UV-C treatment reduced the *Listeria innocua* population and maintained the microbial load at a constant level during storage.		

5.	Fresh-cut apple	Sodium alginate	Lemongrass essential oil	Salvia-Trujillo *et al.*, 2015
Result		Nanoemulsion based edible coatings presented higher *E. coli* inactivation and slower psychrophilic bacteria growth compared to conventional emulsions at the same concentration.		

Banana fruits coated with Cellulose nanofiber based emulsion (0.3%) delayed the ethylene biosynthesis pathway, reduced ethylene and CO_2 production, minimized chlorophyll degradation, weight loss, and firmness of bananas during 10 days of ambient storage (Deng *et al*., 2017). Banana (Cavendish) fruits coated with chitosan nanoparticles 0.2% has a slower skin discolouration by 2-3 days compared to control treatment under 22 ± 1°C (Esyanti *et al*., 2019). Jianmei *et al*. (2019) studied the improvement of banana postharvest quality using a novel soybean protein isolate (SPI) / cinnamaldehyde (CIN) / zinc oxide (ZnO) bionanocomposite coating strategy. Results showed that SPI/CIN/ZnONP nanocomposite coating could effectively delay ripening rate, lowest weight loss (7.83 %), TSS (10.31 %) and high fruit firmness (12.13 N), titratable acidity (65.93 mg malic acid/100 g), sensory quality compared with other SPI-based coating treatments during the whole storage period (7 days).

Barrera-Necha *et al*. (2018) studied the synthesis and characterization of chitosan nanoparticles loaded botanical extracts with antifungal activity on *Colletotrichum gloeosporioides*. In this study, chitosan nanoparticles (CSNPs) and chitosan nanoparticles botanical extracts: EMN-CSNPs (extract methanol of nanche added chitosan nanoparticles) were characterized and evaluated *in vitro* on growth of *Colletotrichum gloeosporioides* isolated from Papaya and Soursop. For *in vitro* evaluation, incorporation of EMN to CSNPs improved the control of *C. gloeosporioides* with amycelial growth inhibition of 79% from papaya and 82% from soursop. Odetayo *et al*. (2022) studied the effect of nanoparticle-enriched coatings on the shelf life of Cavendish bananas. Banana fruits were dipped into: *Aloe vera* 50% (AV), *Moringa oleifera* 10% (MO), *Aloe vera* 50% + chitosan nanoparticle 2% (AV+CN), and *Moringa oleifera* 10% + chitosan nanoparticle 2% (MO+CN). The results showed that adding chitosan nanoparticles to edible coating had a significant impact on the weight loss, firmness, ethylene rate and disease incidence during storage. *Moringa oleifera* + chitosan nanoparticle coating reduced weight loss (23%), ethylene generation (144 µL/kg/h) and disease incidence (58 %) to a larger extent followed by other treatments. In addition, the MO+CN treatment preserved fruit firmness (46 N) and increased the shelf life to 30 days compared to others.

The curcumin-loaded chitosan nanoparticles effectively controlled the anthracnose disease on Papaya under both *in vitro* and *in vivo* assay. The Curcumin alone inhibited the growth of *C. gloeosporioides* at both *in vitro* and *in vivo* assays. However, the Cur-ChNP with formula ratio of 5:5 (w/w), had similar effect with Curcumin treatment to suppress anthracnose disease severity under *in vivo* assay, with the relative disease inhibition rate of 71.19%. This study, demonstrated that Cur-ChNP may be utilized as a potential biocontrol agent against anthracnose disease on papaya (Suryadi *et al*., 2019). Vieira *et al.* (2020) reported that papaya fruits coated with Hydroxypropyl methylcellulose (4%) + silver nanoparticles (0.25%) preserved the quality of papaya evaluated by colour, firmness, lower weight loss, and total soluble solids. Thus, it can be an alternative against fungus development and to increase the shelf life of papaya cv. Golden.

Resende *et al*. (2018) observed that 1% chitosan + 5% CNF (cellulose nanofibril) coating performed better in reducing fruit mass, firmness loss and maintaining overall quality of strawberry under cold storage (1 ± 1°C). Melo *et al*. (2020) studied on *In vivo* and *in vitro* antifungal effect of fungal chitosan nanocomposite edible coating against strawberry phytopathogenic fungi. The results obtained in this study demonstrated that the application of chitosan as a gel, or nanocomposite can control the growth and the viability of the strawberry phytopathogenic fungi (*Botrytis cinerea*; *Rhizopus stolonifer* and *Aspergillus niger*). The application of the nanocomposite edible coating *in vitro* and on strawberries artificially contaminated with postharvest fungi, decreased the infection severity caused by these fungi during fruit storage. Therefore, chitosan nanocomposite edible coatings can be a promising strategy to extend the shelf life of strawberries. Nguyen *et al*. (2020) studied on combination effects of calcium chloride and nano-chitosan on the postharvest quality of strawberry (*Fragaria x ananassa* Duch.). The fruit were dipped in different concentrations of calcium chloride (1 %, 2 %, 3 %, 4 %) before being coated with 0.2 % nano-chitosan. Among six examined treatments, a combination of 3 % $CaCl_2$ and nano-chitosan (NCTS) 0.2 % was the most effective one as maintaining the highest score of overall quality index of strawberry stored at 4 °C up to 15 days.

A bionanocomposite edible coating containing carboxymethyl cellulose (CMC) and cardamom essential oil (CEO) significantly reduced the loss of fruit weight (7.32 ± 2.4%), firmness (1.3 times), total soluble solids, and titratable acidity of tomatoes by reducing oxidative stress and increasing antioxidant enzymes during 15 days of storage (Das *et al*., 2022). Algarni *et al*. (2022) studied on effect of chitosan nanoparticles as edible coating on the storability and quality of apricot fruits. During the storage of the apricots, those treated with CHNPs (1%) showed an obvious decrease in decay percent (Fig. 1) and lipid peroxidation, whereas ascorbic acid and carotenoid content were higher than those in the fruits treated with CH and the untreated fruits (control). The findings of the sensory evaluation revealed a significant difference in the overall acceptability scores and extended their shelf-life (Fig. 2) for up to 9 days at room temperature storage and for 30 days in cold storage between the samples treated with CHNPs and the other samples.

Mohammadi *et al*. (2015) studied on chitosan nanoparticles loaded with *Cinnamomum zeylanicum* essential oil enhance the shelf life of cucumber during cold storage. Chitosan nanoparticles loaded with CEO significantly decreased both disease severity and incidence of infected cucumbers by *P. drechsleri*, during 7 days of storage at 4 ºC followed by 1–2 more days at 20 ºC. Furthermore, the CEO-CSNs was more effective than pure CSNs coating at reducing respiration rates, improving the microbiological quality, and preserving the fruit weight and quality of cucumbers during the storage period. These results demonstrate the potential of chitosan nanoparticles containing cinnamon oil extended the postharvest shelf life of cucumber. Emamifar and Bavaisi (2020) reported that strawberries coated with 1.5% sodium alginate + 1.25 g/L nano-ZnO showed the highest antioxidant activity, antimicrobial properties, sensory attributes, and lowest peroxidase activity and extended the storage life of fresh fruits by up to 20 days.

Saekow *et al.* (2019) studied on effect of carboxymethyl cellulose coating containing ZnO-nanoparticles for prolonging the shelf life of persimmon and tomato fruit. The results showed that the application of coating with carboxymethyl cellulose and carboxymethyl cellulose + ZnO-nanoparticles in persimmon and tomato reduced weight loss and respiration rate, and increased fruit firmness when compared with control during storage time. The CMC + ZnONPs coating effectively delayed the disease severity in the inoculated persimmon and tomato. Maringgal *et al*. (2021) studied on effect of kelulut honey nanoparticles (KHNPs) coating on the changes in respiration rate, ascorbic acid, and total phenolic content of papaya (*Carica papaya* L.) during cold storage. Papayas coated with 15 % KHNPs significantly changed during storage, with an increase in CO_2 and a decrease in O_2 and C_2H_4, while the ascorbic acid and total phenolic content were maintained. The changes in respiration rate were rather slower for coated papayas when compared to the control.

4. Conclusion

Edible coating is one of the promising technologies for extending the shelf life of fresh fruits and vegetables that help to reduce postharvest losses. Incorporating plant extracts and essential oils into edible coatings has proven effective in extending the postharvest life of various fruits and vegetables. Edible coatings enriched with plant extracts are gaining popularity due to their antioxidant properties, affordability, safety, and easy availability. Recent advancements in postharvest technology have provided new methods for integrating these plant extracts into the edible coating matrix. The inclusion of nanoparticles in edible coatings significantly extends shelf life. Recent studies show that nanoparticles loaded with plant extracts and essential oils play a crucial role in developing next-generation edible coatings with enhanced properties for preserving fresh fruits and vegetables. This emerging technology improves the physical stability and effectiveness of active ingredients within edible coatings, offering the potential to enhance the quality and/or nutritional value of fruits and vegetables.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts.

Details of the AI usage are given below:

1. ChatGPT

Competing interests

The authors have declared that no competing interests exist.

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