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RECENT ADVANCES IN EDIBLE COATING TECHNOLOGIES FOR POSTHARVEST PRESERVATION OF FRUITS AND VEGETABLES: A REVIEW

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ABSTRACT

Fruits and vegetables are widely consumed because of their rich nutritional value. Fresh fruits and vegetables are highly perishable, and around 50% of post-harvest losses occur during improper processing, transport and storage. Edible coatings are a viable solution to this problem because they have the potential to incorporate antibacterial and antioxidant substances that enhance food preservation while also providing a protective edible covering for fruits and vegetables. They can serve as individual packaging materials, active ingredient carriers and protective barriers for fresh produce. Edible coatings are produced from edible biopolymers and food-grade additives. The efficiency and functional properties of edible coating materials are highly dependent on the inherent characteristics of biopolymers and other additives. They usually consist of polymers able to provide mechanical strength to the stand-alone thin structure. Coatings are a particular form of film that is directly applied to the surface of fruits and vegetables. Edible coating enhances the quality of food products, protecting them from physical, chemical and microbiological deterioration. Furthermore, the incorporation of various active compounds into the coating's matrix ensures that these substances are bound and can be consumed with fruits and vegetables, which offers a substantial advantage to edible coatings. These coatings extend the fruit's shelf life and enhance its organoleptic and nutritional properties. This vital information could help processors select the most suitable coating material for different fruits and vegetables.

Keywords **:** Edible coatings, Fruits and Vegetables, Hydrocolloids, Shelf life, Preservation.

Introduction

Fruit and vegetables are essential in the human diet due to their high nutritional value. They are rich in vitamins, minerals, antioxidants, bioflavonoids, flavour compounds and dietary fibre (Raghav *et al*., 2016). These health advantages emphasise their importance in daily life. Fresh fruits and vegetables have a postharvest loss of 20-30% and are very perishable, making them more susceptible to biotic (diseases, insects, parasites) and abiotic (temperature, humidity, rain, floods) challenges. Microorganisms are a major cause of postharvest loss in fresh vegetables. Skin damage, blotches and fractures develop as a result of improper handling of fresh vegetables, creating an ideal environment for microbial growth. Many microorganisms enter the food and cause serious health issues, especially pathogenic organisms, which can cause foodborne diseases (Khare *et al*., 2018; Salehi, 2020). The recent literature on bibliometrics shows that annual losses of fresh produce due to post-harvest loss may account for as much as 55%, highlighting the necessity to apply alternative preservation techniques like edible coatings/films (Ali *et al*., 2025a).

An important condition for preserving the shelf life of fruits and vegetables is a proper method of storage and control of their quality parameters such as colour, firmness, atmosphere composition, water content and weight loss (Swathi *et al*., 2017; Mahajan *et al*., 2018). Several methods are used to extend the nutritional attributes and storage life of fruit and vegetables, including modified atmospheric packaging (MAP), low temperature storage, high temperature, irradiation and chemical treatment; however, these techniques require proper care and sometimes may lead to an unacceptable loss of nutritional value (Mohapatra *et al*., 2013).

In recent years, edible coatings have aroused the interest of scholars and the food industry to utilise them as preservative techniques due to their biodegradability, biocompatibility, antibacterial and antifungal activity, as well as their ability to retain food without compromising its nutritional or organoleptic aspects. Edible coatings for food preservation are not a new concept, but they have attracted a lot of interest in recent years due to their protective properties (Hauzoukim and Mohanty, 2020). Edible coatings are used to extend the shelf life of fruits and vegetables.

According to Baldwin (1994), the main aim of edible coating for fruits and vegetables is basically to improve or strengthen the natural barrier, if already present and to replace it in the cases where handling and washing have partially removed or altered it. In addition, this edible covering can be consumed along with fruits and vegetables. The thickness of edible coating is often less than 0.3 mm (Tharanathan, 2003). An edible coating protects the outer membrane of fresh fruits and vegetables (Mohamed *et al*., 2013). Edible coatings are typically tasteless, colourless and odourless, and have good mechanical properties. Edible coatings have good gas and moisture barrier characteristics (Undurraga *et al*., 1995).

Edible coatings form a barrier to chemical, physical and biological changes (Skurtys *et al*., 2005). In terms of biology, an edible coating can provide a partial barrier to water movement that can reduce moisture loss from the fruit surface and modify the atmosphere around the fruit by acting as a barrier to gas exchange (Jongsri *et al*., 2016). In addition to inhibiting fungal growth and improving the fruit's exterior, this coating slows down respiration and senescence without inducing anaerobiosis (Dhall, 2013).

Edible coatings have many physicochemical impacts on fruits. For whole fruits, these effects include improving firmness, raising titratable acidity and improving vitamin C. On fresh cuts, they have the effect of delaying water loss, increasing soluble solid content and preserving product colour. The majority of the effects will likely be seen in both whole and freshly sliced fruits. This has sparked the curiosity of researchers and resulted in a number of in-depth studies. For example, it has been observed that the application of an edible coating was able to decrease the activity of peroxidase (POD) and polyphenol oxidase (PPO), and eventually decrease the physiological impacts on strawberry and sapota fruit, such as anti-browning and decolourisation (Vishwasrao and Ananthanarayan, 2017).

Edible coatings are composed of biological materials such as hydrocolloids (polysaccharides and proteins), lipids and composites. Biopolymer-based films are good gas barriers but have low moisture migration resistance. In comparison, lipid-based films are effective moisture barriers but have low mechanical strength and negligible gas transfer resistance. Composite coating has mostly been employed in fresh produce to give efficient barrier characteristics against both air and moisture (Mohammed *et al*., 2009).

What is edible coating?

Edible coatings are defined as the thin layer of edible material which coats fruits and vegetables, which can be digested and offer a barrier to oxygen, microbes from other sources, moisture and the movement of solutes for food. Edible coatings provide a semi-permeable barrier to improve shelf life by reducing moisture, solute migration, gas exchange, oxidative reaction rates, and respiration. They also minimise the physiological problems of fruits and vegetables (Baldwin *et al*., 1996; Park, 1999). Edible coatings are an appropriate substitute for commercial synthetic waxes, which are manufactured from oxidised polyethylene.

An edible coating or film could be defined as primary packaging made from edible components. A thin layer of edible material can be coated on food or can be formed into a film and used as a food wrap without changing the original ingredients or the processing (Krochta, 2002).

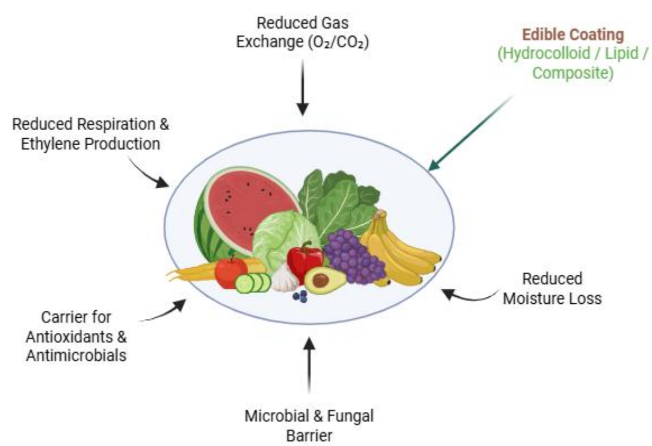

Fig. 1 : Barrier and functional roles of an edible coating layer applied to fresh produce.

Properties of edible coatings

Edible coating properties are basically determined by their molecular structure, not their molecular size or chemical composition. Arvanitoyannis and Gorris (1999) define the particular requirements for edible coatings. They are-

i. The coating should be water-resistant and adequately cover the product when applied.
ii. It should also not deplete oxygen or increase carbon dioxide levels. A minimum of 1-3% oxygen is needed around a commodity to prevent a transition from aerobic to anaerobic respiration.
iii. It should reduce water vapour permeability.
iv. It should enhance appearance, maintain structural integrity, improve mechanical handling, carry active agents (antioxidants, vitamins, etc.), and retain volatile flavour compounds.
v. It should melt at 40°C without decomposition.
vi. It should be easily emulsifiable, non-sticky or not tacky, and have good drying properties.
vii. It should never interfere with the quality of fresh fruit or vegetables or impose an unpleasant odour.
viii. It should be economical and have low viscosity.
ix. It should be translucent to opaque, but not like glass, and able to withstand slight pressure.

Types of edible coating

Edible coatings are divided into three major categories (Fig. 2). Hydrocolloids include polysaccharide-based coatings (starch, chitosan, cellulose, alginate, pectin, gums, etc.) and protein-based coatings (zein, whey protein, wheat gluten, casein, soy protein, egg albumin, gelatin, etc.), lipid-based coatings (waxes, fatty acids, etc.), and composite coatings, which are made up of more than one material or substance (Kurek and Sectar, 2017).

Hydrocolloids

Hydrocolloids are a diverse group of long-chain polymers characterized by their ability to generate viscous dispersions and/or gels when dispersed in water. These compounds were first discovered in tree or shrub exudates, plant or seaweed extracts, flours made from seeds or grains, sticky slimes produced by fermentation processes and a variety of other natural items. The presence of a large number of hydroxyl groups significantly improves their affinity for attaching water molecules, making them hydrophilic substances. They also form a dispersion that is intermediate between a true solution and a suspension, with colloid-like characteristics. Given these two characteristics, they are correctly referred to as 'hydrophilic colloids' or 'hydrocolloids' (Milani and Maleki, 2012). They have a hydroxyl group and may be polyelectrolytes such as Alginate, Chitosan, Pectin, Gums, etc. Hydrocolloids are widely used as coating solutions to enhance the colour, texture, flavour, and shelf life of fruits and vegetables (Williams, 2000). In general, all hydrocolloids are either entirely or partly dissolved in water and their main function is to raise the viscosity of the aqueous phase (continuous phase), i.e. gelling agent thickness (Baldwin *et al*., 1995). They act as an emulsifier due to this stabilizing effect. The hydrocolloids are divided into two categories. They are polysaccharide-based and protein-based hydrocolloids.

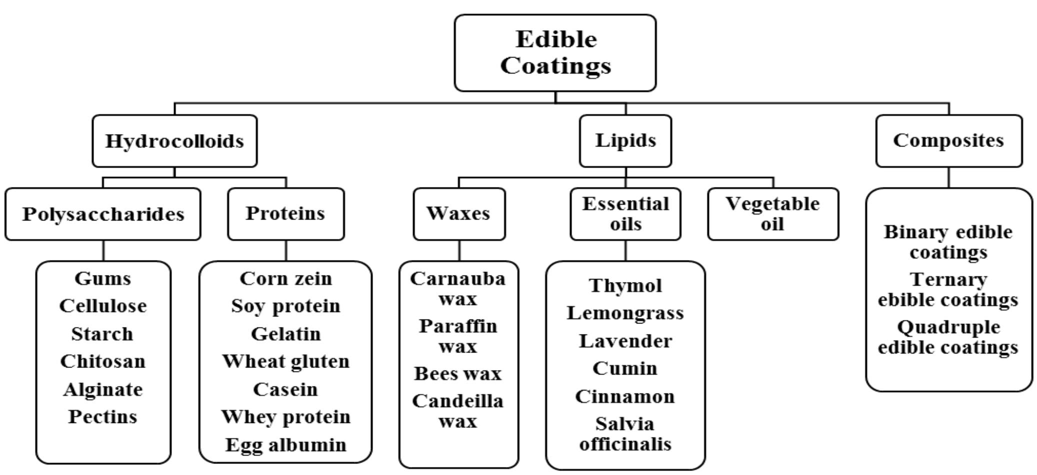

Fig. 2 : Types of edible coating

Polysaccharide based coatings

Polysaccharides are naturally occurring polymers that are used to make edible coatings. Polysaccharides used in edible coatings include cellulose, starch, pectin, seaweed extracts, exudate gums, microbial fermentation gums, and chitosan (Krochta and Mulder-

Johnson, 1997). Polysaccharides are hydrophilic, which results in poor water and gas barrier qualities. Polysaccharide polymer coatings can operate as sacrificial agents, reducing moisture loss from food products (Kester and Fennema, 1986). The edible coating made from polysaccharides contains antioxidants and antimicrobial properties. It is effective in preserving fruits and vegetables while also increasing their quality (Galgano, 2015). Polysaccharide based edible applications on food products are summarized in Table 1.

(a) Starch

Starch is a natural polymer composed of two types of glucose polymers: a linear chain molecule termed amylose and a branched polymer of glucose termed amylopectin (Rodriguez *et al*., 2006). There are several sources of starch such as rice, potatoes, corn and wheat (Alves *et al*., 2007). A starch-based coating featuring antioxidants and antibacterial properties can extend the shelf life of fruits and improve their visual appearance. It is also economical (Jimenez *et al*., 2012). Recent developments in starch-based coatings have proven quite effective at enhancing barrier and mechanical performance through modifications with nanofillers and extracts, thereby increasing the postharvest shelf life of fruits and vegetables (Dai *et al*., 2024).

(b) Chitosan

Chitosan is a polysaccharide derived from alkaline deacetylation of chitin (1-4)-linked 2-acetamido-2-deoxy-b - d -glucan (Abdou *et al*., 2008). Chitin, the most abundant naturally occurring biopolymer (after cellulose), can be found in the exoskeleton of crustaceans (crab and shrimp shells), fungal cell walls, and other biological components (Andrady and Xu, 1997). Chitosan has excellent properties, including a good O_2 barrier, CO_2 permeability and antibacterial activity against microorganisms, without the need for additional additives or antioxidants. Chitosan exhibits excellent mechanical properties. Chitosan has a very high viscosity, similar to natural gums (Raghav *et al*., 2016). Chitosan's transparent and clear coatings extend the shelf life of fruits and vegetables. Coatings are typically smooth, lustrous, cohesive, and free of cracks on the surface (Ribeiro *et al*., 2007). In a recent study, chitosan oligosaccharide coatings effectively maintained postharvest quality parameters and increased the shelf life of mango fruit during storage (Nitu *et al*., 2025).

(c) Cellulose

It is one of the most common natural polymers on Earth. Cellulose ethers are polymer substances obtained by partial substitution of three hydroxyl group positions 2, 3 and 6 on the glucosyl unit of cellulose. The most common celluloses are methylcellulose, hydroxypropyl cellulose, hydroxypropyl methylcellulose and carboxymethyl cellulose (Robertson, 2005). In general, modified cellulose derivative edible coatings and films provide colourless, transparent solutions that are odourless and tasteless. It has good resistance properties to oil and fats and is soluble in water and is slightly permeable to moisture and gas transmission (Krochta and Mulder-Johnston, 1997). The mechanical barrier properties of cellulose edible coatings are determined by the molecular weight of the cellulose, that is the higher the molecular weight, the better the barrier properties (Avena-Bustillos *et al*., 1993). However, cellulose derivative coatings have poor gas and water barrier qualities. Polysaccharide derivatives are hydrophilic in nature, resulting in poor mechanical properties.

(d) Gums

Gums are naturally occurring polysaccharides, which are made up of sugars. Gums are used for making edible coatings on fruits and vegetables due to their texture (Raghav *et al*., 2016). There are three types of gums:

i. Exudate (e.g., gum Arabic)
ii. Extractive (e.g., guar gum)
iii. Microbial fermentation (e.g., xanthan gum).

Xanthan gum is produced by a fermentation process that requires microbial extraction. It spreads quickly in water because of its high viscosity and can be used in both hot and cold phases (Mei *et al*., 2002). Gum arabic, a polysaccharide, is used in the food industry as a coating, thickening, emulsifier and beverage due to its antioxidant and antifungal properties against pathogenic germs (Gado and Aldahmash, 2013). Guar gum comes from the seed endosperm of *Cyamopsis tetragonolobus*. It is commonly used as a thickening agent and packing material due to its nontoxic, high mechanical strength, and antibacterial qualities (Sharma *et al*., 2018).

(e) Alginate

Alginates and carrageenans can be used for making edible coatings. Alginates are salts of alginic acid, a linear copolymer containing D-mannuronic and L-guluronic acid monomers. Alginates create coatings by reacting with divalent and trivalent cations like calcium, ferrum, or magnesium, which act as gelling agents (Cha and Chinnan, 2004). It is important to mention from the latest study that use of sodium alginate with natural antimicrobials ensures controlled release of the bioactive compound as well as provides higher antioxidant activity (Pandey *et al*., 2025).

(f) Pectin

Pectin is a form of polysaccharide derived from plants and can be found in vegetables and fruits. It is beneficial for low-moisture fruits and vegetables, but not a good moisture barrier (Baldwin *et al*., 1997). According to Yossef (2014), adding pectin to strawberries reduced hardness shift, weight loss, and fruit degradation caused by microbes. Current characterization studies of biopolysaccharide films derived from plants, such as pectin films, have established relationships between their water resistance and mechanical characteristics based on the surface properties of fruits and vegetables that help choose appropriate films for coatings (Ferreira *et al*., 2025). In more recent times, the use of pectin derived from cacao shell powder as an edible coating for tomatoes proved to maintain better firmness, weight, pH value, and colour than those tomatoes without coating during storage, indicating the possibility of using agro-industrial wastes as sources of pectin in coatings (Pholsin *et al*., 2024).

Table 1 : Polysaccharide based edible coatings

Commodity	Coating Material	Effect of Coating	References
Pome fruit			
Apple	Tragacanth gum	Prevented softening and senescence, maintained fruit firmness during storage, maintained juice pH and acidity, reduced weight loss, delayed ripening, and improved sensory and external quality.	Jahanshahi *et al.* (2018)
Stone fruit			
Plum	Starch	Reduced weight loss, lowered respiration rate, maintained total phenolics, flavonoids, antioxidant capacity, and free radical scavenging activity.	Thakur *et al.* (2018)
Berry fruit			
Strawberry	Chitosan	Improved firmness and reduced weight loss and decay, preserved anthocyanins and flavonoids, delayed senescence, colour changes, and off-flavour development.	Riaz *et al.* (2021)
Tropical and subtropical fruits			
Mango	Chitosan	Extended storage life up to 60-65 days.	Shweta *et al.* (2014)
Mango	Chitosan oligosaccharides	Maintained postharvest quality and increased shelf life.	Nitu *et al.* (2025)
Banana	Chitosan	Delayed changes in acidity, pH, and weight loss, prevented microbial deterioration and maintained sensory quality during storage.	Hossain and Iqbal (2016)
Papaya	Aloe vera gel	Retained firmness and reduced weight loss, exhibited antifungal activity, maintained pH, ascorbic acid, carotenoids, phenolics, flavonoids, antioxidant activity, and extended shelf life.	Mendy *et al.* (2019)
Pineapple	Aloe vera gel	Delayed ripening by acting as a physical barrier, preserved fruit quality, minimized ascorbic acid loss, delayed softening and extended shelf life to seven weeks.	Adetunji *et al.* (2012)
Guava (cv. Gola)	Xanthan gum (0.25-0.75%)	Reduced moisture loss and decay; improved TSS, titratable acidity, and sugar-acid ratio, preserved phenolics, flavonoids, and antioxidant capacity.	Gull *et al.* (2024)
Jujube	Xanthan gum (0.3%)	Delayed firmness loss and ripening, suppressed cell wall-degrading enzymes and reduced respiration and ethylene production.	Naveed *et al.* (2024)
Cucurbit fruits			
Fresh-cut melon	Chitosan	Maintained firmness, prevented off-flavour and reduced microbial growth.	Poverenov *et al*. (2018)
Fruit vegetables			
Tomato	Gum Arabic (5-20%)	Ten per cent Gum Arabic reduced ripening and ethylene production, and maintained antioxidant activity for a longer period.	Ali *et al.* (2013)
Tomato	Pectin (cacao shell powder)	Reduced weight loss and improved retention of firmness, pH, colour, and total soluble solids during storage.	Pholsin *et al.* (2024)
Cucumber	Arabic gum	Reduced weight loss, maintained nutritional and sensory quality and extended shelf life.	Al-Juhaimi *et al*. (2012)
Root vegetable			
Carrot (minimally processed)	Aloe vera gel + safe salts	Improved physical quality and physicochemical properties during storage.	Ahmed *et al.* (2024)

Protein based coatings

Edible coatings based on protein come from plants and animals. Plant-based protein coatings include zein (from maize), soy protein, and gluten (from wheat), while animal-based proteins include whey protein, milk protein casein, egg albumin, and gelatin (Baldwin *et al*., 1995). Protein-based edible coatings have excellent O2 barrier properties at low relative humidity. Protein-based coatings are not effective barriers to water vapour due to their hydrophilic nature, but they have excellent organic and mechanical properties (Krochta, 2002).

(a) Corn zein

Corn zein, the most significant protein in corn, is insoluble in water. It is a prolamine protein in corn endosperm and therefore dissolves in 70–80% ethanol (Landry, 1997; Dickey *et al*., 2002). Zein proteins are derived from maize and corn gluten flour. Zein protein is immiscible in water but can be dissolved in aqueous alcohol and glycol esters. Zein protein exhibits good coating, adhesion, and binding properties. Corn-Zein protein is good in preventing colour change, hardness, weight loss and increasing the shelf life of fruits and vegetables. It has a good barrier property to oxygen (Park *et al*., 1994a).

(b) Soy protein

Soybeans have a protein concentration of 38-44%, which is significantly greater than cereal grains' (8-15%) protein content. A variety of globular proteins make up the soy protein. The two main protein fractions that make up soy protein are called the 7S (conglycinin, 35%) and 11S (glycinin, 52%) fractions (Cho and Rhee, 2004). According to Kinsella *et al.* (1979), the majority of the protein in soybeans is soluble in diluted neutral salt solutions but insoluble in water.

(c) Wheat gluten

Wheat gluten is a general term for water insoluble proteins of wheat flour, which is made up of a mixture of polypeptide molecules, considered to be globular proteins (Dhall, 2013). When wheat gluten protein is combined with glycerol, it can form a fibrous network that enhances the stiffness, flexibility, and ductility of coating films (Alves *et al*., 2017). Wheat gluten edible coating can help preserve fresh food under controlled conditions (Mujica-Paz and Gontard, 1997).

(d) Whey protein

Whey protein is a byproduct of cheese production and is high in β-lactoglobulin. When processed properly, it forms flexible but brittle films. It has a high nutritional value and has been extensively investigated as an edible coating (Kaya and Kaya, 2000). Whey protein isolates (WPI) are purified forms of whey protein. WPI can carry various substances, including antibacterial agents. This increases storage life and improves packaged food safety by keeping high concentrations of active ingredients on the food surface for longer periods of time (Ponce *et al*., 2008). Recent research has confirmed that whey protein isolate coatings, even used as the sole polymeric component, can effectively extend the shelf life of commercial strawberries by reducing weight loss and preserving marketability (da Silveira *et al*., 2025).

(e) Gelatin

Gelatin is obtained by controlled hydrolysis of the fibrous insoluble protein collagen, which is found naturally as a major component of skin, bones, and connective tissue. Gelatin is distinguished by its high amino acid content, which includes glycine, proline, and hydroxyproline. Gelatin also contains a mixture of single and double unfolded chains with hydrophilic properties (Bawn, 1987). Gelatin is used widely as an encapsulating agent in hard and soft gel capsules for low-moisture or oil-based food ingredients, dietary supplements, and pharmaceutical applications. (Baldwin, 2007).

Table 2 : Protein based edible coatings

Commodity	Coating Material	Effect of Coating	References
Pome fruits			
Apple	Whey protein	Reduced weight loss and respiration rate, maintained firmness and colour and extended shelf life.	Shendurse *et al.* (2018)
Pear	Soy protein	Maintained moisture content and fruit firmness during storage.	Dave *et al.* (2017)
Stone fruits			
Apricot	Zein	Reduced moisture and acid loss, inhibited microbial growth and extended storage life.	Baysal *et al.* (2010)
Peach	Gelatin + trans-cinnamic acid	Improved barrier, antimicrobial and antioxidant properties, extended shelf life while preserving quality, sensory, and nutritional attributes during 20 days of cold storage.	Sultan *et al.* (2024)

Berry fruits			
Strawberry	Gelatin	Gelatin coating containing grapefruit seed extract increased shelf life while maintaining sensory quality and reducing microbial spoilage.	Lim *et al*. (2010)
Strawberry	Whey protein isolate (WPI)	Reduced film solubility, enhanced water resistance and contributing to prolonged shelf life.	da Silveira *et al*. (2025)
Tropical and subtropical fruits			
Papaya (fresh-cut)	Zein + ascorbic acid	Delayed colour changes, reduced weight loss, retained firmness and carotenoids, inhibited microbial growth and extended shelf life to 12 days.	Beulah and Sucharitha (2025)
Ber (*Ziziphus mauritiana*)	Aloe vera gel + tamarind starch + whey protein	Delayed physicochemical changes provided the best quality retention at 4 ± 1°C in polypropylene packaging.	Bhadu *et al*. (2023)
Avocado	Soy protein isolate–cellulose nanocrystal	Developed a techno-economically and environmentally sustainable bio-based coating that was cost-competitive with conventional wax coatings.	Rajendran *et al*. (2024)
Fruit vegetables			
Tomato	Zein	Delayed colour changes, reduced firmness and weight loss and extended shelf life.	Park *et al*. (1994a)

Lipid based coatings

People have been using lipid-based coatings for over eight hundred years. Lipid-based coatings have historically been used to wax fruits and cover confectionery products (Kester and Fennema, 1986). Lipid coatings are known for their hydrophobic properties, which effectively prevent moisture loss. Lipid-based coatings can prevent water loss, reduce respiration, lengthen shelf life, and provide a shiny and glossy appearance to food. Additionally, they protect against chilling damage, which usually happens during cold storage (Dhall, 2013). Common lipid-based coating materials include carnauba wax, beeswax, paraffin wax and essential or vegetable oils. Lipids have strong water barrier capability (Raghav *et al*., 2016).

Waxes

Wax-based coatings include paraffin wax, candelilla wax, beeswax, carnauba wax, polyethylene wax, etc. Carnauba wax (CW) is the toughest commercial natural wax, with the highest melting point. This wax is made up of aliphatic esters and diesters of cinnamic acid, making it the least soluble wax. It comes from the leaves of the Brazilian palm carnauba (*Copernicia prunifera*). It is used in food as a carrier, glazing agent, acidity regulator, bulking agent and anticaking agent in surface treatment, among other applications (De Freitas *et al*., 2019). Paraffin wax (PW) is a solid hydrocarbon derived from a fraction of crude petroleum. it has only suitable for raw fruits and vegetables, it serves as a moisture barrier and provides a shiny, glossy appearance (Shih *et al*., 2011). Recently, a study conducted on edible coatings made from carnauba wax applied to oranges indicated better retention of firmness, weight, and visual quality, in addition to delayed ripening during cold storage, proving that wax coatings are still important in managing citrus fruits post-harvest (Babarabie *et al*., 2024).

Beeswax is derived from honeybees. Beeswax coating improves quality attributes like moisture and gas permeability resistance, as well as the physical and mechanical properties of edible films (Sajid *et al*., 2019). Candelilla wax (CW) is derived from the leaves of Euphorbia antisyphilitica and Euphorbia cerifera, which grow in the southwestern United States and northern Mexico. Several research have examined the efficiency of candelilla wax in edible films for extending the shelf life of fresh food (Aguirre-Joya *et al*., 2017).

Essential oils

Essential oils have antimicrobial, anti-browning, and colourant properties due to their hydrophobic and volatile structure. Incorporating essential oils in edible coatings enhances their functionality and improves shelf life and freshness (Barzegar *et al*., 2020). Aromatic plants produce essential oils, which are secondary metabolites with a variety of biological functions. Essential oils are considered safe (GRAS) by the American Food and Drug Administration (Sivakumar and Bautista-Banos, 2014). According to the recent reviews, essential oil-based nanoemulsion coatings provide an environmentally friendly way of providing controlled release of antimicrobials and antioxidants to preserve fresh and fresh-cut fruits and vegetables (Sharma *et al*., 2024).

Thymol is a natural essential oil that is certified as generally regarded as safe (El Asbahani *et al*., 2015). It is commonly used as an aromatic spice, antioxidant and antifungal against Botrytis cinerea (Campos *et al*., 2011). Lemongrass oil has antibacterial properties against gram-positive and gram-negative bacteria, as well as yeast and mould (Naik *et al*., 2010). The primary components of lemon essential oil, which is derived from citrus lemon, limonene, ocimene and valencene (Moufida and Marzouk, 2003). Lavender essential oil, derived from the herb Lavender (Lavandula spp.), has been used for centuries as a therapeutic treatment. It possesses antibacterial, carminative, sedative, anti-inflammatory, and anti-depressant properties (Cavanagh and Wilkinson, 2005). Cinnamon essential oil prevents grey mould and rhizopus rot, which can damage strawberry fruit (Yousef *et al*., 2019).

Vegetable oils

Vegetable oils such as sunflower, olive, rapeseed, and maize oil are widely available, affordable, nonvolatile, non-depletable, nontoxic, and contain monounsaturated fatty acids. As a result, their use as an edible coating on food has been linked to numerous health benefits (Ma *et al*., 2012).

Table 3 : Lipid based edible coatings

Commodity	Coating Material	Effect of Coating	References
Pome fruits			
Apple	Cinnamon essential oil	Increased antioxidant potential, reduced microbial growth, maintained acidity, colour and firmness during storage.	Rashid *et al*. (2020)
Fresh-cut apple (cv. Braeburn)	Chitosan + oregano & cinnamon leaf essential oils	Enhanced antioxidant and antimicrobial activity, thereby extending the shelf life of fresh-cut apples.	Ali *et al*. (2025b)
Berry fruits			
Strawberry	Cumin essential oil	Reduced discolouration, delayed fungal decay and colour changes, and extended shelf life.	Asghari *et al*. (2009)
Strawberry	Bergamot essential oil + natural antioxidant extract	Extended shelf life through enhanced antioxidant and antimicrobial protection.	De Bruno *et al*. (2023)
Tropical and subtropical fruits			
Mango	Wax	Retained dark green peel while allowing normal yellowish-orange pulp development, Reduced weight loss and preserved carotenoids and ascorbic acid, Increased shelf life and reduced fruit decay.	Mandal *et al*. (2018)
Avocado	Carnauba wax	Reduced mass loss, maintained colour and firmness without off-flavour development, delayed ripening and extended shelf life	Feygenberg *et al*. (2004)
Citrus fruits			
Orange (cv. Moro)	Carnauba wax	Retained firmness, reduced weight loss, maintained visual quality, and delayed ripening during cold storage.	Babarabie *et al*. (2024)
Organic orange & lemon	Carnauba wax + essential oils/fruit by-products	Reduced fungal decay and sporulation (≈75%) caused by *Penicillium digitatum*.	Martínez-Zamora *et al*. (2025)
Mandarin orange	Carnauba + shellac wax + carvacrol nanoemulsion	Reduced weight loss and maintained firmness, total soluble solids, and titratable acidity, doubled shelf life to 30 days under ambient storage.	Devi *et al*. (2025)
Fruit vegetables			
Tomato	Beeswax	Reduced weight loss and firmness loss, reduced microbial deterioration, and maintained colour, taste, and flavour during storage.	Zewdie *et al*. (2022)

Composite coatings

Composites or Multicomponent coatings consist combination of protein, polysaccharides and lipid-based materials. In recent years, there has been a great focus to the creation of bilayer or composite coatings that include polysaccharides, proteins, and/or lipids for improved coating functional quality. Because every coating substance has a distinctive but restricted purpose. The functionality can be enhanced by combining two different kinds of coating materials. The main function of composites is to get greater benefit by the highest achievable performance of the mixture while keeping the qualities of the individual components stable. Edible coatings with composite properties can be created by combining different materials (Khalid *et al*., 2022). Composite coatings are classified into binary films and coatings, ternary edible films and coatings and quadruple edible films and coatings. Bilayer composites consist of two layers coated with different or similar materials, such as lipid/lipid, protein/protein, polysaccharides/lipid, and polysaccharides/ polysaccharides (Suppakul *et al.*, 2016). The latest developments in the technology of nanoparticle-based coating composites have enhanced the sustainability and antimicrobial efficacy of fruit and vegetable packaging (Awlqadr *et al.*, 2025).

Table 4 : Composite based edible coatings

Commodity	Coating Material	Effect of Coating	References
Berry fruits			
Blueberries	Chitosan + quinoa protein + sunflower oil	Reduced weight loss and respiration rate, maintained pH, soluble solids, and acidity during storage, controlled microbial growth and extended shelf life.	Abugoch *et al.* (2016)
Blueberry	Caseinate + carboxymethyl chitosan + soybean oil	Extended postharvest shelf life through improved film-forming, antimicrobial, and moisture-barrier properties.	Mohamed and Ramaswamy (2025)
Strawberry	Apple pectin + soy protein isolate + punicalagin	Improved film functional properties and antioxidant activity, resulting in better strawberry preservation.	Guo *et al.* (2024)
Tropical and subtropical fruits			
Guava	Aloe vera + chitosan + alginate	Maintained firmness, reduced weight loss, and minimized discolouration, reduced respiration rate, preserved ascorbic acid, anthocyanins, total phenolics, and antioxidant activity.	Kumar *et al.* (2017)
Ber (*Ziziphus mauritiana*)	Pectin + karonda polyphenols	Improved postharvest life and quality retention.	Kaur *et al.* (2024)
Longkong	Carboxymethyl cellulose + gelatin + melatonin	Reduced chilling injury and pericarp browning during low-temperature storage.	Venkatachalam *et al.* (2024)
Citrus fruits			
Orange	Sodium alginate + locust bean gum	Maintained firmness and reduced weight loss, exhibited antifungal activity.	Aloui *et al.* (2015)
Citrus fruits	Hydroxypropyl methylcellulose + beeswax	Reduced weight loss, delayed changes in acidity and soluble solids, preserved sensory quality, extended shelf life and reduced fungal decay.	Guimaraes *et al.* (2019)
Mandarin	Chitosan + phenylalanine	Enhanced retention of postharvest bioactive compounds during shelf life and cold storage.	Jurić *et al.* (2025)
Fruit vegetables			
Tomato	Soy protein + carboxymethyl cellulose + oleic acid	Extended shelf life under ambient conditions, slowed changes in pH, total soluble solids, total sugars, and reducing sugars, while delaying losses of acidity and vitamins during storage.	Nandane and Jain (2011)
Root vegetables			
Carrot (sliced)	Yam starch + chitosan	Prevented yeast and mould growth, improved quality, and extended shelf life.	Durango *et al.* (2006)

Methods of application of edible coating

1) Dipping
2) Spreading
3) Extrusion
4) Spraying
5) Solvent casting

Dipping

The dipping method is commonly used to apply edible coatings to fruits and vegetables. This involves dipping them in a coating solution for 5-30 seconds and then allowing the excess coating to drain as it dries and solidifies (Grant and Burns, 1994). Dipping is the easiest approach and involves three steps: immersion, deposition and evaporation of solvent (Tavassoli-Kafrani *et al.*, 2016). According to Grant and Burns (1994), dip-coating is excellent for producing high-quality, uniform coatings but requires precise control and a clean environment. Dipping application is usually adequate for small quantities of commodities.

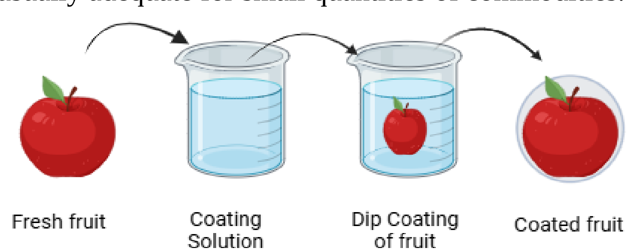

Fig. 3 : Dip coating method.

Spreading

The spreading technique is suitable for coating solutions with a high viscosity. The wetting level and spreading rate are crucial elements in determining how the coating solution spreads on the food surface. Coating deposition efficiency depends on several factors, including substrate quality, drying conditions, liquid properties, and surface geometry (Kumar and Prabhu, 2007). This technique is used to specially control the escalation of suspension onto the surface of the material. Its method is applied to the production of polysaccharide and protein-based films. This is the alternative to the casting method (Khan and Nasef, 2009).

Extrusion

The extrusion process is based on the thermoplastic properties of polymers when plasticized and heated above their glass transition temperature under low water content conditions. The extrusion processing of polymer products often needs the addition of plasticizers such as polyethylene glycol and sorbitol in an amount of 10% to 60% w/w. In comparison with the solvent casting method, the extrusion method is attractive for industrial processes since it does not require solvent addition and time of evaporation (Valverde *et al*., 2005).

Spraying

Spraying is the process of using a set of nozzles to spread smaller droplets on the fruit surface. Spraying methods are used in three different ways, such as air spray atomization, pressure atomization and air assisted airless atomization. In addition, the coating thickness is more than that of the dipping method due to the low viscosity of the solution (Andrade *et al*., 2012).

Fig. 4 : Spray coating method

Solvent casting

The casting method (also known as solvent casting) is the most widely used method for film formation in laboratories and on pilot scales. This technique involves three steps to prepare a film from biopolymers: i) Solubilising the biopolymer in an appropriate solvent, ii) Casting the solution in the mould, and iii) Drying the casted solution (Rhim *et al*., 2006). The formulation of edible films begins with the selection of the polymer or polymer mixture that will form the basic film. The selected polymer is dissolved or dispersed in a suitable solvent; this is known as solubilisation. In the casting procedure, the obtained solution is poured into a predefined mould or teflon-coated glass plates. The drying process provides enough time for evaporation of the solvent, which makes a polymer film that adheres to the mould (Suhag *et al*., 2020).

Advantages of edible coatings

Advantages of edible coatings (Nisperos-Carriedo *et al*., 1991; Park *et al*., 1994b; Guilbert and Biquet,1996; Sothornvit and Krochta, 2000) include:

i. Enhances exterior attractiveness by adding gloss to the fruit surface.
ii. Helps retain fruit freshness by reducing weight loss and keeping it firm.
iii. Reduces respiration and ethylene production, delaying senescence.
iv. Protects fruits and vegetables against chilling injuries and storage issues.
v. It acts as a barrier to free gas exchange.
vi. Serves as a carrier for postharvest chemical treatments.
vii. Contains fragrance compounds, antioxidants, pigments, anti-browning agents and vitamins.
viii. Reduces the use of synthetic packing materials.
ix. Edible coatings enhance the retention of acids, colour, flavour, and sugar.
x. Ensure the quality of fruits and vegetables during storage.
xi. Reduce polymer packaging and waste.
xii. Edible coatings can be consumed along with fruits and vegetables; they contain health-beneficial nutrients.

Disadvantages of edible coatings

Disadvantages of edible coatings (El Ghaouth *et al*., 1991; Park *et al*., 1994b) include:

i. Thick coatings may inhibit oxygen exchange, resulting in off-flavour development.
ii. Edible coatings have good gas barrier properties, which cause anaerobic respiration due to this normal ripening process being disturbed in fruits and vegetables.
iii. Some edible coatings are hygroscopic, which helps to increase microbial growth.

Current Challenges and Research Gaps

Despite significant advancements in edible coating technology, there are still a number of issues that need to be resolved before the technology can be commercialized. Optimal balance between moisture barrier capacity, gas permeability and mechanical strength is still a big challenge as each biopolymer class has inherent functional limitations. Furthermore, the performance of the coatings is significantly affected by the formulation composition, characteristics of the commodity, storage conditions and environmental factors, making the preservation efficacy vary depending on the application.

Another important constraint is the ability to scale up the results of the laboratory to industrial production. However, there are many coating formulations that have shown considerable promise in controlled experimental conditions that need the process and cold-chain compatibility, coating uniformity, long-term stability, and economic viability to be tested. Moreover, bioactive ingredients such as essential oils and nanomaterials bring up issues about regulatory compliance, safety evaluation, and consumer acceptance. The broadening of sensory properties and the lack of harmonized regulatory systems and evaluation protocols also make the commercialisation of edible coating technologies difficult.

Future Perspectives

Researches in the future should focus on the development of multifunctional edible coating systems, which possess better barrier property, mechanical property and antimicrobial activity. Nanoformulations such as nanoemulsions and nanocomposites have become interesting alternatives for improving the functionality of the coating and for achieving controlled release of the active compounds. In the same way, composite and multilayer coatings based on polysaccharides, proteins and lipids are effective solutions to the drawbacks of using single-component biopolymers. The use of AI and machine learning in coating formulation will likely aid in coating formulation optimization and better prediction of coating performance under various storage conditions. Additionally, there is a potential for further development of edible coatings in combination with intelligent packaging features such as biosensors and freshness indicators, which will enable real-time monitoring of product quality throughout the supply chain. The valorization of agro-industrial by-products as sustainable coating materials and long-term commercial validation and assessment of the safety is also recommended. Solving these research gaps will play a crucial role in making edible coatings a viable alternative to traditional food packaging for the industry.

Conclusion

Edible coatings are promising systems for improving food quality and enhancing shelf life without affecting its safety and quality parameters because they act as a barrier to oxygen, moisture and other external factors. This reduces food waste by keeping perishables fresher for longer. Fruits and vegetables are stored in the food industry for several years using edible films and coatings. Natural, renewable resources such as proteins, polysaccharides, and lipids are used to create edible coatings, offering an environmentally acceptable alternative to standard non-biodegradable packaging and safety when consumed with fruits and vegetables. Therefore, edible coatings are progressively gaining popularity as a potential alternative to synthetic packaging. This manuscript suggests that edible coatings can delay ripening, slow mould and microbial growth, increase shelf life and preserve qualities like texture, freshness, vitamin C content, and nutritional value. Research has been done to enhance the mechanical characteristics, barrier capabilities, and durability of edible films and coatings, increasing their usefulness and acceptance for food applications. Moreover, the majority of research focuses on assessing how coatings affect the nutritional qualities of fruits and vegetables. There is little research on the health advantages of eating coated fruits and how these coatings may increase the positive impacts of fruit and vegetable consumption. It provides a novel strategy for additional study that may increase the value and usefulness of biopolymers in the food industry.

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