Reducing Post-Harvest Losses of Fruit and Vegetable Through Edible Coatings: An Effective Strategy for Global Food Security and Sustainability

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Abstract*— A substantial quantity of fresh fruits and vegetables (F&V) experience post-harvest loss, representing approximately one-third of the food produced worldwide. Because of its perishable nature and being affected by several factors, fresh F&V has a limited shelf-life. Inadequate storage facilities and mismanagement, during and after harvest, result in up to 50% post-harvest loss for F&V. Among the different accessible research developments, Edible Coating (EC) is emerging as a unique technology that has been proven to be a safe and successful approach in the post-harvest industry. EC extends the shelf-life of fresh F&V and minimises post-harvest loss, negating human health risks. Comprised of food-grade additives, EC technology is environmentally friendly and effectively regulates moisture, gaseous exchange, oxidation, and other biochemical processes in harvested F&V. Thus, EC is significantly contributing towards food security by ensuring more fresh produce and nutrition for the incremental population in a sustainable way. This review discusses the overview, perspective, and future research trends of EC for reducing post-harvest losses of fresh F&V.

Indexed Terms- Fruits and Vegetables; Sustainability; Edible Coating; Shelf-life; Post-harvest; Environment friendly

I. INTRODUCTION

The global population is increasing rapidly, and meeting the dietary requirements of this growing population is a noteworthy concern for humanity. As an obvious consequence, developing countries have already begun to face challenges related to food security. By 2050, the world's population is projected to reach 9.7 billion, requiring a 70% increase in the production of fresh fruits and vegetables (F&V) to ensure that everyone is fed proper nutrition (FAO, 2018). However, globally, fresh F&V is rendered unfit for consumption due to spoilage and experiences an estimated post-harvest loss of 20–30% (about 1.3 billion tonnes) worth about US $1 trillion (FAO, 2011) (Fig. 1). Climacteric F&V (*e.g.*, apple, avocado, banana, mango, tomato, potato), which continue to ripen even after harvesting due to increased ethylene production and strong cellular respiration, are more vulnerable to post-harvest losses than non-climacteric fruits (*e.g.*, grapes, berries, cherries, peppers, root vegetables).

Proper post-harvest management and storage techniques of fresh F&V are necessary to minimise losses and preserve the nutritional values (Zhang et al., 2021) (Fig. 2). Cold storage is commonly used worldwide to delay or control ripening-related changes such as ethylene production, softening of fruits, colour and acid level changes, respiration rate, and weight loss (Fragoso and Paz, 2016). However, cold storage alone is insufficient to preserve the quality of fresh F&V in the value chain system, especially during transportation and marketing. Moreover, in developing countries, inadequate cold storage facilities and unorganised packhouses significantly contribute to postharvest losses of F&V (Mohan et al., 2023). While industrialised nations experience most of the losses at the retail and consumer levels, developing nations face higher post-harvest losses just after the harvest and processing stages (Rajapaksha et al., 2021). At the global consumer level, the demand for high-quality fresh F&V with a longer shelf life and without chemical residue is increasing each day (Ssemugabo et al., 2022). According to FAO estimates, worldwide F&V losses range between 40 and 50%, with 54% occurring during cultivation, post-harvest, handling, and storage, and 46% occurring during processing, distribution, and consumption. Therefore, it is crucial to combine appropriate post-harvest management technologies with cold storage to ensure the quality, longevity, and increased shelf-life of F&V.

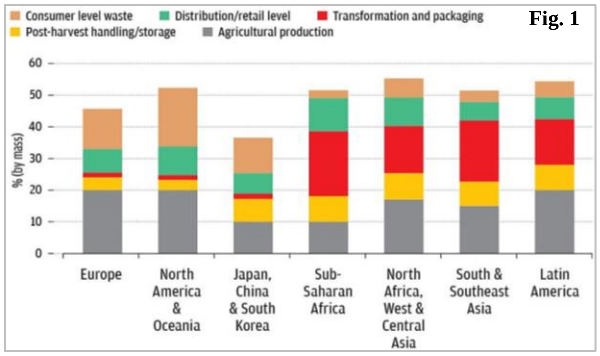

Fig. 1

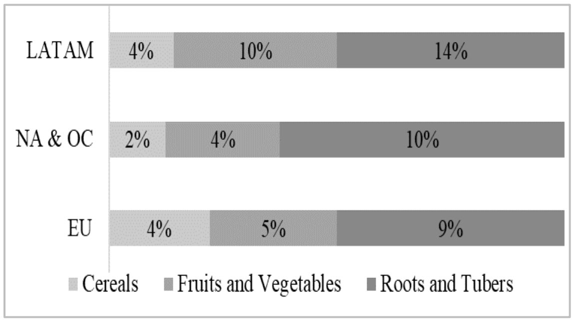

Fig. 2

Figure 1: Wastage and loss (%) of fruits and vegetables at different stages of the value chain worldwide (*Source: FAO report 'Global food losses and food waste-Extent, causes and prevention, 2011)*
Figure 2: Estimated post-harvest losses (%) on handling and storage in major regions (*Adapted: Gustavsson et al., 2011*).

EU=Europe (including Russia); NA & OC=North America & Oceania; LATAM=Latin America. Fruit and Vegetables: citrus, bananas, apples pineapples, dates, grapes tomatoes, onions, other fruits, and other vegetables.

Roots and Tubers= potatoes, sweet potatoes, cassava, yams, other roots

Cereals= wheat, rice (milled), barley maize, rye, oats, millets, sorghum, other cereal.

By understanding the gaseous and ambient parameters, it is possible to create a partially permeable protective layer that extends the shelf life of fresh produce of F&V after harvest. This layer or film effectively delays the biochemical processes associated with ripening and senescence. This technology is broadly termed 'coatings', which are applied directly to the surface of fresh produce to establish a protective layer to preserve freshness and maintain shelf-life (Tokatl and Demirdoven, 2021; Ungureaunu et al., 2023). Coating application also benefits in filling up any bruises on the pericarp that occur due to mechanical damage or environmental stress (Azam and Saad, 2023). Several studies have highlighted the effectiveness of coatings in prolonging the freshness of highly perishable fresh F&V (Kumar et al., 2016, 2017; Thakur et al., 2018; Tokatl and Demirdoven, 2021; Yang et al., 2014; Khorram et al., 2017). Moreover, the coating layer further causes the stomata and lenticels to close, which delays the occurrence of physiological disorders such as a decrease in weight loss (Lufu et al., 2021). Thus, coating offers a viable strategy by naturally enhancing the appearance of fresh F&V and significantly reducing post-harvest losses by extending shelf-life and minimising cell membrane dis-organisation, transpiration, and respiration rates (Pham et al., 2023; Bisen and Pandey, 2008; Mditshwa et al., 2023; Valenzuela et al., 2023). *Age-old traditional wax* coatings are *the most preferred way to preserve* F&V and can be either non-edible (paraffin oil) or edible (beeswax, carnauba wax, candelilla wax, and sugarcane wax). However, recently, 'edible, non-wax coatings' are more preferred and are gaining acceptance, justifying sustainability and safety in food and human health (Summo and Angelis, 2022; Wong et al., 2021).

'Edible coating' (EC) is a layer of edible material (safe to be consumed) applied to the surface of F&V to create a barrier against moisture, oxygen, and solute movement (Davis and Song, 2006; Kester and Fennema, 1986; Biquet and Labuza, 1988; Cuq et al., 1995; Pavlath & Orts, 2009; Owusu-Akyaw Oduro, 2022). These types of coatings offer mechanical, physical, and biological safeguards to fresh produce as well as protection from light and ultraviolet rays (Socaciu et al., 2018; Umaraw et al., 2020; Diaz Montes & Castro-Munoz, 2021; Kumar et al., 2020, 2022). ECs can be derived from both vegetable and animal ingredients. In recent years, EC has been considered 'green technology' and has gained significant attention due to its sustainable, environment-friendly advantages over chemical or wax coatings (Matloob et al., 2023; Chhikara et al., 2022). Food-grade ingredients used in EC improve the structural characteristics of the coatings, thereby offering a safe-to-consume commodity as well as enhancing the quality of the fresh produce (Pavlath and Orts, 2009; Alvarez et al., 2011; Diaz-Montes and Castro Munoz, 2021). EC degrades more rapidly compared to traditional polymeric materials due to their renewable compositions as ingredients (Guerrero et al., 2010; Kouhi et al., 2020).

Several researchers have reported different types of EC in fresh and minimally processed fruits and vegetables (Yousuf et al., 2018; Lin et al., 2007; Tahir et al., 2019; Jafarzadeh et al., 2021; De Castro, 2020; Cakmak et al., 2019). However, a comprehensive cumulation of the current perspective and research trends on EC is lacking. Therefore, the purpose of this review is to provide comprehensive information on edible coatings by summarising and analysing their current status and developments. The selected information was obtained from online publisher databases and were screened for accuracy, clarity of presentation, and relevance. Each chosen article was mentioned with a proven shelf-life assessment by edible coating technology.

II. FACTORS AFFECTING SHELF-LIFE OF FRUITS AND VEGETABLES

According to a published report by the FAO 2019 in the State of Food and Agriculture (SOFA), 14% of the food produced globally is wasted during the post-harvest production stage before reaching retail through the food chain. The shelf-life of horticultural products may be described as the amount of time between harvest and consumption during which the product is safe to consume and retains its recommended harvest quality (Echeverria et al., 2008). Post-harvest losses of F&V occur at all points in the value chain, from production in the field to being placed on a plate for consumption (Palumbo et al., 2022; Mditshwa et al., 2023). Fruits and vegetables make a significant contribution to food security, nutrition, and poverty reduction, as well as to generating economic development for society. Fresh F&V are extremely perishable due to their active metabolism and robust physiological post-harvest activities, which cause ripening and maturity, making marketing propositions difficult (Pott et al., 2020). The major factors that impact the post-harvest shelf-life of F&V are explained in more depth as follows (Martinez-Romero et al., 2006; Esti et al., 2002).

A. Physiological factors:

From harvest to storage, the quality and shelf-life of fresh F&V are affected by temperature, relative humidity, pH, quality, and light intensity. Particularly at higher temperatures with sizable vapour pressure differences, fresh F&V loses a considerable amount of weight. Thus, storage life is reduced by improper temperature management. Low temperatures are frequently used to extend storage life, although they can occasionally result in chilling injuries in tropical F&V (Suput et al., 2015). Low relative humidity during storage results in fruit weight loss, whereas high relative humidity promotes microbial development (Singh et al., 2014).

a. Respiration:

Even after harvesting, plant tissues are still alive and continue to breathe; carbohydrates are broken down during this metabolic process, and energy is released (Fonseca et al., 2002). In general, the rate of respiration has an inverse relationship with the storage life of horticultural produce and is directly related to quality characteristics such as firmness, sugar content, fragrance, and taste (Perdones et al., 2012; Fallik and Aharoni, 2004). Decreased oxygen availability causes total metabolic activity to decline, which results in slowing down respiration rates, less ethylene production, and less sensitivity to ethylene, which slows down ripening in storage conditions (Isenberg, 1979; Karen et al., 2010).

b. Temperature:

Temperature is the single most important factor in post-harvest storage and handling. Any rise in temperature above the ‘product-appropriate set point’ (the optimum temperature at which the product must be kept during transit or storage) will result in a lowering of the quality and shelf-life of fresh F&V (Thompson, 2002). Temperature significantly affects the appearance, shelf-life, texture, and nutritional qualities of stored F&V. According to the van’t Hoff rule (van’t Hoff, 1896), a biological reaction multiplies by 2 to 3 for every 10°C temperature increase. The shelf-life of fresh F&V diminishes because of increased metabolic activity caused by increase in temperature, which translates to increase in respiration rate. Low temperatures have been employed to increase the shelf-life of F&V, with the added benefit of preserving sensory qualities (Paull, 1999). Moreover, as enzymatic activity slows down at lower temperatures, the shelf-life of F&V is known to be extended. The impact of temperature on fresh produce is greatest during logistics operations. When fresh F&V is stored at low temperatures after heat treatment, damage can occasionally occur (Paull and Armstrong, 1994). The vitamins and other nutrient contents in many F&Vs are also affected by storage temperature (Weichmann, 1987; Ezell and Wilcox, 1959). A change in the sugar, acid, and volatile molecule content of fruits influenced by the differential long-term storage temperature causes a loss of flavour (Reyes and Paull, 1995).

c. Functional:

According to Kays (1991), when a commodity is exposed to cold temperatures, the tissues or cells of fresh produce are disrupted, and the product's quality suffers. This is particularly noticeable in several tropical and subtropical regions. A crop suffers damage when stored below its freezing point (Salunkhe et al., 1995). Internal browning, pitting, uneven ripening, off-flavour development, and an increased likelihood of decay were all caused by the chilling injury. The pace of physiological damage associated with storage conditions may be accelerated by low O_2 levels, high CO_2 levels, and excessive ethylene concentrations (Saltveit, 1996).

B. Biochemical factors:

Chemical and metabolic changes result in unpleasant sensory qualities in fresh F&V. Mechanical damage to F&V can activate endogenous pectinases, resulting in microbial attack. The most prevalent cause of food spoilage is non-enzymatic browning, known as Millard's reaction. This process causes bitter flavours, dark colours, and reduced nutritional accessibility of particular amino acids (Pott et al., 2020).

a. Ethylene and ripening:

Ethylene (C_2H_4) is a natural phytohormone produced from methionine and has a harmful impact on the growth, development, and storage life of fresh produce. It is a simple organic molecule in gaseous form that governs the physiological processes of fresh F&V after harvest, with the primary function of promoting fruit ripening (Abeles, 1992). Ethylene is a plant hormone that plays a key role in the ripening process of climacteric fruits, and the presence of ethylene is required for the expression of ripening-related genes even in the mature stages of the fruit (Hoeberichts et al., 2002; Alexander and Grierson, 2002). Many F&Vs are vulnerable to ethylene levels as low as 0.1 ppm if exposed for the longest possible time. In general, the perishability of climacteric fruits is more rapid and severe than that of non-climacteric fruits (Mishra and Gamage, 2007). Strawberries, for example, produce very little ethylene but are particularly vulnerable to it (Pierik et al., 2006). When a larger surface area is exposed to the environment, ethylene production increases, resulting in tissue softness and an unfavourable reaction within F&V. Physical injuries, disease incidence, water stress, increasing temperatures (up to 30°C), and maturity stage are all variables that impact ethylene production (Saltveit, 1996). When F&V is maintained at low temperatures, the rate of ethylene production is reduced because of a decrease in O_2 levels and an increase in CO_2 levels around it (Saltveit, 1999).

b. Enzymatic browning:

The presence of polyphenol oxidase causes enzymatic browning in several F&V samples during processing and storage (Mayer and Harel, 1979). Enzymatic browning results in the loss of functional, nutritional, and organoleptic properties, such as softening, darkening, and off-flavor alterations (Zawistowski et al., 1991). It causes undesirable changes in sensory qualities as well as a decrease in market value and is thus identified as a major contributor to economic losses for fruits such as apples, pears, bananas, and grapes, as well as vegetables such as lettuce, potatoes, and mushrooms. A vast range of F&V strains have also been shown to experience enzymatic browning after harvest and in storage due to physiological or mechanical stress and microbial infection.

III. EDIBLE COATINGS FOR POST-HARVEST MANAGEMENT

A. Characteristics:

Edible coatings are any material that remains with a thickness of less than 0.3 mm (Embuscado and Huber, 2009) on the surface of fresh F&V and is formed from a combination of biopolymers and different additives dispersed in aqueous media (Morales-Jiménez et al., 2020; Castro-Muñoz and González-Valdez, 2019). An edible coating generally possesses or potentially provides the following features:

- Safe to consume, non-toxic, non-allergic, fully digestible, and easily biodegradable (Guimarães et al., 2018).
- High dissolution factor in solvent (*e.g.,* water, alcohol, acetone, or their mixture) during manufacturing (Erkmen and Barazi, 2018).
- Possess good, uniform, and homogenous adhesion to the surface of food (Falguera et al., 2011).
- Post-harvest protection in transport, handling, mechanical damage, and storage (Liyanapathiranage et al., 2023; Debeaufort et al., 1998; Rangel-Marrón et al., 2018)
- Facilitate the exchange of solutes (*e.g.,* salts, additives, and pigments), water and organic vapours (*e.g.,* aromas and solvents), and gases (e.g., oxygen, carbon dioxide, nitrogen, and ethylene) between fresh F&V and the atmosphere (Falguera et al., 2011).
- Act as a barrier against mechanical damage of F&V (*e.g.,* dents or cuts) (Guimarães et al., 2018).
- Increase the shelf-life of fresh produce in storage and retail (Falguera et al., 2011).
- May possess bioactive (*e.g.,* antioxidants) (Salvia-Trujillo et al., 2017) and antimicrobial properties (*e.g.,* silver nanoparticles, plant extracts) (Kraśniewska et al., 2020).
- May be integrated with healthy microorganisms (*e.g.,* probiotics) that confer health benefits to the consumer (Romano et al., 2014).
- Maintain the internal equilibrium of gases involved in aerobic and anaerobic respiration of F&V (Erkmen and Barazi, 2018).
- Adversely affect the characteristics necessary for consumer acceptance, such as odour, flavour, taste, and appearance (Park, 2003).
- Simple manufacturing process, economically feasible, and easy to operate (Owusu-Akyaw Oduro, 2022).

B. Types and ingredients of Edible Coatings:

Lipids, polysaccharides, and proteins are the main biomolecules used in the development of ECs; however, other components such as resins, solvents, plasticizers, and additives must also be employed to achieve diverse formulations (Pham et al., 2023; Díaz-Montes, Castro-Munoz, 2021; Salvia-Trujillo et al., 2017) (Table 1). Plasticizers provide flexibility and permeability while solvents provide tensile strength, and resins restrict water vapour permeability with lustre (glossiness) (Table 2).

a. Biomolecules:

Polysaccharides used for ECs include cellulose, starch, and pectin derivatives; seaweed extracts, exudate gums, microbial fermentation gums, and chitosan (Krochta and Mulder-Johnson, 1997). Polysaccharides are highly compatible with F&V, and although reported with various source, composition, structure, and characteristics, they generally have good gelation, film-forming, mechanical, and barrier properties and are abundant, renewable, edible, and biodegradable (Zhao et. al., 2021).

Lipid compounds are used for protective coatings consisting of acetylated monoglycerides, natural wax, and surfactants. The most effective known lipid substances are paraffin wax and beeswax. The primary function of a lipid-based coating is to block the transport of moisture because of its relatively low polarity. In contrast, the hydrophobic characteristics of lipids form thicker and more brittle coatings (Morillon et al., 2002).

Protein-based coatings are formed from solutions or dispersions of the protein as the solvent or carrier evaporates, which are limited to water, ethanol, or ethanol-water mixtures (Kester and Fennema, 1986). Thus, protein-based coatings are competent as oxygen barriers even under low relative humidity conditions.

In composite ECs, the ingredients in a formulation may be heterogeneous, consisting of a blend of polysaccharides, proteins, and/ or lipids (Kurek et al., 2014).

Table 1: Different components of edible coatings with their ingredients.

Types	Components	Ingredients	References
Biomolecules	Animal proteins	Whey protein, collagen, gelatin, casein, egg-white protein, feather keratin, fish myofibrillar protein,	Pająk et al., 2013; Kim and Ustunol, 2001; Silva et al., 2007; Wani et al., 2012
	Plant proteins	Soy protein, corn zein, wheat gluten, rice bran protein, pea protein, peanut protein, cottonseed protein	
	Linear, neutral polysaccharides	Agar, curdlan, cereal b-glucan, hydroxypropyl methylcellulose, pullulan, methylcellulose, konjac glucomannan, inulin, microcrystalline cellulose	Elsabee, 2014; Kocira et al., 2021; Gao et al., 2019; Hassan et al., 2018; Draget et al., 2005; Shao et al., 2020; Dai et al., 2020
	Linear, anionic polysaccharides	Sodium alginate, propylene glycol alginate, gellan gum, pectin, carboxy-methylcellulose, carrageenan	
	Linear, cationic polysaccharides	Chitosan	
	Linear, substituted, neutral polysaccharides	Fenugreek, guar gum, locust bean gum, tara gum	
	Linear, substituted, anionic polysaccharides	Xanthan gum	
	Branched polysaccharides	Gum arabic, karaya, larch arabinogalactan, gum ghatti	
	Lipids	Acetoglycerides, beeswax, paraffin, carnauba wax, candelilla wax, rice bran wax	Hassan et al., 2018; Baldwin et al., 1997
	Resins	Shellac, terpene, asafoetida, benjoin, chicle, guarana, myrrhe, sandaraque, opoponax, styrax	Hall, 2012; Beyza et al., 2018
Plasticizers	Polyols	Glycerol, polypropylene glycol, polyethylene glycol, propylene glycol, sorbitol, corn syrup	Al-Hassan, and Norziah 2012; Navarro-Tarazaga et al., 2008; Smits et al., 2003
	Others	Sucrose and water	
Additives	Flavors	Oil based flavors, citrus, mints, volatile oils	Nasution et al., 2015; Valencia-Chamorro et al., 2011; Ganiari et al., 2017; Moura et al., 2018; Quezada-Gallo 2009; Hassan et al., 2018; Palou et al., 2015; Sajid, and Syeda, 2017
	Colors	Pigments	
	Antimicrobials	Organic acids (acetic, benzoic, lactic, propionic, sorbic); polypeptides (lysozyme, peroxidase, lactoferrin); fatty acid esters (glyceryl-mono-laurate); nitrites and sulfites, chitosan, bacteriocins (nisin, pediocin), parabens, sodium chloride	
	Antioxidants	Ascorbic acid, 4-hexylresorcinol, amino acids (cysteine and glutathione), citric acid.	
	Nutrients	Vitamin e, calcium, zinc, aluminum	
	Emulsifiers	Fatty sucrose esters, fatty acids, fatty alcohols, lecithins, mono- and diglycerides, mono- and diglyceride esters	
	Lipid emulsions	Fatty acids, edible waxes	

Probiotic organisms	*Bifidobacterium* (*bifidobacteriumlactis* bb-12)
Plant essential oils	Cinnamon, oregano, lemongrass, savory, sweet inula, vanilin, citronella, thyme, clove

b. Plasticizers:

These are small-molecular-weight hydrophilic agents that are added to EC to improve their properties by embedding themselves in the polymeric network and competing for chain-to-chain hydrogen bonding along the polymeric chains. Plasticizers promote flexibility and minimise blistering, flaking, and cracking on the F&V surface. Plasticizers are added to enhance polymer melt flow during extrusion (Dahiva et al., 2009) and have good flexibility, enabling them to adapt to morphological changes in the fruit cuticle during storage (Riva et al., 2020).

c. Emulsifiers and surfactants:

Emulsifiers are surface-active compounds with both polar and non-polar characteristics capable of modifying interfacial energy at the interface of immiscible systems, such as a water-lipid interface or water-air surface, and surfactants that are added to improve coating adhesion. For better distribution, surfactants are frequently employed to emulsify waxes and reduce surface tension.

d. Antimicrobials:

Antimicrobial substances were applied to enhance the decay control of EC. Food producers are looking for new, more natural options that can sufficiently guarantee the safety of their products in the retail chain to satisfy consumer demands. When addressing new advancements in this field of food preservation, it is important to keep in mind that the use of natural antimicrobials in actual practice is governed by legislative regulations, which might vary greatly around the world (Smid and Gorris, 1999).

e. Antioxidants:

Antioxidants can be natural or synthetic. Antioxidants are added to EC formulations to prevent oxidative rancidity, degradation, and discoloration during postharvest storage. Further addition of antioxidants to the formulation of films and coatings can improve the preservative function, inhibit browning, and reduce the undesirable effects of nutrient oxidation (Bonilla et al., 2013).

f. Bioactive compounds:

Nano-compounds (e.g., metal oxides such as ZnO or TiO_2) are functional chemicals and are increasingly recognised as important components for preserving the shelf-life of fresh produce. Among the most used bioactive compounds are antioxidants, antimicrobials, probiotics, and flavours, in addition to nutraceutical substances (Ayala-Zavala et al., 2011; Muranyi, 2013).

Table 2. Components of the edible coating and their influence on quality parameters of fruits and vegetables.

Category	Main ingredient	Additional ingredient	Crops	Benefits	References
Polysaccharides	Chitosan	Acetic Acid	Broccoli	Microbiological growth reduced. Storage life extended. Sensory qualities maintained. Fruit firmness maintained. Prevented off flavor	Hernández-López et al., 2020; Hira et al., 2021, Arnon-Rips et al., 2021, Poverenov et al., 2018, Fan et al., 2019, Qiu et al., 2023;
		Glycerol, Canola Oil	Bell pepper		
		Acetic Acid, Alginic Acid, Ammonia	Japanese pear		
		Vanillin, Trans-Cinnamaldehyde, Mandarin Extract	Fresh-cut melon		
	Sodium Alginate	Konjac Glucomannan, Starch, Lotus Leaf Extract	Goji berries	Reduced weight loss and decay. Sensory qualities maintained.	

	Pectin	Maltodextrin, Sodium Chloride	Starfruit	Extended shelf-life. Maintains physicochemical characteristics.	Moalemiyan et al., 2012; Veiga-Santos et al., 2005
	Xanthan gum	Edible Rose, Basil Seed Gum	Apple	Effective bacterial growth inhibition. Increased shelf-life.	
		Citric Acid, Glycerol, Polyvinyl Pyrrolidone Catechol, Sodium Phosphate, Folic Chocolate, Gallic Acid	Fresh lotus root		
Protein	Zein	Glycerol, Essential Oils	Melon	Effective disease control.	Tran et al., 2021, Miranda et al., 2022, Boyac et al., 2019; Mendes-Oliveira et al., 2022; Moalemiyan et al., 2012; Ghadermazi et al., 2019; Aitboulahsen et al., 2018
		Resveratrol	Apple slices	Reduced moisture loss. Increased color retention.	
	Pectin	Pullulan With Vitis Vinifera Grape Seed Extract	Peanuts	Lowered lipid oxidation. Antibacterial effect.	
	Soy protein isolate	Hydroxypropyl Methylcellulose, Olive Oil	Pear	Maintained moisture and firmness.	
	Gelatin	Frog skin Oil, Glycerol	Persimmon	Controlled weight loss. Maintained firmness and color.	
		Mentha Pulegium Essential Oil	Strawberry		
Lipid	Glycerol	Ginger Extract	Walnuts	Reduce rancidity. Inhibition of fungal growth. Improved nutritional quality. Extended shelf-life.	Shaukat et al., 2023; Zhang et al., 2022; Das et al., 2022; Chen, et al., 2019; Peng and Gnsman, 2008
	Carnauba wax	Conventional Carnauba Wax Emulsion	Fresh tomatoes	Extended shelf-life. Increased shine. Reduction of weight loss	
		Nanoparticles, Xanthan Gum	Guava	Reduced weight loss. Maintained firmness and color	
		Glycerol Monolaurate	Jujube		
		Montmorillonite Nano-Clay	Orange	Improved physicochemical properties and antioxidant activity	
	Fatty acid	Glycerol	Cucumber	Reduced weight loss.	
Composite	Loquat leaf extract, Alginat (lipid/ polysaccharidic)	Citric Acid, Sucrose Ester, Absorbic Acid	Nanfeng tangerines	Delay respiration rate and nutritional degradation. Reduced post-harvest spoilage.	Zhang et al., 2022; Shin et al., 2022

			Higher non-enzymatic antioxidant.
Carboxymethyl cellulose, Cardamom essential oil (Polysaccharides/ lipids)	Glycerol	Tomato	Increased shelf-life

IV. APPLICATION MEANS OF EDIBLE COATINGS

There are several ways to apply EC to the surfaces of F&V and understanding both the coating ingredients and cuticular characteristics is essential to selecting the best application method for prolonged maintenance of produce quality. Thus, after the application of EC, quality criteria for F&V (*e.g.,* colour change, firmness loss, ethanol fermentation, decay ratio, and weight loss) must be assessed and monitored throughout the storage period for optimum post-harvest management (Sharma et al., 2019; Lin and Zhao, 2007; Andrade et al., 2012; Mendy et al., 2019; Saberi et al., 2017).

A. Dipping:

This is the most fundamental commercial technique that is still in use and is employed with various viscous coating solutions. The primary objective of this technique is to fully saturate the surface of the fresh F&V by immersing it in the coating solution (Tavassoli-Kafrani et al., 2016). Subsequently, the excess coating is removed by draining the solution and dried to ensure a well-formed coating (Andrade et al., 2012). Previous studies have demonstrated that several factors, such as immersion time, withdrawal speed, number of dip-coating cycles, coating solution parameters (*e.g.,* density, viscosity, surface tension), substrate surface characteristics, and drying conditions, influence the density and morphology of the formed coatings (Tang and Yan, 2017). However, the dipping approach often results in a thick coating, which can significantly reduce fruit respiration, damage to food surfaces, and impaired functionality. In addition, a substantial amount of coating solution is required per unit mass of product to achieve optimal dipping conditions (Lin and Zhao, 2007).

B. Vacuum impregnation:

This method is an enhancement of the dipping technique, in which fresh produce is submerged in a hermetically sealed vacuum instead of a conventional dipping tank. Consequently, while the fruit material remains immersed in the coating solution and is subjected to atmospheric pressure, it is exposed to atmospheric restoration (Owusu-Akyaw Oduro, 2022).

C. Layering or Spreading:

This process generates multilayer films that can enhance the efficiency of coatings where it relies on the sequential deposition of polyelectrolytes with opposite charges to effectively control the characteristics and functionality (Martín-Belloso et al., 2009). The spreading method was found to be effective with high-viscosity coating solutions. The key factors that determine how the coating solution spreads across the fruit surface are typically the wetting level and spreading rate. The efficacy of coating deposition through spreading is influenced by various factors, including the quality of the substrate, particularly the drying conditions, liquid properties, and surface geometry (Kumar and Prabhu, 2007). Brushing is typically performed by skilled operators and specialists; thus, the human element significantly impacts the quality and uniformity of the coating.

D. Spraying:

Spraying is a method commonly used to distribute small droplets onto the surface of the F&V. This technique involves the use of nozzles and is most effective for applying thin coating solutions that can be sprayed at high pressure. There are three main types of spraying techniques: air spray atomization, pressure atomization, and air-aided airless atomization (Andrade et al., 2012). The drying time and temperature play significant roles in the formation of polymeric coatings when using the spraying technique. This method allows for the application of multiple layers, including interlayer solutions, and ensures a consistent coating with uniform thickness (Martín-Belloso et al., 2009). Electrospraying, on the other hand, utilises a high electric field to produce charged droplets for coating applications.

E. Foaming:

Conventional methods employed in coating applications include foaming and dripping. In the dripping technique, the coating is applied to the fruit surface using brushes. Conversely, foam application involves the addition of a foaming agent to the coating, followed by the introduction of compressed air into the applicator tank (Díaz-Montes and Castro-Muñoz, 2021). To ensure uniform distribution, the foam is subsequently broken down through a rigorous tumbling motion.

F. Cross-linking:

In this method, polymer chains are combined using both covalent and noncovalent bonds. To enhance the stability and compactness of the coating, a cross-linking agent was introduced. Cross-linked coatings offer several significant advantages, including improved mechanical properties, chemical and thermal stability, and enhanced molecular migration (Skurtys et al., 2010). This technique has proven particularly successful for biopolymer materials composed of proteins or polysaccharides (Dai et al., 2020).

V. ADVANTAGES OF EDIBLE COATINGS IN POST-HARVEST MANAGEMENT

The use of EC as an alternate to packaging provides an additional method to reduce the loss of firmness and moisture, delay oxidative browning, prevent the growth of microorganisms, and control the respiration rate (Warriner et al., 2009) (Fig. 3). During storage, the relative humidity and temperature of the storage space were maintained under control. Fruits and vegetables are often coated with various edible components, forming a semipermeable membrane on the surface that suppresses respiration, controls moisture loss, and performs other activities (Li and Barth, 1998). Fresh F&Vs benefit from EC to satisfy the requirements of consistent quality, market safety, nutritional content, and low manufacturing costs. It minimises the loss of natural volatile flavour compounds and colour components from fresh commodities by limiting the exchange of volatile compounds into the surrounding environment *via* gas barriers. Edible coatings serve as transporters for additional functional components such as nutraceuticals, flavours, and antibacterial and antioxidant compounds to reduce microbial loads, delay oxidation and discoloration, and improve quality (Rooney, 2005).

A. Moisture barrier:

EC prevents moisture loss, aroma loss, or water uptake by the food material as well as oxygen penetration, resulting in good storage conditions for these food products. EC improves the texture and appearance of the product and extends its shelf life by creating semi-permeable barriers. Emamifar and Bavaisi (2020) used a bio-nanocomposite covering of sodium alginate and nano-ZnO on strawberries. On mangoes, titanium and silver nanocomposite packing produced the same results (Chi, 2019).

B. Oxygen scavengers:

The presence of oxygen can have a significant negative impact on fresh F&V. Some ECs have been discovered to have oxygen scavengers and humidity control features that significantly lower the gases that contribute to F&V spoilage. According to Resende et al. (2018), a chitosan/cellulose nanofibril coating reduces oxygen transport, lowers respiration, and slows strawberry oxidation through an ascorbic acid reaction.

C. Ethylene scavenger:

Controlling ethylene throughout storage is critical for increasing the shelf life of fresh fruit. Kaewklin et al. (2018) discovered that the ethylene control action of chitosan-TiO2 nanocomposites on tomatoes revealed reduced levels of ethylene.

D. Antimicrobial properties

One of the primary causes of F&V contamination is the lack of suitable packaging. An antimicrobial active packaging system containing antimicrobial compounds can be used to reduce fresh food deterioration and control microbial development.

Strawberry coated with 1.5% sodium alginate and nano ZnO demonstrated the lowest development of microorganisms, according to several studies. Antimicrobials in EC extend the shelf-life and safety of fruits and vegetables by inhibiting bacterial growth and causing harm (Jafarzadeh, 2021). Organic acids such as citric acid and lactic acid, microbial bacteriocins such as lactic acid bacteria, and polypeptides such as lysozymes are examples of antimicrobial compounds (Salas-Méndez, 2019).

E. Antibrowning and antioxidant properties:

Enzymatic browning is associated with the discoloration of phenolic compounds catalysed by polyphenol oxidase (PPO), which transforms polyphenolic substrates into dark pigments in the presence of oxygen. Edible coatings, particularly those containing antibrowning agents, can limit PPO activity while acting as strong oxygen barriers. Ascorbic acid, thiol-containing chemicals (cysteine and glutathione), carboxylic acids (citric and oxalic acid), phenolic acids, and resorcinol are the most used antibrowning agents. These o-quinones were reduced by PPO enzymes back to their phenolic substrates (El-Hosry, 2009).

F. Inhibition of physical damage

Because pectolytic enzymes cause firmness loss in fruit tissues, any attempt to block their activity will result in firmness retention. Textural weakening of fruits and vegetables during storage may be reduced by using edible coverings containing active compounds known as texture enhancers. These chemicals inhibit polygalacturonase activity while maintaining membrane structural integrity. Calcium salts are often employed as firmness retainers to control softening phenomena in fresh-cut fruits (Owusu-Akyaw Oduro, 2022).

G. Nutraceutical supplements:

Minerals, vitamins, and bioactive compounds are potential nutraceutical compounds that can be incorporated into the formulation of active coatings to enhance the nutritional value of some fruits and vegetables where these micronutrients are present in low quantities (Basaglia et al., 2021).

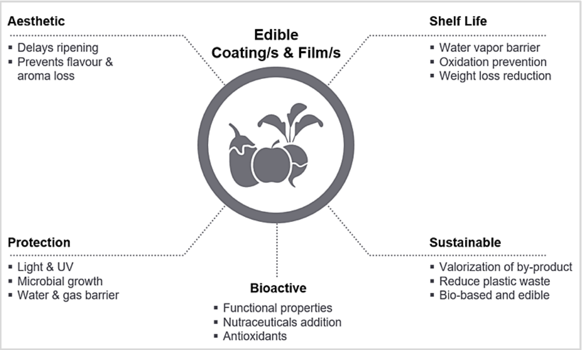

Figure-3: Various uses of edible coatings *(Source: FutureBridge) Analysis)*

VI. LEGISLATION AND REGULATIONS OF EDIBLE COATINGS

The ingredients used in EC make direct contact with the F&V and consumer, thus they are supposed to gain safety approval before being used for commercial purposes. In addition, the use of approved natural plant extracts and essential oils may result in some allergic reactions with a few toxic effects depending on the dosage. Therefore, proper measures must be implemented to periodically check the toxicity and allergic nature of edible coating formulation. For examples The edible components must be Generally Recognized as Safe (GRAS) by the federal agency, the American Food and Drug Administration (FDA) (Paidari et al., 2021) in USA. The materials used in EC formulations must be food-grade and non-toxic, and the production has to follow Goods Manufacturing Practice (GMP). Generally, components of EC are categorised as food additives, food ingredients or substances, and food packaging materials as per the US FDA regulations and European directives in 2006 and 1998, respectively (Dhall, 2013). According to European directives, the ingredient must comply with the guidelines of the European Food Safety Authority (EFSA). However, the list of acceptable additives in each country varies to domestic regulations. For example, in the European regulation directive, shellac, pectin, lecithin, polysorbate arabic gums, karaya gums, and beeswax are regarded as food ingredients (Vargas et al., 2008) whereas US FDA allows the use of castor oil, cocoa butter, polydextrose, and sucrose fatty acids as food additives. For a clear understanding of the nature of chemicals present in the food industry, the FDA and EFSA grouped chemicals under three different categories namely food coating materials

(FCM), Food contact articles (FCA), and food contact substances (FCS) (Priya et al., 2023). The incorporation of nanoparticles, antimicrobial, antibrowning, antioxidant, and antifungal-like agents into the coating formulation is termed FCM whereas FCA are the finished result of packaging such as coatings or films, and FCS are the materials used to make them (Umaraw et al., 2020). Wax coating of fresh F&V using carnauba or bee wax is permitted in India by the Prevention of Food Adulteration Act (PFA), which regulates proper labeling and declaration of the material used for edible coating (Dhall, 2013). The application of synthetic and chemically modified resins for the EC of F&V is monitored based on the standards provided by the US FDA and European legislation.

VII. FUTURE TRENDS AND CHALLENGES

Emerging trends in polysaccharide-based EC (with chitosan, alginate, cellulose, starch, *etc.)* have shown promising beneficial effects on F&V because of their highly functional bioactive, nanostructured, and multilayered composite materials in various combinations (Akhtar, 2018). Several EC formulations have been developed recently, not only to preserve F&V quality but also to lower post-harvest decay caused by phytopathogens (Alvarez et al., 2017). By adding organic acids to the mixture, the coating worked well to delay browning, stop mold and yeast growth, and keep fresh-cut fruits for an additional 35 days. These formulations offer a bio-rational and sustainable substitute for contemporary wax coatings mixed with synthetic fungicides. Pectin-beeswax coating with eugenol may be a successful commercial strategy for preventing degradation and preserving the quality of citrus fruit. Probiotics and antioxidants incorporated within ECs are also becoming more popular because of their potential advantages for consumer health (Davachi et al., 2021). Freshly cut apples were coated with a double coating of zein and probiotics in a study by Wong et al. (2021). To keep bananas, strawberries, cucumbers, and tomatoes fresh longer, Davachi et al. (2021) created a covering that also included probiotic lactic acid. Probiotic lactic acid led to worse hydrophilicity, increased water solubility, and increased surface roughness. During one week of storage, *Listeria monocytogenes* development was slowed down in the coated samples, whereas the probiotic *Lactobacillus plantarum* concentration remained constant (>6 log10 CFU/g). Research is speeding up on encapsulating bioactive compounds within EC for their controlled release at a certain amount and time to maintain the quality of fresh produce in the food value chain (Lopez-Polo et al., 2021).

Nano-emulsion is another novel method that is gaining popularity as it is recognised to be more effective than conventional emulsions in maintaining the stability of EC. Moreover, nanoemulsions reduce the oxidation of bioactive compounds and enhance the sensory quality parameters of F&V (Al-Tayyar et al., 2020). Moving forward, attention should also be paid to EC with nanoparticles, which are referred to as “smart edible coatings,” which act as nano-indicators to detect the change in colour and temperature as a critical reference, indicating potential food spoilage in the value chain (Parameswaranpillai et al., 2021). However, detailed research on EC is still in its developing stages, and rigorous validation is being conducted before the wide-scale industrial deployment of developed formulations. The development of new ECs must aim to maintain distinctive qualities and flavours and not modify the sensory profile of fresh F&V. As a result, it is anticipated that research on EC will rely on a thorough understanding of how each ingredient interacts with physicochemical, antibacterial, and toxicological properties with a clear risk assessment.

Although EC has been thought to be a way to increase the shelf-life of F&V, their commercialization still confronts several difficulties. Consumer approval may occasionally be impacted by the effects of these coatings on sensory qualities. Unwanted flavours may be added to the products using various herbs, spices, antimicrobials, and antioxidants. The rates of food respiration and transpiration, as well as the storage conditions, are the main determining factors in choosing an edible coating. Fruits and vegetables have different rates of respiration, gas diffusion, and skin resistance; therefore, a covering made for one product might not be appropriate for another. The permeability of pores is influenced by the coating’s thickness and application technique, which have an impact on attributes that are connected to transport. Anaerobic conditions are created by refined mineral oil-based coatings, which harm fruit (Moalemiyan et al., 2012). Anaerobic respiration causes fermentation and the emergence of off-flavours that harm the product’s sensory quality. Fresh-cut fruit aromas may be negatively impacted using essential oils in EC at greater concentrations as antimicrobials. According to Azarakhsh et al. (2012), even when lemongrass oil was applied in small amounts to cover fresh-cut pineapple with an alginate-based coating, the sensory score was reduced. When employed in higher doses, antibrowning chemicals such as glutathione and N-acetylcysteine may produce unpleasant odors. Thus, minimising negative alterations in sensory qualities might be a promising research topic in the future.

CONCLUSION

The food industry is concerned and always optimistic about the development of sustainable and innovative technologies to improve the quality and shelf-life of fresh produce to minimise post-harvest loss and ensure food security. One major advantage of EC is their recognition as safe to be used on F&V, justifying health safety without compromising nutritional and sensory attributes. In the modern world, EC is a ‘green technology’, which significantly reduces post-harvest loss of F&V and has also been proven to cut down expenses on complex packaging and logistics (Peerzada et al., 2023). Thus, for F&V growers and value chain actors around the world, EC is generating possible economic benefits. However, to maintain food safety, textural integrity, and biodegradability, it is vital to comply with global food safety legislation. The global regulatory authorities of most countries and regions have recommended ingredients as safe to use and their acceptable limits.

It might be possible to expand the use of EC for shelf-life enhancement of diverse F&V crops experiencing significant post-harvest loss. Moreover, the traditional synthetic polymers and waxes might be substituted with more affordable, effective EC, extending the shelf life and increasing the nutritional value of F&V. Thus, it is essential to build a greater technical understanding of the mode of action of new-age edible coatings and generate awareness of sustainability among consumers for accelerated adoption by value chain agents. Surely, there is a dearth of research on EC, and that could heighten the benefits of fruit consumption and minimise post-harvest loss. Despite the extensive and well-defined research plan, from improving shelf life to preserving a high nutritional value, it is perpetually relevant to deep dive into investigated known data on the use of EC on agricultural produce, which will accelerate innovative product development. This effort will translate into developing economical, effective, compatible, and ecologically safe EC formulations. The global EC market size is expected to reach US$4.2 billion by 2028, rising at a market growth rate of 7.5% CAGR (Markets & Markets, 2021). However, there is still much that needs to be done to improve the marketing potential and promotion of EC, even though earlier efforts led to the commercialization of a handful of products in the post-harvest industry. Edible coatings hold the strong sustainable potential to ensure food security by reducing post-harvest waste, extending shelf life, and preserving the quality of fruits and vegetables worldwide.

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