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A Comprehensive study in enhancing the shelf life of Papaya (*Carica papaya* L.) through edible coatings

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Abstract
Papaya is one of the world's most popular fruit crops, which has excessive nutritional content and medicinal use. In India, papaya has highest production rates among all fruit crops. Due to its perishable nature, 40-60% of the entire yield from several papaya cultivating locations is lost. As a climacteric fruit, it experiences losses after harvest because of living (microorganisms) as well as non-living difficulties (oxidative damage), resulting in an extremely less shelf life, up to four weeks. Papaya is susceptive to physical harm as well as postharvest injuries because it has thin skin. Edible coatings are adequate eco-friendly method to provide additional safety to intact or fresh-cut fruits, to preserve the quality and extend the shelf life of fresh fruits. They generate a partially permeable membrane which reduces permeability to water vapours while inhibiting microbial decomposition. Different kinds of edible coatings have been used for coating fruits, which have their own advantages. They add market value to fruits by enhancing appearance and preserving their quality. This review paper provides an overview of different edible coatings used for papaya and their coating techniques.

Keywords: Papaya, postharvest losses, edible coatings, shelf life, quality

Introduction
Papaya (*Carica papaya* L.) is one of the world's popular fruit crops, both nutritionally as well as economically. Papaya is called 'wonder fruit of the tropics' because it contains large concentration of vitamins, minerals, antioxidants, and phytochemicals with chemoprotective, anti-diabetic, anti-bacterial, and anti-fungal effects (Saeed *et al.,* 2014; Heena and Sunil, 2019) [52, 25]. India is the world's largest producer of papaya having 149-thousand-hectare area and 6050 thousand MT production (Anonymous, 2018-2019) [7], followed by Brazil. The fruit's peel is green and as it ripens it changes to yellow-orange. In general, papaya trees live between five to ten years (Singh and Rao, 2011) [61]. Papaya is said to be one of the most valued fruits, since it serves as an excellent source of antioxidant nutrients such as carotenes, vitamin C, and flavonoids, the B vitamins folate and pantothenic acid, the minerals potassium and magnesium, as well as fibre. Papaya also contains the enzyme papain which is used in the industrial production of brewed beverages, tenderizing meat, pharmaceuticals, beauty and cosmetic products (Evans and Ballen, 2012) [18].

Postharvest losses and their economic impact
Fresh fruits, until consumed and marketed are stored in suitable environments. Fresh fruits are reaped periodically in maximum amounts all over the world. They are living organisms which respire even after harvesting (Gatto *et al.,* 2011; Terry and Joyce, 2004) [21, 64]. In the course of storage and transport, fresh produce deteriorates their quality. Hence, fresh fruits and vegetables need to be stored carefully (Kader, 1989) [30]. In India, significant production rates are there in papaya. Papaya has the highest yield of all fruit crops in the country. However, 40-60% of gross yield from several papaya cultivating areas is lost. This is because the spoilable characteristic of this popular crop leads to the reduction of product quality and quantity. This seriously affects marketing and the income of papaya growers as waste is categorized as the overall value lost (Prasad & Paul, 2021) [47]. Nevertheless, as a climacteric fruit, this fruit undergoes losses after harvest because of living (microorganisms) and non-living challenges (oxidative damage),

resulting in an extremely less shelf life, up to four weeks (Ali *et al.*, 2011 and Rong *et al.*, 2024) [4, 51]. Coating design focuses on incorporating antibacterial compounds into polymeric matrix. Non-toxic antifungal chemicals in edible coating can prevent fungal deterioration, a leading cause of postharvest losses in fruits and vegetables (Saper and Chiralt, 2018) [56].

Limitations of conventional preservation methods

After harvest, fruits and vegetables lose solutes because of living organism actions. Losses after harvest of fresh produce result in loss in weight, changes in colour, structure, and enzymatic browning due to losses after harvest. Refrigeration is necessary for postponing maturity that include production of ethylene, becoming soft, changes in pigment, respiration, decreased loss in weight and antifungal activity (Saidi *at al.*, 2021; Gholamhosseinpour *et al.*, 2023) [55, 22]. Cold storage, in combination with other strategies, is not sufficient for maintaining fruit and vegetable quality at marketing level because it causes spoilage below 12 °C. But it is not enough to preserve quality of a product, satisfactory results are obtained through the application of edible coatings for extending postharvest life and reduction of production costs (Paidari *et al.*, 2021) [40]. Traditionally, the control of diseases in papaya involves the application of chemical fungicides both on the crop and during storage. However, repeated use has resulted in microbial resistance and Homo sapiens harm. Alternative postharvest procedures include precooling, surface sterilization, hot water treatment, along with natural alternative methods such as waxing and packaging using ethylene scrubbers, are becoming increasingly popular. Research suggests that although postharvest change in fresh fruits cannot be completely prevented, various techniques can successfully slow them down within specific limits (Sebastian and Bindu, 2024) [57]. This study aim for standardizing postharvest methods to delay maturation along with extending the period of storage of the fruit with minimal nutrients depletion, recognizing the importance of both pre and postharvest treatments in improving produce quality and storage (Aglar *et al.*, 2017) [3].

Edible Coatings: A Sustainable Approach

Edible coatings have been regarded as an eco-friendly method to provide further safety to fresh fruits by generating a partially permeable membrane reducing permeability to water vapours while inhibiting microbial development (Marín *et al.*, 2021) [35]. These coatings are made up of bio polymers or in certain cases suitable added ingredients that are applied directly to their surface of fruits and vegetables. These are typically less than 0.3 mm thick (Pirozzi *et al.*, 2020) [45]. These coatings have traditionally been used for preserving perishable foods from spoiling by slowing water loss, decreasing respiratory metabolism, improving texture, retaining unstable taste components, inhibiting microbiological development (Salehi, 2020) [53]. The rapid process of extension in fruits decreases water loss, because partially permeable covering of coating covers the stomata, thus limiting gases exchange and respiratory metabolism (Nogueira *et al.*, 2021) [39]. The edible coating is a thin layer of formulation that is applied to fruits and vegetables to increase their shelf life. The coating materials can be dissolved in any organic or inorganic solvent to create the coating solution. These substances may consist primarily of proteins, lipids, polysaccharides, or various composites (Dhall, 2013) [17]. As in present scenario, environment friendly coatings made from biological sources are used on fruits to increase storage life of fruits (Martins *et al.*, 2024) [37]. The first edible coating used on fruit surfaces was wax, which was made in 1992 (Priya *et al.*, 2023) [48].

For maintaining the quality standards of fruits and vegetables, edible coatings should possess certain characteristics:

- Low gaseous permeability is a significant feature of edible coatings because it slows respiration and transpiration rate, lowering ripening and senescence (Umaraw and Verma, 2017) [67].
- It restricts the movement of oxygen, carbon dioxide, solute molecules, and moisture from the surrounding environment into the fruits and vegetables (Lacroix and Vu, 2014) [34].
- Coating compounds must be inert for ensuring that they are non-reactive with the fruits and vegetables.
- It should be transparent.
- It keeps fruits fresh as well as juicy (Bhagath and Manjula, 2019) [9].
- The coating substance shouldn't give the food an unpleasant taste, odour, or dark hue.
- Edible coating should have minimum permeability barrier against water vapor.
- The ingredients used to make edible coatings should not be toxic and should be digestible (Umaraw and Verma, 2017) [67].
- The coating solution should not be sticky (Dhall, 2013) [17].
- The coating solution should be less viscous, affordable, as well as should have a fast-drying rate (Dhall, 2013) [17].
- Keeping the correct ratio of stickiness and cohesiveness particles is critical for consistent coating solution spreading (Azeredo, 2012) [15].

Edible Coating Materials for Papaya

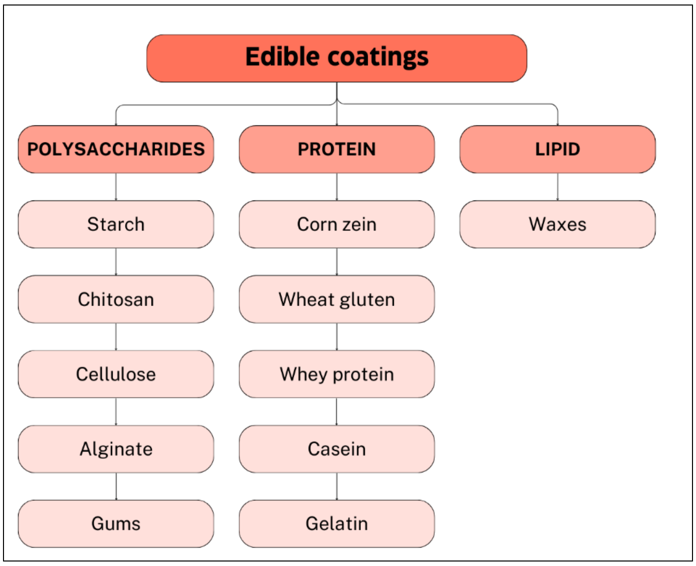

Fig 1: Types of edible coating materials

Sources that are natural vary and involve varied functional properties of the corresponding chemicals. Biopolymers are derived from polysaccharides which include pectin, cellulose, starch, gums, and lipids which include fatty acids, acetylated glycerides, surfactants, waxes, and proteins which include fatty acids, collagen, gelatin, waxes, resins, whey (Rodrigues *et al.*, 2020; Yildirim *et al.*, 2021; Panahirad *et al.*, 2021) [50, 68, 41]. Generally, bio-polymers that are heavily influenced by molecules with hydrophilic properties, possess a significant amount of transparency, are inexpensive, have no taste, and include a large content of phosphate ester, allowing their transparency to be seen. Composite coatings are applied to bilayer composite such as polysaccharides/proteins, polysaccharides/lipids, proteins/proteins, and gum combination (Galus *et al.*, 2020, Martinez *et al.*, 2019) [20]. Functional coatings are improved by adding bioactive compounds such as anti-microbials, flavonoids, anti-oxidants, colours, textures, sensors, and vitamins (Fang *et al.*, 2022; Shaukat *et al.*, 2023) [19, 58].

Polysaccharides based edible coatings

- **Starch:** It is a polymer that occur naturally made up of amylose (soluble in water) and amylopectin (insoluble in water), glucose molecules that can create powerful gels. Starch is generated from a variety of sources, such as wheat, corn, potatoes, and rice (Alves *et al.*, 2007) [6]. Coatings based on starch are viable ingredient to extend the storage life of fresh fruits that is easily accessible and inexpensive, and it contains anti-oxidants and anti-bacterial properties that are used for improving the visible appearance of fruits (Jimenez *et al.*, 2012) [28].
- **Chitosan:** Chitin is a natural occurring biopolymer that exists in crustacean exoskeletons, fungal wall of a cell, and various other biotic materials. Chitosan is formed through the deacetylation of the chitin in an environment that is alkaline (Abdou *et al.*, 2008) [1]. It is an effective film-forming agent. These coatings have selective permeability to gases such as CO2 and O2 and also have high mechanical properties. Chitosan has anti-bacterial and anti-fungal properties, and also being low in toxic effects and biodegradable (Ribeiro *et al.*, 2007) [49]. It has a significant disadvantage that when dissolved in an acidic solution, chitosan loses its mucoadhesive properties because of deprotonation (Suksamran *et al.*, 2011) [63].
- **Cellulose:** Cellulose, a natural polymer, is a linear an-hydro-glucose molecule that can be found in abundance. Because it is made up of 1-4 linked D-glucose molecules, it forms a strong hydrogen-bonded crystallized microfibre. Cellulose usage as a coating is challenging because it is insoluble in water and has closely connected crystallized form. Certain of its derivatives, such as hydroxyl propyl methyl cellulose, hydroxyl propyl cellulose, carboxy methyl cellulose, and methyl cellulose, are capable of overcoming the constraints related to its original form (Zugenmaier *at al.*, 2006) [69].
- **Alginate:** Brown algae produce structural polysaccharides known as alginates. Alginate possesses specific colloidal characteristics that help to stabilize emulsions and preserve fruit texture. Alginate is commonly utilized as anti-browning agent for coating of fresh fruits (Acevedo *et al.*, 2012) [2]. Polyvalent cation cross-linking enhances barrier characteristics, resistance to mechanical contact, viscidness, and rigidity in this coating (Cazón *et al.*, 2017) [13]. Adding vegetable oils such as rapeseed, coconut, or hazelnut, improves both the thermal and mechanical characteristics of sodium alginate films (Kadzińska *et al.*, 2020) [31].
- **Gums:** The term "gum" describes a group of naturally formed polysaccharide with commercial applications globally because of their ability to form gels, produce visco us solutions, and stabilize emulsion systems (Salehi *et al.*, 2020) [53]. Guar gum, as a surface additive, increased the shelf life of freshly harvested fruit with no altering consistent characteristics including loss of weight, stiffness, and total soluble solids (Minh *et al.*, 2019) [38].

Protein based edible coatings

- **Corn zein:** It comprises the corn storage protein, making up 45 - 50% of the protein content in corn. The zein-based coating has a reduced water vapor permeability than other protein-based coatings (Hauzoukim and Mohanty, 2020) [24].
- **Wheat gluten:** It is a protein found in wheat and other grains, like rye and barley. Gluten, often known as wheat seed proteins, can be recyclable and capable of being renewed. This coating is flexible enough to form a web-like network when combined with glycerol, which results in mechanical properties of rigidity, versatility, and elasticity (Alves *et al.*, 2017) [5].
- **Whey protein:** Whey protein edible films are colourless, flexible, transparent, and tasteless, with a low oxygen permeability (Hong and Krochta, 2006) [24]. Whey protein isolate serves as a good carrier of different substances, including antimicrobial agents. This leads to an increased shelf life and food safety while retaining a high concentration of the active component on the surface of food for a longer time (Ponce *et al.*, 2008) [46].
- **Casein:** Casein constitutes around 80% of the total milk protein. These coatings, therefore, are transparent, tasteless, and versatile which make it attractive in products. These were utilized to improve the quality of fresh fruit by applying edible coatings such as cellulose and pectin-based coatings (Panahirad *et al.*, 2021) [41].
- **Gelatin:** As for the studies on the manufacturing and ability to produce coatings using fish gelatine, film-forming characteristics were investigated: translucent, soluble in water, colourless, and flexible films (Carvalho *et al.*, 2008) [12].

Lipid based coatings

Waxes: Paraffin wax is a mixture of solid hydrocarbons obtained from a portion of crude petroleum. It has confined utility in covering raw fruits, but it functions as a moisture barrier, giving them a glossy surface (Shih *et al.*, 2019) [59]. Beeswax is obtained from honeybee. Beeswax coating works for preservation in retaining the quality attributes, including moisture resistance and resistance to permeability to gases and improving the functional characteristics, including mechanical and physical characteristics of the edible coatings (Sajid *et al.*, 2019). Carnauba wax is made from the leaves of *Copernicia prunifera*, utilized, among other things, as a carrier in food, glaze agent, regulator of acidity, and a substance that prevents caking utilized for the treatment of surfaces (de Freitas *et al.*, 2019) [16].

Coating Techniques

➢ **Dipping**

Dipping method is commonly used coating technique used in to increase shelf life of fruits. This method helps to achieve complete and consistent coating over the fruits. Fruits are immersed in the coating solution for a specific time period and then dried at room temperature (Ju *et al.*, 2019). Dipping consists of the following steps: Immersion of fruit, thin layer coating deposition and coating evaporation (Tavassoli-Kafrani *et al.*, 2016) [66]. Contact time usually relies on the density, surface tension, and solution consistency, it will take around 5 seconds to 3 minutes (Suhag *et al.*, 2020).

➢ **Spraying**

Using an atomizer, the coating solution is sprayed over the food sample. As the solution is sprayed at a higher pressure, small droplets of varying sizes are formed across the fruit. The efficiency of spray coating depends on the rheological parameters of the fluid, such as surface temperature, viscosity, and temperature (Suhag *et al.*, 2020) [62].

- **Brushing**

The brushing technique is appropriate for thick coating solutions. The degree of wetness and spreading factor are crucial elements in determining how the coating solution spreads on fruit surface. Coating deposition effectiveness depends on several factors, including substrate quality, drying conditions, liquid properties, and surface geometry (Kumar and Prabhu, 2007) [33]. In the brushing approach involved placing the coating solution in a petri dish and using a brush to evenly apply to the fruits. The fruits used as control were rinsed with distilled water and subsequently dried (Chettri *et al.*, 2024) [14].

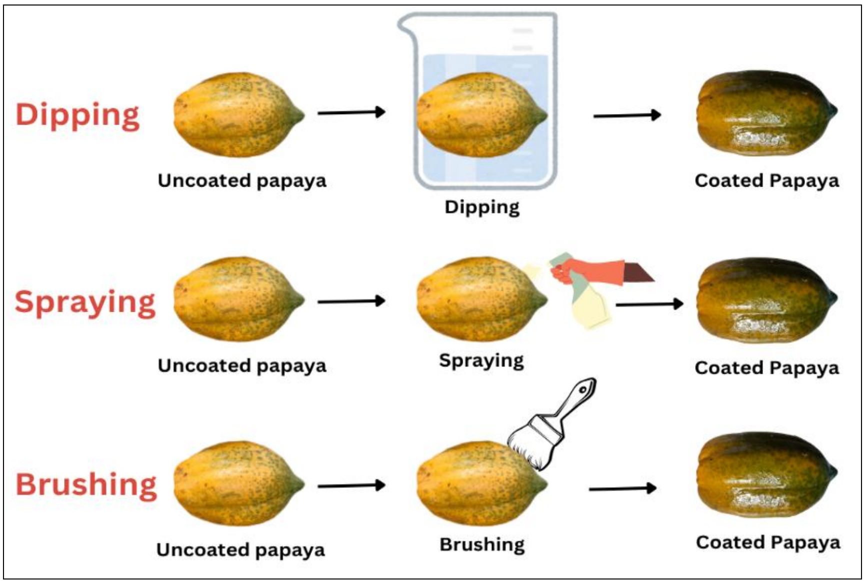

Fig 2: Coating techniques

Effects of Edible Coatings on Papaya Quality

Addition of various compounds to edible coatings can modify their sensory, nutritional, and functional qualities, mechanical properties also. Hydrocolloids (polysaccharides) are matrix components of edible coatings (Han, 2014). By using plasticisers (elasticity and extensibility), emulsifiers (emulsion stability), and cross-linking agents (physical qualities) coating matrix can be changed. Edible coatings are applied on fruits directly, therefore edible coatings can also include other food additives such as antioxidants, flavourings, and so on, altering their functional qualities (Dhall, 2013; Pérez-Gago *et al.*, 2010) [17, 43].

Future Trends and Challenges of Natural Films and Coatings

In some cases, coatings have been shown to increase the nutritional value of papaya by minimizing vitamin and antioxidant loss. The use of nanoparticles into edible coatings is developing as an intriguing area of study. Nano-sized particles such as nano clay, silver nanoparticles, and carbon nanotubes can significantly improve the barrier properties of edible coatings. These nanoparticles can form more compact and dense film structures, effectively reducing gas diffusion, hence extending shelf life. Nanomaterials can be used to enclose and control the release of active compounds from the coating matrix, ensuring that antimicrobials, antioxidants, and other bioactive substances reach the fruit's surface in a consistent and targeted manner, providing more effective postharvest decay prevention.

Conclusion

This review thoroughly studied how to extend the shelf life by using edible coating and preserve the quality of papaya. The incorporation of active substances such as essential oils (e.g., lemongrass, oregano), antioxidants (e.g., vitamin C, vitamin E), and antibacterial agents has significantly increased the efficacy of edible coatings in avoiding microbial deterioration and maintaining fruit quality. Optimization of coating properties, such as concentration, viscosity, and application method, has shown crucial in achieving optimal performance while minimizing detrimental effects on fruit sensory quality. Edible covers have effectively extended the shelf life of papaya by minimizing weight loss, lowering decay rates, and delaying ripening. They have also been shown to maintain fruit firmness, colour, and overall sensory attributes like flavour and texture. In some instances, coatings have been proven to improve papaya's nutritional value by reducing vitamin and antioxidant loss.

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