Bulgarian Chemical Communications, Volume 57, Special Issue B (pp. 131-149) 2025 DOI: 10.34049/bcc.57.B.A0020

Recent advances in the development of edible coatings and films to extend the shelf life of fruits and vegetables: a review

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Revised: February 05, 2025

The vegetables and fruits can be packed with films or coated with a substance that is edible which forms thin layers to protect them from damage during handling from chemical changes and microbial invasion. Rapid respiration, high moisture content, and transpiration rate in fruits and vegetables make them perishable. Combining edible coatings/films with storage at controlled temperature and relative humidity is one way to make agricultural produce last longer after it is harvested. It can modify the internal atmosphere thereby minimizing the physicochemical changes in the agricultural produce. Nutrients, flavors, and antimicrobial substances are some of the important components that are found in edible coatings/films. The main parameters usually affected under storage are firmness, sensory attributes, weight loss, and nutrients. In this article, we review films and edible coatings, their different types, and the scope of their most recent developments, as well as the ways films and edible coatings affect the physicochemical properties, sensory qualities, and microbial inactivation of fruits and vegetables.

Keywords: Edible coating, edible films, types of edible coating, and physical barriers

INTRODUCTION

A transparent covering of edible material less than 0.3 mm thick is called an edible film or coating. In contrast, edible films are preformed edible layers molded into sheets that will be applied as wrapping over the products. They are made by combining various biopolymers in an aqueous dispersion medium with additives [1]. A thin coating that covers the surface of food is called edible coating. It could help reduce the permeability of water vapor, carbon dioxide, and oxygen [2, 3]. This should not result in the complete depletion of oxygen because it can facilitate anaerobic respiration leading to ethanol formation and development of off-flavor. It can also deliver a barrier against oxygen, microbial load, moisture, and solute transfer in food products. The efficiency of edible coatings depends on the type of fruit and the materials used for the coating. Commercially, these coatings play a crucial role in maintaining product quality, meeting market standards, and reducing production and packaging expenses. They control the movement of substances such as oxygen, carbon dioxide, flavors, lipids, moisture, and dissolved compounds, thereby lowering respiration rates and minimizing weight loss [4]. Lipids, proteins, and polysaccharides are contained in three main categories of edible coatings. Edible coatings or films upon application to the food surface can serve as physical barriers that prevent ripening by altering the internal conditions of the fruit. Use the following healthy substitutes to increase the longevity of fresh, lightly processed fruits and vegetables after they have been harvested [5]. When edible films or food coatings are used, they cause no problem for release since they are eaten along with the film or the coating [6]. Producing semi-permeable barriers, these coatings help prolong the shelf life of various fruits e.g. papaya, kiwi, and strawberry by retaining gases and water vapor. These coatings keep the fruit's shiny looks and quality during part of the storage period, causing a fall in the respiration rate that tends to be minimal [7-10]. This can also be used as a vehicle for the delivery of flavor, color, and anti-browning agents shown in Figure 1 [11]. Many fruits such as papayas, kiwis, and strawberries benefit from using edible coatings which prolong their shelf lives. Additionally, they help maintain the glossy aspects of the fruit's appealing taste and provide nutritional value for health benefits [12-14].

An essential element of food preservation involves packaging the food because it protects it from various environmental factors like microbes. Additionally, it offers comprehensive product information, significantly influencing the commercialization and distribution of food items [15]. The choice of suitable packing material depends upon the physicochemical characteristics of food products.

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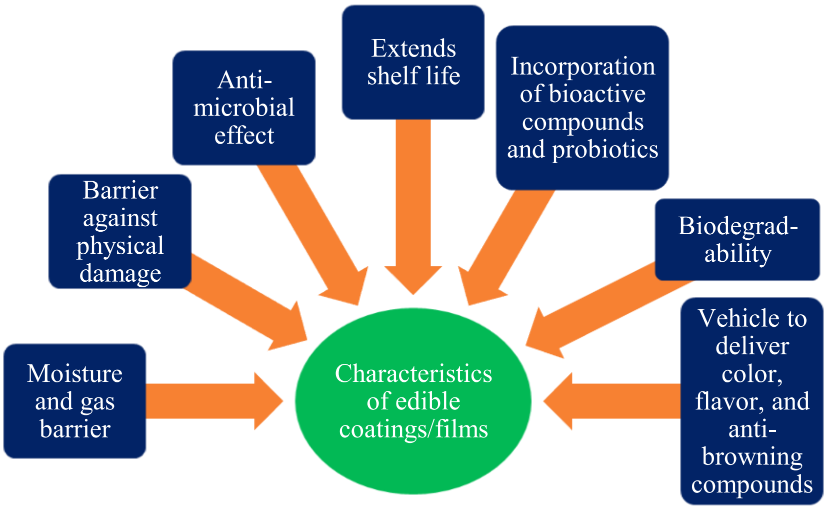

Figure 1. Characteristics of edible coatings/films.

The application of the different traditional kinds of wrapping materials such as paper, glass, cardboard, and plastic has caused massive junk [16]. Recycling packaging materials is also becoming difficult because they are made up of various types of materials with different characteristics [17]. Recently, experts have started checking on how edible films can be used against the deficiencies seen in normal package materials as alternative biodegradable packages [18, 19]. Different parameters that are generally affected during storage are firmness, sensory attributes, weight loss, ascorbic acid, dietary fiber, and antioxidant activity. The edible coatings/films are also beneficial for the environment and consumers [20, 21]. Nanotechnology presents a novel technique for synthesizing new material layers for fresh food preservation and coating through the diminution of the material to the nanometric scale. Due to the combination of larger specific surface area and higher mass transfer rates, nanoparticles are more penetrative, chemically and biochemically reactive, enzymatically active, catalytically active, and quantum active than larger particles of the same material [22]. This review aims to outline various edible coatings and film types, their current advancement, and their microbiological activity, taste characteristics, and physicochemical properties of fruits and vegetables.

DISPERSION SYSTEMS EMPLOYED IN THE PREPARATION OF EDIBLE COATINGS/FILMS

By effectively mixing oil and water with emulsifiers, emulsions are created to form a consistent mixture. There are several types of emulsions depending on their properties, such are water-in-oil and oil-in-water emulsions [8]. The structure of these emulsions can interact with polar and nonpolar compounds due to their dual nature containing hydrophilic and hydrophobic components in their structure [23]. The first type is based on the properties of oil and water. The preferred form of emulsion in preparation of edible coatings or films is oil in water due to the easy solubility of various lipophilic compounds like bioactive and plant-based essential oils [24, 25]. Emulsions are described as oils and aqueous phases that are being homogenized by emulsifiers. They have unique properties that enable them to be classified into water in oil (w/o) emulsions and oil in water (o/w) emulsions based on these properties [26]. Therefore, emulsions are A typical system for the generation of edible coatings or films due to the unique nature of the substances involved which are capable of effectively preserving and retaining additives [27, 28]. The gelling of the coating solution can be induced by the addition of calcium ions through the oxidation of compounds present in the pectin and by the synergistic effect in gelatin. The alginate chains can be held together by calcium ions to form junction zones followed by the gelling of the solution [29]. The starch-based coating suspension can be prepared by heating the solution by which starch can be dissolved until gelatinization followed by cooling to room temperature and mixing with other components [30].

Spreading, dipping, spraying, and wrapping are some of the techniques used to apply edible coatings or films as illustrated in Figure 2 [31].

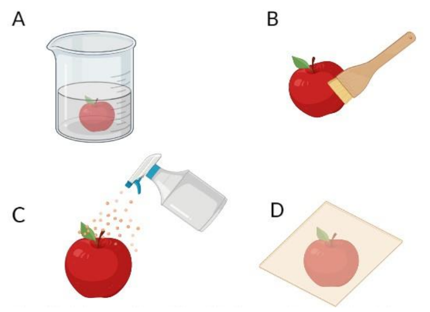

Figure 2. Techniques used for applying edible films or coatings on food products: (A) Dipping (B) Spreading (C) Spraying (D) Wrapping.

Dipping is a simple method used for edible coatings which comprises three different steps such as immersion and dwelling, deposition of coatings over the surface, and evaporation of solvents remaining on the surface at ambient temperature or using dryers. The thickness and morphological characteristics of edible coatings are dependent on various factors like immersion time, withdrawal speed, drying conditions, and characteristics of coating solution (density and viscosity). The disadvantages of this method are the requirement of the high amount of coating solution per unit area of the product and the chances of the formation of layers with a higher thickness which in turn affects respiration and surface damage. The other drawbacks include contamination of the coating solution by the dirt and microorganisms present on the surface of agricultural produce posing problems in scale-up. The spreading technique is more suitable for highly viscous coating solutions. The spreading rate and wettability are the important factors affecting the coating process. Parameters like surface geometry, drying conditions, and composition of coating solution also affect the efficiency of the coating process. The specialized technicians generally perform brushing because human factor influences the quality and homogeneity of coatings on the products. Spraying is a way of applying a layer of coating fluid uniformly over an object's surface by using many nozzles clustered together which release tiny droplets. Since the coating fluid has less thickness, Its result is usually thicker compared to dipping methods., the formed coating ends up being thicker than what the 'dipping' method produces [32].

Usually, the food products are wrapped in a solid sheet of edible film, which acts as the primary packing material. This can be prepared using molding, steel belt conveyors, extrusion, electrospinning, and thermoplastic methods. In casting, the liquid will be poured over the mold followed by solidification whereas, in steel belt conveyors, the coating solution is allowed to spread uniformly on steel followed by drying. Extrusion is preferred over the casting method due to the less energy and processing duration requirements. The specific mechanical and processing barrel temperature is required to synthesize edible film using an extruder. Electrospinning is an economical method where the droplets of the solution are electrified to create a jet that is strengthened and elongated for the synthesis of fibers. The thermoplastic method is better suited for chitosan and gelatin-based films. It involves the continuous synthesis of edible films under high pressure and temperature, with reduced water usage [33].

PARAMETERS AFFECTED DURING THE STORAGE OF FRUITS AND VEGETABLES

Firmness, ascorbic acid retention, sensory attributes, weight loss, and antioxidant activity are among the several factors commonly impacted during the storage of vegetables and fruits.

Firmness

Fruit and vegetable firmness is an essential aspect when assessing their overall quality. The important properties that determine firmness are maturity, shelf life, and optimum harvest date. Typically, force and deformation are generally used to describe firmness. The acoustic resonance test, destructive Magness-Taylor compression test, and non-destructive compression test are the three comparatively easy methods for determining hardness. Therefore, it is feasible to establish connections between the described firmness characteristics, and it's essential to determine which trait is suitable for defining the maturity and/or ripeness or firmness of a particular type of fruit [34].

Sensorial analysis

As depicted by ISO 9000:2015, the quality of food is defined as the extent to which an object's intrinsic properties meet requirements. The assessment of the kinesthetic qualities of food has long gone hand in hand with the analysis of sensorial attributes. With the application of advanced texture analyzers, the desired product can be developed. Food quality is also estimated in terms of textural properties by consumers. Recent studies demonstrate that a food's crispness and crunchiness are mostly related to its texture analysis profile. Hence, instrumental analysis and sensory analysis are two independent approaches for evaluating the right sharpness or food palatability and other kinesthetic properties, including crunchiness. The instrument used for textural analysis was the TA.XT PlusC™ texture analyzer (Stable Micro Systems Ltd., Godalming, UK) and the method was compression/acoustic type [35]. Examined by sensory analysis are the attributes of appearance, flavor, brightness, texture, and color [5]. Pigments like anthocyanin and carotenoids often undergo chemical degradation leading to color fading and also bioactivity loss [36].

Weight loss

Vegetables and fruits lose weight after they are harvested. Several factors contribute to the weight of these products, such as the loss of water from inside and outside the cells, the breakdown of sugars, cellular respiration, and the collapse of the cell walls due to cell death [37]. Loss of weight is another crucial quantitative approach to understanding the shelf life of non-coated and coated vegetables and fruits [38].

Ascorbic acid and dietary fiber

Ascorbic acid is a vital phytonutrient with potent antioxidant activities that can neutralize the body's generated reactive oxygen species, defending against a variety of severe diseases [39]. Edible coating treatments can retain the maximum ascorbic acid content by limiting the oxygen availability required for the oxidative breakdown of ascorbic acid [40]. Although ascorbic acid content starts increasing during the different stages of ripening, it tends to decrease after reaching the fully ripe stage [41]. The degradation rates of ascorbic acid in horticultural products will vary depending on genotype, stage of development, and storage conditions [37]. The continuous respiration and cell wall thickening of the agricultural produce may lead to a small increase in fiber content when being stored [42]. Vegetables and fruits contain trace amounts of soluble dietary fiber [43].

Antioxidant activity

Fruits are very important for human survival because they carry many essential elements that can prevent cancer and heart diseases by cutting down on the body's toxic load as a result of their micronutrient and antioxidant properties; hence they are the best sources of polyphenols which are antioxidants found in natural foods. Numerous diseases are prevented by antioxidants, including endothelial dysfunction, which has been linked to illnesses associated with aging, including hypertension, hypercholesterolemia, and atherosclerosis [44]. Many antioxidative enzymes that help the body eliminate the effects of free radicals, like glutathione peroxidase and thioredoxin reductase, depend on it as a cofactor [45].

DIFFERENT TYPES OF EDIBLE COATINGS FOR VEGETABLES AND FRUITS

The three common types of edible coatings used to preserve important quality characteristics such as firmness, sensory properties, pigmentation level, nutrient retention quality, and reduction in weight loss, are proteins, lipids, and polysaccharide-based coatings (Figure 3).

Polysaccharide-based edible coatings/films

The key polysaccharides utilized in polysaccharide-based edible coatings include plant gums, pectin, starch, cellulose, dextrin, alginates, and chitosan. Polysaccharide coatings that can be ingested are used with antioxidants or antimicrobials to enhance food quality as well as shelf life during storage [46]. For instance, a variety of polysaccharides including alginate, cellulose, cellulose, carrageenan, gum arabic, starch, and guar are widely classified as safe by the US Food and Drug Administration [47].

- *Alginate.* The food industry uses alginate as a gelling agent that is naturally obtained mainly from bacteria and brown algae. Colloidal properties such as solid gels are characterized by the interaction with multivalent metal cations, such as calcium which leads to insoluble polymers [48, 49]. Alginate-based edible coatings and films are noteworthy for preserving fruit quality, they also make sure that the shelf life is extended by decreasing dehydration, controlling respiration, improving product appearance, stifling microbial growth, and boosting mechanical properties [50]. In [49] Menezes *et al.*'s study, they used a dipping method to investigate how fruit pectin and sodium alginate-based coatings, containing 2%, affected sapota fruits after being kept in them for two or four min. Consequently, the sample was kept under refrigeration conditions at about four °C over a period of thirty days. Between the control group and coated sapota fruits, there was a noticeable change in terms of physicochemical properties. The polysaccharide coating with a 2 min dipping time proved successful in retaining the fruit's organoleptic characteristics (sensorial attributes). During storage at 4°C for 12-15 days, the outer layer of a newly sliced watermelon was made of three concentrations of sodium alginate (0.5%, 1%, and 2 %), with an antimicrobial ingredient trans-cinnamaldehyde, calcium lactate and pectin for each concentration used [51]. The antimicrobial edible coating has not affected the pH (5.2) and water activity (0.99) of fruits.

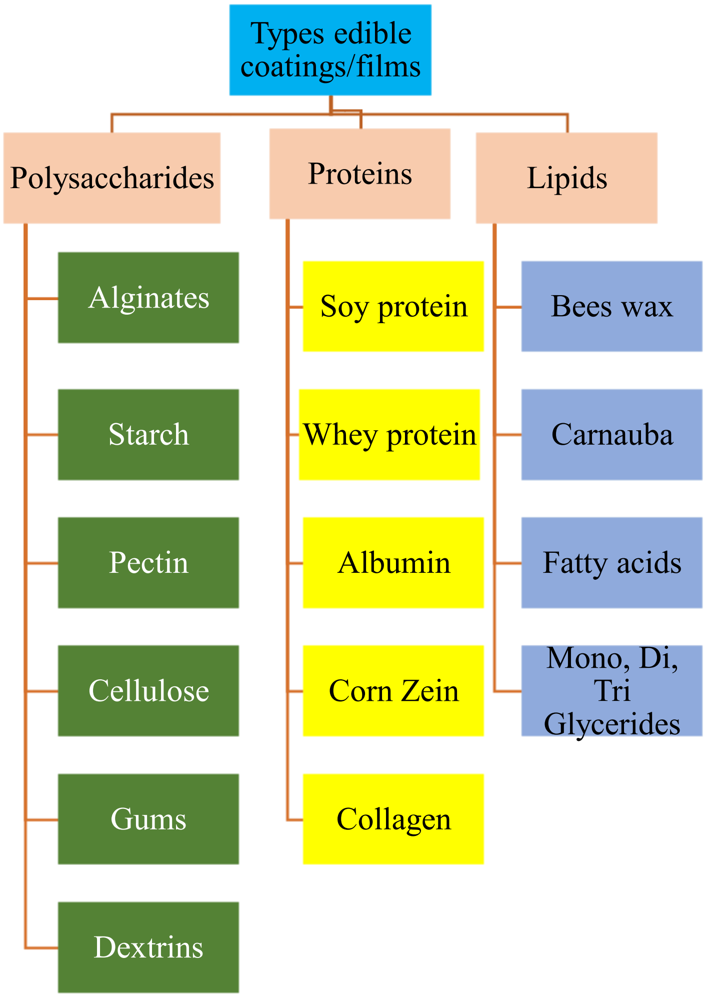

Figure 3. Different types of edible coatings.

Microscopic analysis showed that the coating with 2% pectin, 1% sodium alginate, and 2% natural antibacterial agent was consistent and had high adherence across the entire fruit surface. Sensory analysis indicated flavor, color, or odor of coated fruits was not affected during storage.

Ghavidel *et al.* [52] used edible coating of fresh-cut apple wedges by different solutions like carrageenan (0.5%), alginate (2%), whey protein (5%), and soy protein (5%). Storing for 15 days at 4°C alginate-based coating retained higher water content and better texture compared to other coated fruits. However, the sensory analysis showed that whey protein-based coated fruits were preferred over other coated fruits regarding color, appearance, and odor. Bal *et al.* [50] stated that edible coating of cherry tomatoes with alginate (2%) with or without UV-C treatment was stored at 10°C for a maximum of 20 days. UV-C treatment alone retained the nutrients when being stored during at early storage period but declined during the final stages of storage. The retention of ascorbic acid, phenol, and lycopene content was enhanced by the combination of UV-C and alginate coating, which also helped to reduce respiration rate and weight loss.

- *Gums and mucilage.* Dietary fiber with mucilage had the ability to take in huge amounts of water., dissolve, and spread out to form a viscous or gelatinous mass known as a colloidal mass [53]. Almost all plants and specific microorganisms produce mucilage, which is a thick, glue-like substance Hence, it is a metabolic by-product generated within the cell and is not easily dissolved in water. Mucilage can operate as a water-transfer barrier despite being hydrophilic, which could decrease water loss and increase fruit flesh hardness. Several plants, such as fenugreek, aloe vera, cactus, okra, and taro, contain mucilage [54]. Mucilage has been utilized in numerous fruit preservation strategies which include cellulose, amino acids, and water-soluble polysaccharides [13]. The gum can be created from naturally existing polysaccharides having the capacity to hydrate in water, stabilize emulsion systems, or form a gel [55]. The traditional source of psyllium gum is the psyllium seed husk which is a mucilaginous material that is rich in both soluble and insoluble fibers. Yousuf *et al*. [56] studied how adding psyllium gum (0.5-1.5%) to edible coatings containing sunflower oil could be used in preserving fresh-cut papaya fruit at 4°C for 2 weeks. Results showed that the coating applied at a 1% concentration of psyllium gum reduced mass loss, promoted better ascorbic acid retention, and contributed to a stable level of titratable acidity, soluble solids, and color quality. The sensorial attributes of coated papaya fruits 12 days after being stored were similar to those of fresh papaya fruits. After nine days of storage at 5°C, researchers studied the mucilage-based fruit coating extracted from the cladodes of Opuntia ficus-indica [40]. Throughout the storage, mucilage maintains the weight, total soluble solids, firmness, sensorial attributes, visual appearance, and content of ascorbic acid and betalain, because it's a glycol protein-based edible coating. Coated fruits exhibited a lower increase in microorganisms while in storage than did uncoated fruits. The effect of probiotic mucilage (quince, flax, and basil) based edible coating on strawberries, cucumber, tomato, and banana was studied by Davachi *et al.* [57] Coated agricultural produce retained freshness for a longer duration than uncoated products. Quince-based probiotic films kept more bacteria alive and were more stable mechanically, physically, and morphologically.

The reddish-brown peel of almonds protects the kernel from oxidation because the peel is rich in antioxidants while the peeled almonds suffer from shorter shelf life. Hence, studies are being conducted on edible coatings to improve shelf life. Farooq et al [58] reported mastic gum edible coatings (0.5-2%) of peeled almonds during storage at 25-27°C for 4 months. The mastic gum-based coatings at different concentrations prevented moisture absorption and reduced the thiobarbituric acid, peroxide, mold growth, and total yeast throughout the storage duration. Ghosh et al [59] studied guar gum (4-10%) based edible coating of tomatoes for a storage period of 32 days. The 6% guar gum concentration was effective in terms of overall acceptability during sensory analysis and also lesser weight loss during the storage period. The lycopene, carotenoid, phenol, and TSS content of tomatoes was also maintained. People can preserve tomatoes within a maximum time of thirty-two days by using a coating of edible guar-gum which slows down ripening. This decrease in the rate at which tomatoes lose weight can be attributed to the ability of the coating to act as a partially permeable barrier through which air and other gases, as well as water vapor and solutes, cannot pass thereby slowing down respiration, desiccation, and oxidation.

According to Saberi *et al.* [60], edible films were used in Valencia oranges stored at 5°C for 4 weeks and then transferred to 20°C for an extra 7 days. By employing the layer-upon-layer technique, coatings like guar gum, pea starch, shellac, and oleic acid were developed. Lipid compounds also allowed decreasing a rate of respiration, an ethylene formation, loss of weight, and a decay presence and ensured orange texture preservation. Oranges covered with a layer of guar gum and pea starch alone, as well as shellac, guar gum, and pea starch, kept their consistency and color characteristics fresh throughout storage. Even though the layer-by-layer approach improved the firmness, and reduced respiration rate and weight loss, this has resulted in the formation of ethanol causing off-flavor. When compared to commercial wax-based coatings, guar gum combined with citrus fruit shelf life can be effectively increased with edible coatings based on pea starch.

- *Starch.* Starch contains amylose and amylopectin; it is the most widely utilized biopolymer [61]. It is mainly derived from maize and a huge number of smaller amylose molecules coexist with amylopectin molecules [62]. The presence of amylose in starch is responsible for its film-forming ability. The starch-based coatings are biodegradable, affordable, and eco-friendly when compared to traditional packaging materials. Starch is hydrophilic which in turn makes them a poor water barrier [63]. According to Hernández-Guerrero *et al.* [30] having a starch-based coating, the shelf-life of stenospermocarpy mangoes can be increased by putting the fruit in those two conditions; stenospermocarpy mangoes that had a starch-based coating when they were kept in that manner [10 days at 10°C and then 5 more days at 22°C for ten days]. Tropical fruits were used to extract the starch like banana pear, soursop, and mango. The coated fruit storage temperature at 10°C for 10 days has not affected the fruit color, firmness, total soluble solids, and organoleptic properties. However, further storage at 22°C resulted in increased weight loss in treated fruits in 5 (3.32%) and 10 (3.36%) days of storage. The storage of mangoes treated with mango starch resulted in reduced weight loss, soluble content, and higher firmness compared to uncoated fruits. Mango starch-based coatings also increase the shelf life to fifteen days or five days at 22°C and ten days at 10°C.

Strawberry fruits are perishable with a very short post-harvest life due to mold decay caused by quick metabolic reactions. Garcia *et al.* [61] assessed storage at a temperature of 5°C for 15 days and an edible coating made of a 3% concentration of cassava starch and potassium sorbate. Apple-based coating increased weight loss, and firmness and decreased the respiration rate, while the uncoated fruit has consumed 9 days; the concentration of potassium sorbate does not influence bacterial spoilage. The cassava starch-based coatings have better sensorial characteristics and extend strawberries' shelf life to twelve days. Adjouman *et al.* [64] reported cassava starch edible coating of tomatoes with and without microcrystalline cellulose (30%) followed by a storage temperature at 20°C for 4 weeks. Both edible coatings improved physicochemical parameters. Titratable acidity, noticeable firmness, total soluble solids, sugar/acid ratio, and color corresponded with the storage period. Aly *et al.* [65] alleged that fresh-cut taro shelf life was prolonged by 100 % chitosan-starch edible coating at 4 °C to 20 days. This has also led to adorable product quality as far as moisture content, firmness, soluble solids, and sensory characteristics are concerned, as well as halting the development of microbes including yeast and mold. Moreira *et al.* [63] reported modified starch and gelatin-based edible coatings enriched with peppermint oil (0.5-1.5%) for preserving the guava fruits for storage temperature at 25°C for up to 15 days. The physicochemical properties like acidity, firmness, soluble solids, and pH, weight loss were better maintained with the modified starch and gelatin-based coating without essential oil. The filamentous fungal and bacterial growth was reduced in fruits that were coated with modified starch and gelatin-based coatings containing 1.5% peppermint oil.

- *Cellulose.* One of the most common polysaccharides is cellulose which can form films and have a wide range of permeabilities to gases and water vapor [66]. Various biopolymers and biometrials can be used to increase the biocompatibility and processability of carboxy methylcellulose [67]. Commercially available cellulose derivatives are hydroxypropyl methylcellulose, carboxymethyl cellulose, and methylcellulose. Transparency, flexibility, absence of flavor or odor, water solubility, and resistance to O_2 and CO_2 permeability are the common characteristics of coatings and films created from these cellulose ethers [68]. Carboxymethyl cellulose is an essential derivative of cellulose that is commercially in use. It is not soluble in water and has a good ability to combine into a coating. Most carboxymethylcellulose-based coatings are flexible, translucent, odorless, and tasteless [69]. Vegetables and fruits are kept firm and fresh because of the barrier qualities of cellulose to the movement of moisture and oil [70]. Tumbarski *et al.* [71] studied the enrichment of bacteriocin obtained from *Bacillus methylotrophic* BM47 in a carboxymethylcellulose (0.5%) based edible coatings on the enhancement of the shelf life of strawberries. The bacteriocin and carboxymethylcellulose-based edible coatings maintained antioxidant activity values similar to that of fresh fruits. The absence of fungal growth on the surface of fruits has been observed after the 8th day of storage under refrigerated conditions. Ballesteros *et al.* [69] reported edible coatings based on carboxy methyl cellulose enriched with polysaccharides and phenolics extracted from spent coffee grounds of goldenberries kept between 20 and 4°C. The carboxymethylcellulose-based edible coating containing 0.2% polysaccharides or 0.2% phenolics effectively controlled the fungal growth. This coating has reduced the gas diffusion rate by pore blockage over the fruit surface which in turn altered the internal gas composition (high carbon dioxide and low oxygen). Both the coated and uncoated fruits suffered weight loss while it was higher in higher-temperature storage compared to low-temperature storage. Coated fruits retained more ascorbic acid and phenolic substances while retaining the same sensory qualities.

Panahirad *et al.* [72] reported carboxymethylcellulose (0.5-1.5%)-based coatings of plum fruits. The higher titratable acidity, firmness, ascorbic acid, and minimal weight loss were observed in plums coated with 1% carboxymethylcellulose. All the coated fruits retained higher antioxidant activity, anthocyanin, and flavonoid content than uncoated samples. In all the coated fruits, peroxidase activity was found to be increased while a decrease in polyphenol oxidase and polygalacturonase was observed. Vishwasrao *et al.* [66] reported the hydroxypropyl methylcellulose and palm oil-based edible coating being stored at 24°C to maintain the quality of pink guava fruits. The fruits coated with 1% palm oil plus 0.3% Hydroxypropyl methylcellulose HPMC retained ascorbic acid, chlorophyll, and soluble solids, reducing sugar and titratable acidity to a greater extent. It also reduced peroxidase and polyphenol oxidase peroxidases. The enhanced shelf life of fruits coated victorious over uncoated fruits by staying for twelve days compared to nine days is due to their delays and increase in enzyme activities for PPO and POD enzymes. An edible coating made up of carboxymethylcellulose derived from banana rachis on strawberry fruits was examined by Abdullah *et al.* [12] The coatings can effectively enhance the shelf life of strawberry fruits to six days at the temperature of 22°C and 16 days at 4°C. Anthocyanin, weight, soluble solids, retardment of senescence, pH, ascorbic acid, and sensory attributes and firmness of coated fruits when being stored at the temperature of storage samples at a temperature of 4°C gave better results compared to those stored at 22°C. Njoku *et al.* [73] examined the application of commercial carboxymethylcellulose in comparison with carboxymethylcellulose extracted from coconut husks in the edible coating of tomato fruits for 40 days at ambient conditions. Edible coatings based on commercial carboxymethyl cellulose help control weight loss more successfully than CMC extracted from coconut husks and uncoated samples, and increases both sugar-acid ratio and lycopene content well.

- *Pectin.* Plant cell walls contain pectin which is a soluble component of plant fiber. According to [74], pectin could help in making environmentally friendly films and coatings that are used in the packaging of food. Also, in the development of a multi-layered coating for vegetables and fruits pectin is combined with other functional components. Panahirad and other authors determined that when plum fruits were kept at 19°C, an edible coating made from pectin (0.5–1.5%) helped to preserve their antioxidant activity [75]. The pectin concentration of 1 and 1.5% was better in retaining the higher concentration of antioxidant activity, ascorbic acid, flavonoid, anthocyanin, total phenolics, and peroxidase activity compared to 0.5% pectin-coated and uncoated fruits. There was a decrease in polyphenol oxidase activity in treated fruits when compared to the uncoated samples. Maftoonazad *et al.* [76] focused on the effect of a consumption-based coating, composed of monoglycerides, sorbitol, beeswax, and 3% pectin, on the post-harvest shelf life span of lime fruits at ambient temperatures of 10 to 25°C. At an equal temperature with uncoated lime fruits, the rate of respiration for these in coated conditions had exceedingly reduced significantly. The loss of mass from fruits was minimal compared to control samples. Pectin forms a barrier to gas aiding in averting oxidation and thus enhances retention of ascorbic acid thereby leading to an increased shelf life of up to 40 days at the above temperatures compared to 13 days where the fruit was uncoated. The ripening of fruits during storage decreases the firmness while this change was reduced during low-temperature storage and coated fruits.

According to Heristika *et al.* [77], edible coatings for red chilies were made using pectin and gelatin in different ratios (50:50, 75:25, and 25:75) with garlic essential oil being stored at 29°C for 14 days. A blend of pectin, gelatin, and essential oils altered the acidity, ascorbic acid, weight loss, texture firmness retention, and antioxidant activity; 2% to 3% garlic essential oil was contained in the above products (50:50 w/w). Using pectin and a gelatin-based coating containing garlic essential oil can enhance the shelf life of red chilies for the temperature at 29°C up to 14 days. According to Gragasin *et al.* [78], they extracted pectin from mango peels and used it to cover mangoes between 8–10°C storage and 25–27°C storage. At 25-27°C and covered, the mangoes were well kept for 12 days thereby preventing ripening, and disease attacks and at the same time maintaining firmness and soluble solid constant unlike in those left uncovered which lasted only 6 days. The coated fruits at chilled storage reduced the metabolic reactions and preserved the quality in terms of visible disease resistance for up to 24 days. The uncoated mangoes were affected by 50% damage and disease development in 12 days. The pectin coating (2-4%) can be effectively used for coating mango fruits to extend the post-harvest life.

The higher moisture content of tomatoes facilitates higher respiration and transpiration rates that in turn affect the shelf life and quality. These physiological processes can be minimized by harvesting at the specific stages of maturity and by suitable coatings. Completely mature tomatoes, turning green, and light red were harvested, stored at 22°C and coated with chitosan and pectin [79]. The turning stage tomatoes showed better results compared to other stages of maturity. Compared to uncoated tomatoes, fruit that was coated significantly decreased weight loss, ripening index, and disease severity. The pectin and chitosan-coated tomatoes retained higher lycopene, phenolics, ascorbic acid, and total soluble solids compared to uncoated tomatoes. Table 1 prrsents several edible coatings for food products that are based on polysaccharides, whereas untreated fruits had a shelf life of 10 days which is 16 and 17 more days than pectin-coated and control fruits, respectively.

Table 1. Reports on polysaccharide-based edible coatings on various food products.

S. no	Edible coatings	Fruits and vegetables	Remarks	Ref.
1	Sodium Alginate	Sapota	weight loss reduced, its pH levels went down, it also became less firm, had a color change, and lost some of its total soluble solids content (TSS). Consequently, acidity was lowered in it during the storage at 4 degrees Celsius. Maintained organoleptic qualities for up to 30 days.	[49]
2	Alginate-based multi-layered antimicrobial coating	Watermelon	Reduced weight loss, no change in pH, a slight difference in color, and extended shelf life with original quality storage for 12 and 15 days at a temperature of 4°C.	[51]
3	Alginate (sunflower oil)	Fresh cut apples	Improved texture quality and water retention, maintained sensorial attributes and visual appearance. When kept in storage at 4°C, fresh-cut apples had a 15-day shelf life.	[52]
4	Alginate coating with UV-C	Cherry tomato	low ascorbic acid and total phenolic content; low respiration rate; and less weight loss.Extended the postharvest life at 10°C for up to 20 days.	[50]
5	Mastic gum	Peeled fresh almond	Prevented moisture absorption and increased shelf life of the coated almonds for 4 months at room temperature.	[58]
6	Psyllium gum	Fresh cut papaya	Maintained color, textual and visual appearance, and taste. Increased quality and shelf life up to 2 weeks.	[56]
7	Guar gum	Tomato	Decreased ascorbic acid, weight loss, and respiration rate. Increased lycopene content, carotenoid content, and TSS. The color of the treated tomatoes transitioned from green to a yellowish-orange hue throughout storage. Preserved quality of tomato during storage for up to 32 days	[59]
8	Guar gum	'Valencia' oranges	Absence of color change, together with decreases in respiratory rate, weight loss, ethylene production, and firmness.	[60]
9	Starch	Mango	Reduced weight loss, and titratable acidity. Firmness, color, and TSS are not affected. The shelf life was prolonged for a duration of up to 15 days.	[30]
10	Starch	Strawberries	There was no significant impact on the color, pH, soluble solids, or titratable acidity of strawberries. Strawberries' shelf life was increased, though, and could last up to 12 days while stored.	[61]
11	Cassava starch	Tomato	Enhanced physicochemical parameters including titratable acidity, total soluble solids, and firmness were observed. Tomatoes saved at 20°C were longer preserved at least for four weeks.	[64]
12	Chitosan/starch	Fresh cut taro	The moisture content decreased while firmness increased. By using chitosan starch, the shelf life of fresh-cut taro samples can last up to twenty days.	[65]
13	Starch/gelatine	Guava	We kept the weight, pH, and soluble solids the same, but made sure that the food stayed fresh for up to 15 days without refrigeration.	[63]
14	Carboxymethylcellulose	Fresh golden berries	Maintained all physicochemical parameters without changing sensory characteristics. Extended shelf life of golden berries fruit after 12 and 28 days when being stored.	[69]
15	Carboxymethylcellulose	Plums	The overall phenolic content did not significantly change with slight variations observed in flavonoid content and total anthocyanin. Extended post-harvest storage for up to 8 days at 19°C.	[72]

16	Hydroxymethyl cellulose	Pink Guavas	TSS content was maintained, TA decreased, and instead of 9 days, its overall quality shelf life was 12 days.	[66]
17	Carboxymethylcellulose	Strawberries	Maintained the TSS content, decreased TA, and maintained an overall quality twelve-day shelf life as opposed to nine days.	[12]
18	Carboxymethylcellulose	Tomatoes	Increased weight loss. Reduced TSS, ascorbic acid, and firmness. Postharvest treatment slowed the aging process of coated fruits at 4°C.	[73]
19	Pectin	Plum	Increased levels of phenolic, anthocyanin, flavonoids, and ascorbic acid. Retained their capacity to absorb antioxidants. PPO activity decreased while POD activity increased. The postharvest life of plum fruits treated with a pectin-based edible coating was extended to an eight-day shelf life at 19°C.	[75]
20	Pectin	Lime fruit	Diminution of firmness, respiration rate, ascorbic acid content, and reduction in weight loss. While at 25 °C, the system quality stayed within acceptable levels for only seven days, it was higher than at 15 °C but less than 22 days in duration.	[76]
21	Gelatine-pectin	Red chilies	Weight loss was reduced while maintaining levels of vitamin C, antioxidants, total dissolved solids (TDS), and acidity. When placed at ambient temperature (29°C, 69% relative humidity), its shelf life became longer by fourteen days.	[77]
22	Pectin	Tomato	Reduced weight loss, firmness, ascorbic acid, and respiration rate, while increasing titratable acidity (TA) and pH. Under ambient conditions, the shelf life was extended to 17 days.	[79]
23	Pectin from mango peel	Mango	A decrease was seen in weight decrease, respiration rate, ascorbic acid content, total soluble solids (TSS), and firmness as well. Water–soluble mango pectin at various concentrations ranging from 2 to 4% may prevent rapid spoilage of undried mangoes.	[78]

TSS- Total soluble solids; TA- Titratable acidity; TDS- Total dissolved solids; PPO-Polyphenol oxidase; POD-Peroxidase; AA- Ascorbic acid

Proteins

Proteins have exceptional mechanical strength and gaseous (O_2/CO_2) permeability due to the intimate interactions among the chains during the coating's deposition involving covalent, non-ionic interactions and hydrogen bonding, essential in preserving the freshness of fresh fruit for longer periods [80]. Various edible coatings are made of milk, gelatine, soybeans, peanuts, wheat, or corn are reported. The majority of hydrophilic surfaces, protein-based films, and coatings work effectively, although they often exhibit minimal resistance to water vapor transport. Edible coatings made of proteins have weak mechanical properties but better water and carbon dioxide barrier properties [81].

- *Soy protein.* Protein materials of soybeans are more suitable for application in edible coatings because of their permeability which has been low to carbon dioxide along with oxygen as well as their reasonable price. Soybeans are plant protein. Most plant protein sources have few amounts of essential amino acids like histidine, methionine, lysine, and cysteine and many anti-nutritional substances and unbalanced composition of non-essential amino acids [82]. The shelf life of walnut kernels and freshly cut eggplants has been extended by the application of substances derived from soybeans. Zhang *et al*. [83] suggested that a soybean-chitosan coating improves the retention of fruit chelator and water-soluble pectin as well as increases weight loss, titratable acidity, soluble solid content, and hardness. The untreated apricot fruit demonstrated a firmness of 2.69 N after 42 days of storage as against 4.15 and samples of 4.26 N coated with soybean protein isolate and soybean protein isolate -chitosan, respectively. Apricots covered with chitosan-coated with soybean protein isolates showed a weight decrease that was visible and significantly less than observed in the controlled group. On the other hand, the soybean protein isolate and chitosan-coated apricots had weight reduction that was less than that in the control group, but it was still observable. On the 35th day weight loss of 19.93% for the fruits coated with soybean protein isolate and 18.10% for the non-treated fruit, respectively, was observed.

When compared with the control fruit, TA declined during storage in the coated fruit a little bit more slowly. Maintained quality and extended post-harvest of coated apricot fruits when being in storage periods and also maintained better firmness of the fruits. The apricot's physicochemical properties were maintained by soybean protein isolate-chitosan coating after 42 days due to inhibition of water loss mainly linked to weight loss similar to the group that was covered with soybean protein isolate.

- *Whey proteins.* The milk protein-based coatings and films that are edible serve as a barrier between food ingredients or as a protective layer on foods. Their crucial features include mechanical defense, mass transfer control, and sensory attributes [84]. As a by-product of producing cheese, whey is a good source of amino acids that contain sulfur, methionine, and cysteine. The whey-based films made from whey protein isolates and concentrates contain 90% and 50-80% of protein, respectively. The ability of whey-based film formation is determined by the heat denaturation of whey protein in an aqueous solution [85]. Galus *et al.* [86] reported whey protein edible coating containing lemongrass and lemon essential oil on fresh-cut pears in comparison to the uncoated fruits upon storage temperature at 4°C. Incorporating essential oil in whey protein-based coatings enhances their ability to block gases. All edible coatings inhibited the browning of pears, except lemongrass oil whose yellow color contributes to its non-effectiveness in controlling browning. The fruit's texture was maintained throughout the storage for 28 days except for the lemon oil-based coating. The use of edible coatings made from whey proteins did not affect the color, taste, and smell of fruits. Essential oils led to a reduction in the general acceptability of fruits during sensory analysis.

Elsayed *et al.* [87] reported that they can use a 1-3% concentration of mango peel extract to extend its shelf life while also preserving the post-harvest quality of fresh-cut broccoli with an edible coating made from whey protein for 28 days if stored at 5°C. Whey protein-based coatings in combination with mango peel extract resulted in better retention of green color and reduced weight loss in broccoli which has been compared with uncoated broccoli. The ascorbic acid, sulforaphane, and phenolic content retention were also better in coated fruits. An edible coating derived from whey protein with mango peel extract (3%) coated broccoli received higher sensory scores and a reduction in bacterial and fungal counts. In their findings, Rossi-Márquez *et al.* [88] devised a method that involved applying an edible whey protein coating consisting of pectin along with transglutaminase onto roasted peanuts to extend their shelf life. As a result of the presence of these mixtures, the peanuts could maintain balanced moisture levels as well as peroxide while at the same time preventing them from getting spoiled within a short period thus promoting long ordinarity. This situation arose due to improved moisture barrier capacities that come with such envelopes. The enzyme within those combinations lowers the surface charge of the whey-protein pectin compound hence the peanut's surface coating solution is seen with better wettability and adhesive properties [88]. During sensory analysis, >50% of the consumers preferred coated peanuts compared to uncoated samples over storage for 50 days. The peroxide value was in the acceptable range for the coated peanuts (20 to 30 $mEqO_2/Kg$). The uncoated peanuts attained a higher moisture level (>8%) after 2 weeks of storage whereas coated peanuts maintained a moisture content of 2.5-3% throughout the 50 days of storage. The coated samples appeared lighter in color while uncoated samples were darker in color.

- *Cereal protein.* In both the glutelin and prolamin fractions of wheat proteins, wheat gluten, and the prolamin portion of maize zein and maize proteins, their ability to form films has been the focus of extensive study. Films formed of gluten have high mechanical properties, a good capacity to isolate oxygen, and a resistance to water vapor. Comparing the without-treated group to the presence of a substance like mineral oil which has no polarity and is hydrophobic, there is a difference in vapor permeability reduction levels of about 25 % [85]. Corn-zein protein is a renewable and biodegradable substance that can be used in coating and packaging film applications [89]. The incorporation of ethanolic extract of propolis into gelatin-based edible films was studied by direct incorporation and by encapsulation into the zein nanocapsules to control the release of extract [90]. The inclusion of extract in the films resulted in increased elasticity and stretchiness but left their water barrier properties and microstructure unaffected. The incorporation of nanocapsules containing the extract promoted better preservation by improving the antifungal activity compared to the direct incorporation. The reports on protein-based edible coatings on various food products are compiled in Table 2.

Table 2. Reports on protein-based edible coatings on various food products.

S. no	Edible coating	Fruits and Vegetables	Remarks	Ref.
1	Whey protein	Fresh cut pears	Maintained firmness. Reduced flavonoids and polyphenols. Did not affect sensory attributes. Maintained quality attributes of the treated sample during storage for 28 days except lemon oil-based coating at 4°C.	[86]
2	Whey protein	Broccoli	The weight loss, rate of respiration, and levels of bioactive compounds or antioxidant activity were at the lowest level. Maintained post-harvest quality and shelf life at 5°C for 28 days.	[87]
3	Whey protein	Roasted peanuts	Surface charge and water uptake decreased, while wettability and surface adhesivity increased. These improvements helped keep roasted peanuts at top quality even after 50 days of storage.	[88]
4	Soy protein	apricot	There was a decrease in dietary consumption, respiration rate, titratable acidity as well as soluble solids. The quality was maintained and the post-harvest life of coated apricot fruits was extended the temperature up to 42 days of storage.	[83]

TA- Titratable acidity; SSC- Soluble solid content

Lipids

Wax and oils like beeswax, vegetable oil, sucrose, mineral oil, carnauba wax, acetylated monoglycerides, and beeswax esters of fatty acids are used in the production of lipid-based coatings, which are frequently employed as a good water barrier for preserving moisture in the fatty acids based on food materials [91]. Lipid-based coatings are the maintenance of the moisture content in food products of the main advantage. By creating the hydrophobic barrier in products, they can halt moisture loss as well as microbial invasion. It can maintain product quality while improving its aesthetic appeal. The rice processing industry's secondary byproduct that has beneficial nutritional qualities is rice bran wax which is proven to have good film-forming characteristics, making it a useful edible coating ingredient [92].

- *Beeswax.* Beeswax can be used as an effective moisture barrier for perishable commodities. Food preservatives along with beeswax can increase the functional characteristics of edible coatings whereas it can also limit the growth of mold, bacteria, and yeast when being stored and distributed [93]. Due to the hydrophobic nature of beeswax, it enhances air passage but reduces water vapor passage. The freshness and quality of food products can be preserved by reducing transpiration rates and minimizing flavor and weight loss. It has been shown that by using hydroxy propyl methylcellulose-based coatings and the application of beeswax hardness can be maintained over longer periods by several kinds of fruits among which are tomatoes, mandarins, mangoes, plums or guavas [94]. The effects of HPMC and beeswax coating on 'Angeleno' plums were elucidated by Navarro-Tarazaga *et al.* [95] with 0-60% of beeswax lipid content and 4 weeks storage temperature of 1°C, then it was stored for another three weeks at a temperature of 20°C. Beeswax with lower lipid content has been effective in decreasing the softening and bleeding of plums because the surface of the fruit develops a changed atmosphere. The beeswax coating with 20% lipid content is further recommended to enhance the shelf-life of plums with higher quality products.

Formiga *et al.* [96] reported the effect of edible coatings of 'Pedro Sato' red guavas using HPMC and beeswax (10-40%) during 8 days of 21°C storage. The coated fruits appeared greener, firm, and turgid compared to uncoated fruits. The increase in the wax concentration decreased the chlorophyll content when being stored. The guava fruit's shelf life without coating is six days. However, the fruit's quality and its shelf life extension by six days were preserved by HPMC and 20% beeswax. Fagundes *et al.* [93] studied the anti-fungal properties (*Botrytis cinerea)* of HPMC and beeswax coating along with different food preservatives (potassium carbonate, ammonium carbonate, sodium propionate, and ammonium phosphate) on cherry tomatoes stored at 5°C. All the coated fruits showed antifungal activity while sodium propionate-based HPMC and beeswax coating exhibited higher antifungal activities. Ammonium carbonate-based HPMC and beeswax coating maintained firmness and decreased weight loss significantly compared to other combinations. Sousa *et al.* [94] have shown that the storage life of palmer mangoes treated with beeswax and ammonium carbonate HPMC can be prolonged. The study investigated the effects of a hydroxypropyl methylcellulose-beeswax edible coating (10-40%) on mangoes stored for fifteen days at a temperature of 21 ºC. The coating controlled the fruit ripening and maintained pigments, antioxidant activity, soluble solids, phenol, sugar, ascorbic acid, firmness, titratable acidity, and β-carotene content. It has also minimized weight loss, and oxidative stress and does not cause fermentation of fruits during storage. The application of 20% beeswax combination with HPMC enhanced the shelf life for an additional 6 days.

- *Carnauba wax.* Many fruits and vegetables have been treated with carnauba wax, which is an edible coating that is lipid-based so that they last longer after they are harvested. Its main use is to reduce evaporation and keep its shine. This wax comes out of Brazilian palm tree leaves. Commercial carnauba-shellac coatings can prolong the ripening of pears because of the production of more carbon dioxide compared to uncoated fruits, thereby maintaining firmness and delaying color changes [97]. In 2018, the US Food Drug and Administration provided GRAS status to carnauba wax. It also prevents pigment degradation, maintains texture, and enhances the mechanical integrity and aesthetic properties of fruits [98]. Carnauba wax contributes to the product's aesthetic improvement by increasing its shine [14]. Bhattacharjee *et al.* [99] reported edible coating of pointed gourd using chitosan and carnauba wax at 27-32°C. The carnauba wax-coated fruits showed a higher disease reduction index and chlorophyll content, minimal weight loss, and spoilage compared to chitosan-coated fruits. Therefore, Instead of being coated with chitosan-based coatings, products can be coated with carnauba wax to enhance quality and increase longevity. Nazoori *et al.* [100] led the investigation on prolonging the shelf-life of pomegranate fruits by storing them under cold conditions while applying edible coatings of 0.5% carnauba wax and 5 mM or 10 mm GABA for 45 or 90 days. The edible coating maintained freshness decreased the loss of taste, and malondialdehyde formation, improved antioxidant activity, and reduced cold injury. The weight loss was not controlled by the GABA and carnauba-based coatings. Carnauba wax (0.5%) with GABA (5 mM) can be used for storage for 45 days while carnauba wax (0.5%) with GABA (10 mM) storage for 90 days.

Oliveira Filho *et al*. [14] found that *Cymbopogon martini* EO and carnauba wax nanoemulsion (CWN) could be used to coat papaya fruit for storage after harvest. The coated fruits retained higher firmness, pH, decreased weight loss, and lower soluble solids and TA. The edible coating containing 1.5% of CWN+CEO reduced the disease incidence during the 9 days at 16°C of storage. Miranda *et al*. [98] inquired about the utilization of high-pressure-produced carnauba wax nanoemulsion base and the usual 9% and 18% carnauba wax emulsion in enhancing tomato quality and shelf life, which were held at 23°C during 15 days, in their research. The nanoemulsion coating made of carnauba wax fruits had higher gloss and sensory scores compared to carnauba wax emulsion and uncoated fruits. Both the coatings decreased the weight loss but the color and sugar content of tomatoes was significantly affected when being stored. In the study, Singh *et al.* [97] investigated how carnauba wax-based edible coatings influenced eggplant characteristics when it was stored in polypropylene pouches at (20°C). The coated and packaged eggplant retained higher antioxidant activity and firmness compared to the uncoated eggplant. As for shelf life duration extension, one observed that coated packaged eggplants lasted for 12 days more than the untreated ones.

- *Fatty acids.* Lauric acid, a dodecanoic acid that is abundantly present in coconut oil contains a huge amount of lauric acid and it undergoes endogenous conversion to monolaurin, a substance with antiviral, antifungal, and antibacterial activities. The coating-based coconut oil can inhibit the lenticle's opening and stomata, slow respiration and transpiration, and reduce microbial deterioration rates [101]. In the example given by Memete *et al.* [102], some sunflower oil, coconut oil, beeswax, or gelatin-type edible coatings were applied to them and stored at four degrees celcius for eight days. Non-coated fruits presented significantly higher anthocyanin and phenolic content as well as better firmness and sensory scores compared to the other coated fruits. Therefore, the oil-based edible coatings have demonstrated that the mulberries' shelf life could be increased at the storage temperature of 4°C for 8 days while preserving the product important in terms of texture, antioxidant activity, and sensorial score. Nasrin *et al*. [101] have investigated the impact of beeswax and the quality of post-harvest in the edible coatings that have been developed using coconut oil of lemons in ambient conditions (21°C), with and without modified atmosphere packaging (MAP). Using MAP, it was found that beeswax coatings containing 80% coconut oil and 10% lemons were able to prolong their shelf life by 15 days and more. However, uncoated lemon could be acceptable in terms of color, flavor, and texture for only up to 6 days. The coated fruits moderately reduced the shrinkage of lemon while MAP plays an important role in preventing the shrinkage. Manju Danu *et al.* [103] determined that coconut oil edible coating (3%) under refrigerated conditions (T8) has been the most efficient treatment for Malta fruits in terms of TSS: Acid ratio, total soluble solids, fruit juice volume (ml), juice percentage, fruit color, taste, texture, flavor, and overall acceptability. In comparison, mustard oil (T2) and almond oil (T10) coatings were particularly beneficial for maintaining pH and preserving titratable acidity (%). It was concluded that the edible coconut oil coating effectively preserves the chemical and sensory characteristics of Malta.

- *Resins*. Trees and shrubs with specific plant cells respond to wounds by producing and secreting a class of acidic substances known as resins. Petroleum is a component of synthetic resin production. Chauhan *et al.* regarded the tomato as a product to determine the use of shellac resin produced by Laccifer lacca wasps and found in India, as well as aloe vera gel, which was used as an edible coating. Aloe vera gels promote the penetration of water vapor, carbon dioxide, and oxygen into the membrane. The development of the aging process, changes in ethylene synthesis, and the respiration rate occurred more slowly. The fruits' texture and color characteristics were more preserved than the fruits without the coating when labels were stored at 28°C, uncoated. Shelf life increased by 12, 10, and 8 days with the use of shellac, aloe vera, and aloe vera and shellac-based consumable films [104].
- *Rice bran wax.* In the study done by Abhirami *et al.* [90], where rice bran wax was used on edible tomatoes as a coating to prolong their shelf life, the products' weight loss, lycopene content, texture, soluble solids, and respiration rate of the products were kept intact at 27 days of storage by applying a 10% wax coating. This implies that the uncoated samples are maintained for a maximum of 18 days. The tomato wax coating, which blocked the lenticels and stomata, may also be causing the slower rate of weight reduction. Moreover, the reduced tomatoes' respiration rate with coatings might be due to the reduced metabolic processes in tomatoes. Rice bran wax is utilized and prepared as an edible oil source [105]. Reports on lipid-based edible coatings on various food products are discussed in Table 3.

CURRENT CHALLENGES AND FUTURE PERSPECTIVES

Different edible coatings and films that integrate useful components have substantially extended the period within which fruits and vegetables can last. Moreover, the use of edible coatings and films successfully preserved the nutritional value and sensory qualities of the produce while maintaining its post-harvest quality. The main area of research in the use of edible films and coatings has been laboratory work. Therefore, it is essential to conduct scale-up studies to ease the commercialization of the process. Further work can be carried out by incorporating nano-encapsulated compounds to facilitate the controlled release of functional ingredients to provide stability against adverse storage conditions. The layer-by-layer edible coating successfully retained physicochemical characteristics, sustained quality and nutraceutical benefits, and improved the antioxidant enzyme system, aiding in oxidative stress regulation and the functioning of the ascorbate–glutathione cycle (Figure 4) [106]. The layer-by-layer coating treatment effectively reduced decay percentage and Physiological weight loss while preserving total chlorophyll pigments. This, in turn, likely inhibited the accumulation of total carotenoids by suppressing the activities of chlorophyllase (CPS), pheophytinase (Phe), Mg-dechalatase (MGD) and chlorophyll degrading peroxidase (Chl-POD) enzymes in harvested mangoes [107]. The layer-by-layer approach resulted in better retention of product quality but limited research work is available in this area. Therefore, future studies can focus on developing a layer-by-layer approach and/or coatings and films incorporated with nano-encapsulated functional ingredients. The types of edible coatings and their functional benefits are presented in Table 4.

CONCLUSION

Edible coatings and films can replace conventional packaging materials, which are not biodegradable. Most fruits and vegetables can be preserved with edible coatings and films to reduce wastage. These coatings and films consist of proteins, carbohydrates, and lipids - naturally occurring polymers to maintain freshness, microbial spoilage, and moisture loss in agricultural produce. The deterioration rate is slowed down by them acting as barriers to gas, moisture, and solutes. The novel polymers and advancement in formulation techniques can define the new trend in edible coatings and films. Further research can be focused more on improving the stability, barrier ability, anti-microbial nature, and mechanical properties to widen their scope, usefulness, and acceptability. Nanotechnology in the use of edible coatings and films stands out as a possible aid in enhancing their mechanical properties and increasing preservation time for different food products.

Table 3. Reports on lipid-based edible coatings on various food products.

S. No	Edible coating	Fruits and vegetables	Remarks	Ref.
1	Rice bran wax	Tomatoes	Maintained lycopene content, respiration rate, texture, and soluble solids. Increasing the shelf life to 27 days.	[92]
2	HPMC Beeswax	Cherry tomato	Weight loss and respiration rate were reduced, with improved control over water loss and enhanced visual appearance. Tomatoes now last 15 days at 5°C instead of 5 days at 20°C.	[93]
3	Beeswax	Mango	There was a decline in weight loss as well as an increase in firmness and the antioxidant activity remained unchanged. The mangoes stayed at 21°C for 15 days before being extended by another 6 days.	[94]
4	HPMC Beeswax	Guava	The weight loss was reduced and, in the process, color and firmness were preserved. By doing this, it added up to six more days of staying on the shelf.	[97]
5	Coconut oil beeswax	Lemon	Quality, Ph, sensory analysis, ascorbic acid (AA), and total soluble solids were maintained. With the addition of modified atmosphere packaging, the extended shelf life reached 15 days and exceeded 18 days.	[101]
6	Beeswax content on HPMC	Plums	Weight loss decreased, sensorial attributes remained unaffected, and lipid content increased. Extended shelf life of store plums at 1°C for up to 4 weeks, then at 20°C for 1-2 weeks.	[95]
7	Beeswax	Mulberry	Maintained firmness and antioxidant activity. Improved shelf life of mulberry to 8 days at 4°C	[102]
8	Carnauba wax	Eggplant (*solanum melongena*)	Extended eggplants for 12 days at 20°C as a way of reducing weight loss, and increasing firmness and moisture content.	[97]
9	Carnauba wax	Tomato	Weight loss decreased, while ascorbic acid (AA), total soluble solids, and pH remained unaffected. Storage of tomatoes at 23°C increased their shelf life to 15 days.	[98]
10	Carnauba wax Nanoemulsion	Papaya	Decrease in weight loss and maintain its firmness. Temper down on both TSS and TA. Papaya fruits ripen during the 12-day storage period.	[14]
11	Gamma-Aminobutyric acid & carnauba wax	Pomegranate	Weight loss and firmness were reduced, while sensory analysis and nutritional quality were maintained. Extended shelf life of carnauba wax (0.5%) with GABA (10 mM) for 90 days of storage.	[100]
12	Carnauba wax	Gourd	Weight loss was reduced and ripening was delayed. This led to a prolonged shelf life of gourd under ambient storage conditions (27.4-32.3°C and 70-81% RH).	[99]

TSS- Total soluble solid; TA- Titratable acidity; AA- Ascorbic acid; GABA- Gamma-Aminobutyric acid; HPMC- Hydroxy propyl methylcellulose

Table 4. Types of edible coatings and their functional benefits

Type of edible coating	Integrated components	Benefits	Challenges	Future scope	Ref.
Polysaccharide-based	Antioxidants, antimicrobials	Moisture control, barrier properties	Limited moisture resistance	Nano-encapsulation for enhanced functionality	[108]
Protein-based	Sodium alginate, cedar mucilage, calcium chloride Components	Sustainable food production Reduce food waste	Increase Effectiveness and commercial viability	Layer-by-layer approach for better retention	[106]
Lipid-based	Essential oils, hydrophobic agents	Improved water resistance	Poor mechanical strength	Combining with polysaccharides for balanced properties	[109]
Composite coatings/films	Nanoparticles, functional ingredients	Synergistic barrier properties	High-cost, complex production	Scale-up studies for commercialization	[110]

Fig. 4. Advantages of layer-by-layer edible coatings.

Acknowledgement: *The authors are grateful to the Management of Vellore Institute of Technology, Vellore, Tamil Nadu, India for providing the facilities to carry out this work.*

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