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Review

Polysaccharide-Based Active Coatings Incorporated with Bioactive Compounds for Reducing Postharvest Losses of Fresh Fruits

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Abstract: This review reports recently published research related to the application of polysaccharide-based biodegradable and edible coatings (BECs) fortified with bioactive compounds obtained from plant essential oils (EOs) and phenolic compounds of plant extracts. Combinations of polysaccharides such as starches, pectin, alginate, cellulose derivatives, and chitosan with active compounds obtained from clove, lemon, cinnamon, lavender, oregano, and peppermint have been documented as potential candidates for biologically active coating materials for retardation of quality changes in fresh fruits. Additionally, polysaccharide-based active coatings supplemented with plant extracts such as cashew leaves, pomegranate peel, red roselle, apple fiber, and green tea extracts rich in phenolic compounds and their derivatives have been reported to be excellent substituents to replace chemically formulated wax coatings. Moreover, EOs and plant polyphenolics including alcohols, aldehydes, ketones phenols, organic acids, terpenes, and esters contain hydroxyl functional groups that contribute bioactivity to BECs against oxidation and reduction of microbial load in fresh fruits. Therefore, BECs enriched with active compounds from EOs and plant extracts minimize physiological and microbial deterioration by reducing moisture loss, softening of flesh, ripening, and decay caused by pathogenic bacterial strains, mold, or yeast rots, respectively. As a result, shelf life of fresh fruits can be extended by employing active polysaccharide coatings supplemented with EOs and plant extracts prior to postharvest storage.

Keywords: coating; polysaccharide; bioactivity; essential oil; plant extract; polyphenols; antimicrobial; antioxidant

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1. Introduction

Fresh fruits containing essential nutrients, vitamins, and minerals are consumed worldwide in part because of their strong antioxidant potential against chronic diseases [1]. Fresh fruit packaging materials after single use are disposed of in the environment. The application of synthetic and non-biodegradable polymer-tailored packaging materials for fresh fruit has raised potentially alarming consequences for the environment [2]. Conventional packaging materials such as glass, wood, aluminum, tin, and paper have been employed as fresh fruit containers to prevent mechanical damage during bulk transportation [3]. The innovative designs of synthetic packaging materials have been of great convenience to customers in supermarkets [4]. Synthetic packaging materials used for fruits may lack the optimum oxygen and moisture barrier properties to maintain their postharvest quality in the markets [5]. Additionally, the production of synthetic packaging materials may directly have an impact on the sustainability of non-renewable petroleum-based resources [6].

Fresh fruits typically have a short postharvest shelf life due to ongoing physiological and biochemical changes occurring in the living tissues until consumption [7]. Mechanical damages and pathological changes during improper handling and transportation have been associated with heavy economic losses [8]. Conventional synthetic waxes and chemical fungicides have been used as postharvest treatments to minimize losses in fresh

fruits. These materials have been reported to cause health and environmental concerns [9]. Chemical-based coatings fortified with synthetic antimicrobial additives have been associated with the antimicrobial resistance of food borne pathogenic strains. Taking all the research challenges into consideration, the novel idea of active food coatings composed of polysaccharides supplemented with natural essential oils, phenolics, and active nanoparticles has been an effective adjunct to conventional postharvest treatments of fresh fruits [10]. Because several polysaccharides have limited barrier and mechanical properties even after the addition of bioactive compounds, the inclusion of inorganic clays [11] or nanoparticles [12] has been proposed.

During the past decade, several findings reported applications of natural and biodegradable edible coatings that have proven to be sustainable alternatives with excellent barrier properties compared to synthetic plastic packaging commonly used in the market [13]. Edible coating materials employed consisted of a wide range of plant or crustacean-based polysaccharides [14]. Hydrocolloid-based coating forming solutions prepared from starches, pectin, alginate, carboxymethyl cellulose, and chitosan have been applied to delay ripening and prevent senescence or detachment of fruit skin during postharvest storage [15]. In addition to plasticizers, emulsifiers, surfactants, and hydrophobic materials, the use of inorganic clays [11] or nanoparticles [12] have also been proposed.

Essential oils (EOs) have been incorporated as active ingredients in polysaccharide-based coating materials against oxidation of vital nutrients and bacterial and fungal growth. EOs from different herbs such as clove, lemon, cinnamon, tea tree, lavender, oregano, and peppermint are a source of diverse bioactive compounds with higher antimicrobial efficacy for the preparation of active food coating materials employed in fresh fruits [16]. Bioactivity of EOs has been documented because of antioxidant and antimicrobial functional groups present such as monoterpenes, flavonoids, aldehydes, isoflavones, carotenoids, and phenolic compounds that exhibit numerous nutraceutical properties [17]. EOs incorporated in the polysaccharide coating materials to extend the shelf life of fresh fruits have generated tremendous interest and are generally recognized as safe food coating additives [18]. EOs incorporated in polysaccharide-based coating materials may result in a hydrophobic film on the coated fruits to reduce loss of weight and firmness [19]. Biodegradable and edible coatings (BECs) containing EOs may also suppress several hormonal and enzymatic reactions triggered by contact with atmospheric oxygen during postharvest storage of fruit [20]. In addition to physiochemical quality preservation, EOs have been investigated to provide protection against a broad spectrum of food-borne spoilage and pathogenic microorganisms [21].

The use of plant extracts containing alcohols, aldehydes, ketones phenols, organic acids, esters, and terpenes as active coating additives has tremendous scope in the preservation of postharvest physical, oxidative, and microbial quality of fresh fruits [22,23]. Phytochemical polyphenols comprising multiple hydroxyl functional groups attached to benzene rings have been supplemented in different polysaccharide edible coatings [10]. Plant extracts such as pomegranate peel and pineapple extracts incorporated in cassava starch, alginate, and chitosan coatings have been documented to safeguard the postharvest quality of fruits [24]. Furthermore, the bioactive properties of plant-derived natural essential oils and polyphenols along with polysaccharides have been exploited in the preparation of emulsion-based active coatings to combat the postharvest losses of in fruits [25]. EOs and plant extracts containing bioactive compounds have been reported as potential substitutes for chemical additives to ensure food quality and safety of fruits during postharvest storage [26]. Therefore, this review reports the different polysaccharide-based coatings fortified with plant EOs and phytochemical extracts with bioactive properties to prolong the postharvest shelf life of fresh fruits. The review also emphasizes the beneficial effects of the aforementioned eco-friendly coatings on the physical, biochemical, and microbiological quality of fresh fruits. Thus, the heavy losses in the horticulture sector in the future could be prevented leading to the sustainable development of a green economy.

2. Postharvest Quality Constraints of Fresh Fruits

Fruits are commonly harvested on the basis of conventional extrinsic factors such as firmness, color, size, and shape. More recently, intrinsic factors such as nutritional and functional attributes have been considered, including minerals, vitamins, dietary fibers, and other polyphenolic constituents that exhibit beneficial health properties [27]. During postharvest handling, transportation, and bulk storage, fruits may be highly susceptible to biological and/or mechanical hazards that can affect both intrinsic and extrinsic factors [28]. In addition to improper postharvest handling of fruits, mechanical vibrations may affect the fruit quality during transportation, triggering heavy losses during longer storage periods. The quality problems that emerge in metabolically active fruits during postharvest storage include physiological deterioration and microbial deterioration as evidenced by moisture loss, softening of flesh, ripening, and decay caused by pathogenic bacterial strains, molds, or yeast rots [27,29].

Microbial and Biochemical Causes of Deterioration in Fresh Fruits

Fruits after harvesting from the field may be contaminated with pathogenic microbes, insects, and pests. Fresh fruits in unprocessed and raw form contain infectious germs on the skin of fruits that can lead to food borne diseases [30]. The microbial population is an important factor in considering the quality of the food product [31]. The low pH fruits, like ripe tomatoes, in a pH range (3.9–4.5) could inhibit the human intestinal pathogens such as *Shigella* and *Escherichia coli* O157:H7. Melons and soft fruits with a pH of 4–6 can favor the growth and survival of *Botrytis cinerea* and *Penicillium* species [32]. Pathogenic organisms are transmitted from the environment mostly during fruit harvesting from plants, post-harvest displacements, processing, and transport movements [33]. Several types of microorganisms, such as bacteria, yeasts, and fungi that cause deterioration may be transmitted during postharvest storage. Approximately 80–90% of microbial contamination in fresh fruits is due to *Pseudomonas* and Enterobacteriaceae (*Klebsiella*, *Enterobacter*, *Citrobacter*, *Salmonella*, *Escherichia coli*, *Shigella*, *Proteus*, *Serratia*, and other species) referred as Gram-negative bacteria [32,34]. Additionally, lactic acid bacteria, which are a natural flora of fruits, are corrosive and develop unpleasant odors [32]. Moreover, fresh fruits contaminated with fungi (*Rhizopus, Penicillium, Aspergillus, and Eurotiumand Wallemia*) and the yeast (*Debaryomyces, Pichia, Candida, Hanseniaspora, Zygo saccharomyces*), also have major role in the spoilage of fresh fruits during postharvest handling and storage [32]. The use of chemical disinfectants such as organic acids, chlorine dioxide, hydrogen peroxide, hypochlorite, sodium bisulfite, sulfur dioxide, and ozone has been proposed for reducing the bacterial population during postharvest storage [35]. Such chemical-based disinfectants have limited applications due to ill effects on human health and degradation of sensory quality in fruits [36].

Biochemical quality deterioration may depend on the storage temperature and metabolic processes occurring during respiration of living tissues in postharvest storage of fruits. Temperature is an important factor responsible for controlling metabolism of carbohydrates, lipids, and amino acids in respiring fruits. Temperate fruit crops are commonly stored at temperatures (0–1 °C) compared to the tropical or subtropical fruits that must be stored at higher temperatures (7–15 °C) to avoid losses due to chilling injury (CI) [37]. CI may alter the ripening process by damaging the external peel, inducing internal flesh browning, pitting, loss of firmness, and discoloration evidenced after the removal of fruits from cold temperature storage [37].

Appropriate storage temperatures can extend storage life by approximately 2–4 weeks for crops such as apricots, sweet cherries, and peaches, and up to several months for apples, pears, and kiwifruits [37]. The general effect of low temperature storage upregulates stress-responsive genes, blocks signal transduction of ethylene production processes affecting metabolic changes in vital components of fruits [38,39]. Various commercially important fruits, such as apples, pears, kiwifruits, bananas, and nectarines, at physiological maturity are characterized by high starch content that is converted to sugars at low temperatures

during postharvest storage [40]. Induction of chilling tolerance of nectarines stored at near freezing temperatures (−1.4 °C) was shown to reduced activities of sucrose metabolism-associated enzymes that resulted in higher sucrose contents [40]. Moreover, fatty acids are essential cell membrane components forming a selectively permeable barrier between the cells in a fruit matrix. Fruits are composed of different types of fatty acids that show active roles in the biochemical quality degradation during postharvest cold storage. Peaches containing plastidic glycerolipid and triacylglycerides (TAGs) are used as a source of energy during fruit senescence [41]. Phosphatidic acid (PA) is accumulated in pineapple fruit during blackheart development at 10 °C [42]. Increased levels of phospholipase D enzyme activities have been observed in cold stored pears [43,44]. Similarly, chilling injury of "Honeycrisp" apples with soggy flesh showed elevated contents of glycerol and TAGs [45]. During postharvest storage of fruits, proteins may be degraded into free amino acids due to the activation of proteolytic enzymes. Amino acids such as Glu, Gln, Asp, and Asn contents increased in tomatoes stored at 4 °C [46]. Similar results were also documented in kiwifruit that showed increased Thr, Ile, and Val contents [47].

Additionally, temperature fluctuations during turbulent transportation may lead to mechanical bruising of fruits without any postharvest coating, thereby accelerating their decay [48]. In this regard, it is of primary concern to apply different novel coating techniques to delay ripening and senescence in fruits [49]. The aim is to eradicate biochemical quality deterioration during defective cold chain management that may accelerate the rate of respiration in living tissues and induce undesirable ripening (the main cause of senescence), thereby shortening the shelf-life of fruits [50]. Fruit ripening increases the total soluble solids resulting in higher sugar content; it involves several metabolic processes that differ between 'climacteric' and 'non-climacteric' fruits [51]. During the ripening of climacteric fruit, respiration increases until it reaches a peak, which is accompanied by an increase in ethylene production. In contrast, respiration of non-climacteric fruit does not increase during ripening, and ethylene is not required in order to complete the ripening process [52]. Regardless of the type of ripening, this process, as well as other metabolic processes that lead to deterioration, are driven by respiration. After harvest, the fresh produce continues to respire, utilizing food reserves, taking in oxygen, and releasing carbon dioxide and heat from stored carbohydrates [37]. For that reason, postharvest active coating treatments are applied on the fruit surfaces through various methods to reduce respiration, delay deterioration processes, prolong shelf life, and help to maintain produce quality.

3. Application Methods of Polysaccharide-Based Active Edible Coatings in Fresh Fruits

BECs can be applied to fresh fruits after harvesting from the plants or trees using various methods as shown in Figure 1. The selection of BECs mainly depends on the fruit surface hydrophobicity and roughness and the physical properties of the BEC such as surface tension, viscosity, density, coating emulsion stability, cost, and drying conditions for industrial application [53]. The various methods of BEC application for fresh fruits explained in this reviewed work include conventional spraying, electrospraying, dipping, spreading, brushing, and layer by layer deposition techniques, respectively (Figure 1). Spraying is a conventional technique for applying low viscous BEC solutions on the fresh fruit surface [54]. A homogenous spray with fine droplets may form a uniform layer on the fruit surface at a high-pressure atomization in the range of 60–80 psi (4.1–5.5 bar) [55]. The desirable layer of coating thickness mainly relies on the lower hydrodynamic diameter of the droplet and atomizer features (spray gun type, operating pressure, and nozzle temperature) as well as the humidity and flow rate of air or liquid in the BEC solution [56]. Conventional spraying methods applied on the rough surfaces of strawberry fruit have shown lower transfer efficiency and coating evenness compared to the electrospraying method of coating [57].

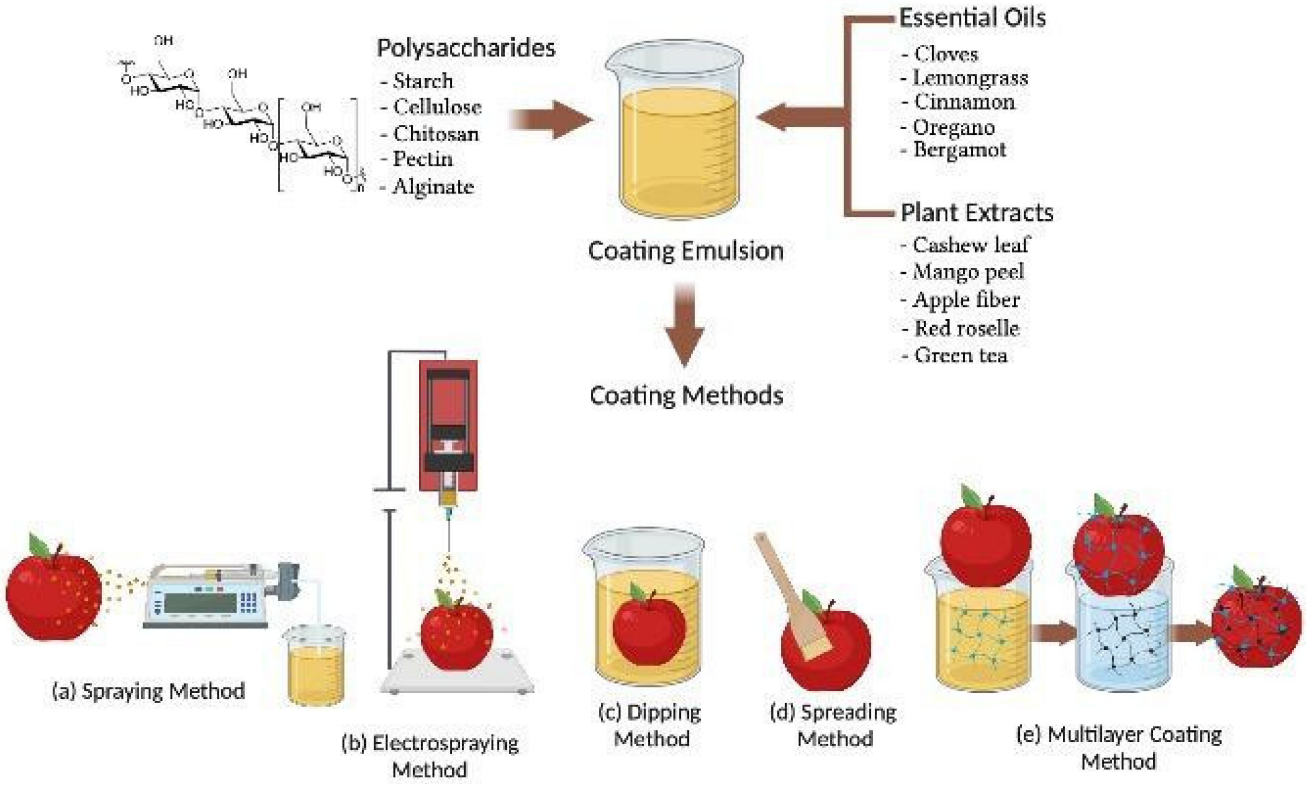

Figure 1. Schematic representation of biodegradable and edible active coating applications via (**a**) spraying; (**b**) electrospraying; (**c**) dipping; (**d**) spreading; and (**e**) multilayer coating methods, employed in the postharvest treatment of fruits.

Electrospraying is a novel method of coating in which a coating material is atomized in the presence of a high-intensity electric field, which enables the formation of micrometric and sub-micrometric charged droplets with an extremely narrow size distribution [58,59]. The tip of an emitter causes the formation of a Taylor cone of the nascent charged droplets and destabilizes the liquid surface to generate a cluster of charged droplets [60]. Electrospraying promotes the efficient adhesion to the surface of fresh fruit compared to conventional spraying because of electrostatic interactions of micrometric-sized charged droplets [61]. The droplet size, deposition rate, and coating thickness during electrospraying depend on the conductivity, flow rate, and viscosity of the coating solution [57]. The electrospraying coating method was employed to obtain even distribution of charged coating material droplets containing micro to nano size magnetic cellulose with special affinity to orient under an electric field, forming a compact coating film [62].

BECs applied by the dipping method undergo in three steps. The first step is immersing fresh fruits in the coating solution and holding for 2 to 3 min so the coating material can adhere on the fruit [63]. The last two steps are deposition and drainage of extra adhered BEC solution followed by evaporation and drying of coated fruit either at ambient temperature or flushed with hot air to accelerate drying [64]. Coating thickness and morphology of the coating's material deposited by the dipping method on the surface of fruits depends on various factors such as immersion time, withdrawal speed, dip-coating cycles, density, viscosity, surface tension, and drying conditions [65–67]. Hydroxypropyl methylcellulose in a dip-coating solution was analyzed for viscosity, density, and surface tension during coating of Fuji apples, after which the internal oxygen and carbon dioxide levels were measured at room temperature for 4 days. Results indicated that coating thickness varied with viscosity, concentration, density, and draining time of the biopolymer solution. Coating thickness relates to the square root of viscosity and the inverse square root of draining time, which agrees with the theoretical approach for flat plate dip-coating in low-capillary-number Newtonian liquids. These results indicate the possibility of controlling coating thickness

and internal gas composition based on coating solution properties [67]. The dipping compared to conventional spraying or electrospraying is more beneficial for coating fruits with complex and rough surfaces, resulting in excellent uniformity [68]. Dipping generally forms a thick coating layer on the fruit surface and may effectively reduce microbial load, contamination, respiration rate, and mechanical damage and prevent physiological changes of coated fruits [69,70].

The brushing method involves the use of a sterile brush for spreading high viscosity BECs on the fruit surface and depends on the wetting degree and the spreading rate parameters followed by a drying process [71]. Brushing of BECs is generally carried out manually by experienced operators and includes several factors to minimize manual error of BEC application and ingredient quality to achieve better coating layer uniformity [15]. The efficiency of BECs is also affected by the roughness of the fruit surface and geometry, viscosity, surface tension, density, drying temperature, and relative humidity [70]. The degree of spreading or wettability of BECs can be characterized on the surface of fruit by contact angle measurements that maintain mechanical equilibrium of the coating drops under the influence of mainly three surface tension forces—solid–liquid, liquid–vapor, and solid–vapor interfaces—to assess the adhesion properties of coating solutions on the fruit surfaces [70,72]. The ideal case of a contact angle value equal to 0° corresponds to a hydrophilic solid surface where total wetting conditions can be attained by an aqueous solution. A contact angle value between 0° and 180° suggests the occurrence of partial wetting, which is higher for a contact angle below 90°. The ideal case of a contact angle equal to 180° corresponds to a hydrophobic solid surface, where no wetting conditions occur when in contact with an aqueous medium. The contact angle can be measured directly on the food surface through the sessile drop method or atomic force microscopy to visualize the thickness and adherence of the coated surface [72,73].

BECs applied via the multilayer coating method include layer by layer deposition of coating solutions for better adhesion, especially on the surfaces of fresh-cut fruits [74]. Multilayer coating adhesion exhibits electrostatic interaction of the charged polyelectrolytes with that of the fruit surface [75,76]. The electrostatic interactions between the multilayer coatings of nano size dimensions may form chemical bonds, thereby providing effective control of physiological, mechanical, and functional properties on coated fruit [77]. In the multilayer coating method, coating materials containing oppositely charged polyelectrolytes are deposited through alternate dipping of the fruit in different coating solutions (Figure 1e). The dipping of fruit in many cycles creates a layer-by-layer deposition of a coating solution that mainly depends on the ionic strength, pH, and charge densities to form a bonded network via electrostatic forces of attraction [74]. Therefore, the application of the multilayer coating method has been reported in polysaccharides and charged polyelectrolytes capable of hydrogen and covalent bonding to increase compactness of the coating layers during postharvest storage of fruits [10,78].

4. Impact of Polysaccharide-Based Active Edible Coatings Fortified with Essential Oils and Plant Extracts on the Postharvest Quality of Fresh Fruits

The various carboxymethyl cellulose (CMC), chitosan, pectin, alginate, and starch-based active coatings supplemented with EOs and plant polyphenolic extracts have been applied over the past five years in published research work as an active coating material for fresh fruits. The aforementioned active BECs have shown promising results with a diverse combination of other plant-based gums (Tables 1 to 3).

Table 1. Polysaccharide-based biodegradable and edible coatings for the quality preservation of fresh fruits during postharvest storage.

Polysaccharide	Fruit Cultivar	Treatment Dose	Coating Method	Comprehensive Findings	References
Sodium alginate and pectin	Sapota fruit	Sodium alginate and pectin (2%)	Dipping	Sensory and physico-chemical quality changes of treated fruit were retarded at 2 min dipping time during 30 days of storage.	[79]
Alginate, pullulan, and chitosan	Strawberry (*Fragaria* × *ananassa Duch.*)	2% chitosan	Dipping	Chitosan coating delayed fruit softening and rot and maintained antioxidant activity of enzymes (peroxidase, catalase, superoxide dismutase, and ascorbate peroxidase) to prevent lipid peroxidation and reduce membrane damage during 16 days of storage at 4 °C.	[80]
Chitosan	Satsuma mandarin (*Citrus unshiu Marc.*)	1% chitosan	Dipping	Chitosan along with clove oil inhibited mycelial growth of *Penicillium digitatum and* enhanced the activities of enzymes chitinase and phenylalanine ammonia-lyase on artificially inoculated citrus fruit.	[81]
Carboxymethyl cellulose (CMC), hydroxypropyl methylcellulose (HPMC), methylcellulose (MC), and chitosan (CH)	Rishon' and 'Michal' mandarins (*Citrus reticulata Blanco*)	Bi-layered coating by 1.5% CMC +1.5% CH	Brushing	Multilayer coating consisted of inner CMC and outer chitosan embedded with glycerol, oleic acid, and stearic acid, delayed ripening and reduced quality losses of mandarins compared to synthetic waxes.	[82]
Carboxymethylcellulose (CMC) and pectin (Pec)	Plums (*Prunus domestica* L.)	CMC 1% +Pec 1.5%	Dipping	Combination of 0.5% Pectin + 1.5% CMC prevented loss of total phenols, flavonoids, anthocyanins corresponding to higher antioxidant properties and maintained firmness of plum fruit.	[83]
Chitosan (CH), alginate (AL), and carboxymethyl cellulose (CMC)	Indian blackberry or Jamun (*Syzygium cumini* L.)	1.5% CH and 1.5% CMC	Dipping	CH (1.5%) and CMC (1.5%) coatings delayed weight loss, improved higher amount of antioxidant compounds, and inhibited cell wall degrading enzymes, thereby prolonged shelf life of Indian blackberry (jamun fruit) for better marketability.	[84]
Alginate (AL), pectin (PE), carboxymethyl cellulose (CMC) or chitosan (CH)	Mango (*Mangifera indica* L.)	0.5% CH	Dipping	Fresh-cut mangoes with CH coating showed lower microbial counts (1 log CFU g^{-1}). AL and CH coatings having different monomers enhanced antioxidant properties and AL, PE, and CMC maintained yellow colour of mangoes. AL-coated samples were toughest with higher consumer acceptance (90.2%) during 14 days of storage at 4 ± 1 °C.	[85]
Sodium alginate (Al), pectin (Pe) and sodium alginate plus pectin (Al + Pe)	Blueberries	Sodium Alginate and Pectin (Al + Pe) in equals amounts of 10 g/kg + 10 g/kg	Dipping	Blueberries coated with Al or Pe, lowered the growth kinetics of mesophilic aerobic bacteria and yeasts. However, Al, Pe and Al + Pe improved the firmness and showed no significant changes in weight loss, pH, soluble solid, and solid content during storage of 14 days at 4 °C.	[86]
Peach gum	Cherry tomato	1% Peach gum	Dipping	Polysaccharides from peach gum with antioxidant and antimicrobial characteristics effectively maintained firmness, inhibited rate of respiration, decreased weight loss, and delayed changes in ascorbic acid, sugar content, and total acidity of cherry tomatoes during refrigerated storage (4 °C)	[87]
Pullulan	Rastali and Chakkarakeli bananas	10% *w/v* pullulan	Dipping	Pullulan coating emulsion prepared at 60 °C and dipping time for 10 min 10% *w/v* level showed reduced weight loss (5.466%), lower color saturation (64.92), minimum browning Index (212.17), decreased peel-pulp ratio (15%), reduced vitamin C content (19%) with augmented firmness (55%) and total sugar contents (12–13%), respectively, in coated bananas stored for 20 days at 25 ± 1 °C and 70% RH.	[88]
Lemon basil seed mucilage (LBSM) and Chinese quince seed mucilage (QSM)	Japanese cucumber fruit (JCF)	0.3% LBSM and 1% QSM	Dipping	JCF coated with LBSM and QSM showed similar coating thickness, reduced weight loss, and minor changes in texture, pH, and peel color up to 18 days of storage at 11 ± 1 °C and 95% RH, respectively.	[89]
Commercial CMC (CMCc) and CMC from pineapple core (CMCpc)	Cherry tomatoes	2% CMCc and 2% CMCpc	Dipping	Cherry tomato coated with CMCc and CMCpc had lower weight loss TSS content and higher vitamin C content. Stored for 20 days at 25 °C and 70% RH.	[90]
Rice starch	'Cavendish' banana fruit	Rice starch (3%, *w*/*w*), ι-carrageenan and glycerol (1%, *w*/*w*)	Spray	Starch-ι-carrageenan coating blended with sucrose ester was developed that delayed the ethylene production, chlorophyll and starch degradation rate, showed reduced weight loss, and increased firmness of coated banana fruit stored at 20 ± 2 °C; RH 52 ± 3%.	[91]
Cassava starch	Mangoes (*Mangifera indica* cv "Tommy Atkins")	Citric acid (CA) (5 g/L) and coated with cassava starch (10 g/L) (CS)	Dipping	CS-CA coating delayed browning reactions, respiration rate with lower carotenoid formation and improved firm ness, color, and consumers acceptance of mango storage at 5 °C for 15 days.	[92]
Cassava starch (CS) and alginate (AL)	Pineapple (Ananas comosus var. comosus)	1.5% Cassava starch + 0.5% alginate + ascorbic acid (AA)	Dipping	CS-AL with AA preserved the fresh like characteristics of taste and odor, and better appearance of pineapple stored at 23 ± 1 °C, 88 ± 2% RH for 18 days.	[93]

Table 2. Polysaccharides combined with essential oils for the quality preservation of fresh fruits during postharvest storage.

Polysaccharide	Essential Oils	Fruit Cultivar	Treatment Dose	Coating Method	Comprehensive Findings	References
Sodium alginate (AL) and pectin (PE)	Citral (Cit) and eugenol (Eug)	Strawberry (*Fragaria* × *ananassa Duch.*)	AL (2% AL + 0.1% Eug) and (2% AL + 0.15% Cit + 0.1% Eug) PE (2% PE + 0.1% Eug) and (2% PE + 0.15% Cit)	Dipping	AL and PE based edible coatings formulations revealed acceptable color, higher firmness and antioxidant activity with lower weight loss and microbial counts in strawberries during storage of 14 days at 0.5 °C.	[94]
Arabic gum (AG)	Cinnamon oil (CO) and lemongrass oil (LGO)	Guava (*Psidium guajava* L.)	5% AG + 1% sodium caseinate (SC) + 2% CO and 5% AG + 1% SC + 2% LG	Dipping	Guava fruits coated with emulsions containing AG, SC supplemented with CO and LGO inhibited PPO, POD and showed higher ascorbic acid, phenol, and flavonoid contents up to 40 days at 25 ± 2 °C	[95]

Table 2. *Cont.*

Polysaccharide	Essential Oils	Fruit Cultivar	Treatment Dose	Coating Method	Comprehensive Findings	References
Gum arabic (GA)	Zataria multiflora Boiss essential oil (EO)	Pistachio (*Pistacia vera* L.) cv. 'Ahmad-Aghaei'	6% GA + 0.3% EO	Spraying	GA (6 and 8%) with Shirazi thyme (*Zataria multiflora*) (0.3 and 0.5%) protect the quality of fresh in-hull pistachio stored at 85 ± 5% RH and 2 ± 1 °C up to 36 days.	[96]
Arabic gum (AG)	Jojoba oil (JO)	Date palm (*phoenix dactylifera L.*)	Jojoba oil (JO) at 5% combined with Arabic gum (AG) at 10%	Dipping	10% AG fortified 5% JO mitigated decay incidence, reduced weight loss, and retained higher firmness, total phenols, flavonoids, tannins, sugars, and antioxidant activity and protected membrane integrity of date palm stored at 0 ± 1 °C and RH 85–90% up to 6 weeks.	[97]
Gum arabic	Cinnamon essential oil (CEO)	Guava (*Psidium guajava L.*)	Gum Arabic (10%), oleic acid (1%) and cinnamon essential oil (1%)	Dipping	Gum Arabic, oleic acid and CEO delayed browning on guava during cold storage at 10 ± 1 °C and 90% RH for 28 days.	[98]
Guar gum (GG)	*Nigella sativa*, *Coriandrum sativum*, *Foeniculum vulgare* and *Laurus nobilis* essential oils (EOs)	Unripe green mango (*Mangifera indica* L.)	0.2 mL of each EOs were supplemented in 1.5% of GG solution	Dipping	GG with EOs extracted in ethanol and methanol had lower changes in physiological, biochemical quality and showed lower microbial counts up to 24 days of storage at 10 °C and 80–85% RH.	[99]
Gum Arabic (GA)	Cinnamon oil (CEO)	Guava (*Psidium guajava* L.)	10% GA +1% CEO	Dipping	GA enriched with CEO preserved color, firmness, chlorophylls, and carotenoids and showed minor changes in pH, flavor index, and TSS content during storage at 10 ± 1 °C, 90–95% RH) for 28 days	[100]
Cassava starch (CS)	Cinnamon oil (CEO)	Table guava cultivar Pedro Sato	2% starch + 0.01% cinnamon essential oil (S + EO)	Dipping	2% CS with 0.01% CEO reduced weight loss by 30.23%, retained firmness of 12.23 N and displayed green color by lowering the activity of pectin methyl esterase guava stored at 25 °C and 76% ± 5 RH for 8 days.	[19]
Gum Arabic (GA)	Oregano (OEO) and rosemary essential oils (REO)	Plums (*Prunus domestica* L.)	GA at 1 mg/mL + OEO at 0.06 mL/mL + REO at 0.25 mL/mL	Dipping	GA with OEO inhibited the mycelial growth, sporulation of *R. stolonifer* and delayed soft rot at 25 °C for 12 days and at 12 °C for 24 days.	[101]
Cassava starch (CS)	Cinnamon bark essential oil (CBEO)	Apples (*Malus domestica Borkh* cv. "Fuji")	2% (*w*/*v*) of cassava starch containing 0.30% (*v*/*v*) of the cinnamon bark essential oil	Dipping	2% CS with 0.3% (*v*/*v*) CBEO inhibited the growth of *Staphylococcus aureus* and *Salmonella choleraesuis*, and 0.30% fennel essential oil inhibited just *Staphylococcus aureus* in coated apple during storage at 5 °C.	[102]
chitosan–cassava starch (CH–CS)	*Lippia gracilis* Schauer genotypes LGRA106 and LGRA107	Guava (*Psidium guajava* L.)	2% cassava starch, 2% chitosan and 3% LGRA106/LGRA107 mixture	Dipping	CH-CS-coated guavas demonstrated excellent microbiological qualities in terms of yeast and mold counts (which are primarily responsible for the degradation of fruit) during storage at room temperature (25 °C) for 10 days.	[103]
Cassava starch (CS)	Babassu flour (*Orbignya phalerata*)	Cagaita and mangaba	Cassava starch with 50% babassu flour	Dipping	CS coating along with babassu flour reduced water loss and increased lightness (a) values and total soluble solids were stable for coated fruits along storage.	[104]

Table 3. Polysaccharides combined with plant polyphenolic extracts for the quality preservation of fresh fruits during postharvest storage.

Polysaccharide	Plant Polyphenolic Extracts	Fruit Cultivar	Treatment Dose	Coating Method	Comprehensive Findings	References
Gum Arabic (GA)	Red roselle extract (RRE)	Blueberries	10% GA + 1% (*v*/*v*) glycerol + 1.5% (*v*/*v*) RRE	Dipping	GA lowered loss of anthocyanins, total phenols, weight loss, and decay with improved firmness of blueberries. Additionally, GA with RRE reduced microbes, enzyme activities, and anthocyanins degradation and enhanced phenolic content during storage at 4 ± 0.5 °C up to 12 days.	[105]
Gellan gum (GG)	Apple fiber extract (APE)	Golden delicious apples	0.2% AFE, gellan gum and ascorbic acid	Dipping	AFE fortified in GG along with ascorbic acid preserved antioxidant properties and firmness of apples stored at 4 °C up to 16 days.	[106]
Chitosan (CH) and alginate (AL)	Pomegranate Peel Extract (PPE)	Capsicum (*Capsicum annuum L.*)	1% PPE+ 1% chitosan	Dipping	PPE in chitosan coating retained firmness, color, and ascorbic acid. PPE in CH and AL coatings retarded microbial growth and extend the shelf life with higher sensory scores up to 25 days at 10 °C, respectively.	[107]
Chitosan (CH)	Green tea leaves extracted (GTE)	Walnut fruit (*Juglans regia* L., Kaghazi cultivar)	Chitosan 10 g/L and GTE 5 g/L	Dipping	The CH and GTE inhibited lipid oxidation and fungal growth during storage of walnut kernels 18 weeks of storage with acceptable sensory properties.	[108]
Sodium alginate (AL) and chitosan (CH)	Apple fiber, orange fiber, inulin and oligofructose	Blueberries (*Vaccinium corymbosum L.*) cv. Emerald	Fiber-enriched CH treatments	Dipping	CH enriched with inulin, oligofructose, and apple fiber enhanced antioxidant properties, lowered yeast/mold counts with higher sensory scores of ready-to-eat blueberries kept at 5 °C up to 18 days.	[109]
Peach gum (PG)	Bamboo vinegar (BV)	Blueberries (*Vaccinium spp.*)	Bamboo vinegar (1.5% *v*/*v*) and peach gum (2% *w*/*v*)	Dipping	The combined treatment of BV and PG increased the activities of defense enzymes such as chitinase; β -1,3-glucanase; phenylalanine ammonia-lyase; peroxidase and polyphenol oxidase during storage at 22 °C, 85–95% RH for 25 days.	[110]
Agar, alginate or agar/alginate matrices	*Larrea nitida* (Ln) extract	Blueberries	1% polysaccharide + 50 mg/100 mL Ln	Dipping	The coatings of agar and Ln extract were able to reduce the infectivity of murine norovirus below the limit of detection after over-night incubation at 25 °C and after 4 days at 10 °C storage	[111]
Chitosan (CH)	Aqueous cashew (*Anacardium occidentale*) leaf extract (CLE)	Lime fruit	2% CH and 5% CLE	Dipping	CH incorporated with CLE revealed higher firmness, color, TA, vitamin C content, antioxidants activities, reduced weight loss, and TSS. CH-CLE *A.* had the lowest percent disease incidence and disease severity *niger* in inoculated lime fruit stored at 15 °C and 90% RH up to 42 days.	[112]
Cassava Starch–Chitosan (CS-CH)	Rosemary pepper (*Lippia sidoides* Cham.) EOs and Pomegranate peel extract (PPE)	Italian Tomatoes (*Lycopersicon esculentum Mill.*)	10 g L^{-1} cassava starch, 10 g L^{-1} chitosan, 10 mL L^{-1} essential oil and 20 mL L^{-1} pomegranate peel extract	Dipping	CS-CH coating with EOs and PPE maintained firmness, TSS, and color values of tomatoes during storage at 25 °C for 12 days.	[113]
Cassava Starch (CS)	Propolis extract (PE)	Strawberry (*Fragaria ananassa Duch.*)	3% cassava starch + 66% ethanolic PE	Dipping	CS-PE coating showed higher vitamin C content, anthocyanin content, and antioxidant activity during 12 days of storage of coated strawberries.	[114]

4.1. CMC-Based Active Coatings

CMC is a cellulose derivative that is generally odorless and tasteless, flexible, transparent, and non-toxic and can be labelled as an edible coating [115]. CMC usually forms a clear, colorless and tasteless solution. It is cold water soluble and shows tolerance to high concentrations of sugar. I is available in a wide range of viscosities and has good heat stability and film forming properties [116]. Several studies have applied CMC or CMC in combination with other polysaccharides as BECs (Table 1). To provide bioactivity in the CMC coating material against physical, chemical, and microbial deterioration, EOs and plant extracts have been incorporated to form active BECs [117]. In some of the recent studies, garlic EO fortified in CMC coatings maintained higher concentrations of total phenols and anthocyanins in strawberries [118]. CMC coatings containing *Mentha spicata* EO inhibited *Listeria monocytogenes* and preserved physicochemical and organoleptic properties of strawberries [119]. CMC-based coatings incorporated with *Zataria multiflora Boiss* EO and grape seed extract (GSE) retarded changes in chemical, microbial, and sensory characteristics of coated fresh food during low temperature storage [120]. CMC coating enriched with clove EO delayed fungal growth and ripening and also reduced the rate of respiration and weight loss with enhanced commercial acceptability of 'Xinyu' mandarin oranges [121]. CMC reduced decay, weight loss, chilling injury, and hydrogen peroxide and malondialdehyde content in 'Kinnow' mandarin fruits during low temperature storage [122]. CMC along with pistachio (*Pistacia atlantica L.*) EO supplemented coating material showed higher anthocyanin, antioxidant capacity, phenol, tannin, and titratable acidity with a slight increment in TSS of grape cv. Rasheh during postharvest storage [123]. CMC *Impatiens balsamina L.* stem extract acted as an antimicrobial barrier to pathogen and gases, reduced the decay rate and weight loss, and inhibited the enzyme activities involved in the biochemical deterioration and softening in "Xinyu" tangerines [124]. CMC acted as a barrier to mold damage by forming a thick layer on the surface of oranges [125]. Methyl cellulose coating with thyme oil retained the higher antioxidant activity and reduced weight loss, total yeast, mold and total plate counts of mesophilic and psychrophilic microorganisms in "Acco" Pomegranate Arils [126].

4.2. Chitosan-Based Active Coatings

Chitosan is a renewable biopolymer derived from chitin. The cationic linear structure of chitosan composed of β-(1–4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit) is derived from crustaceans, fungi, and yeast [76]. Chitosan incorporated with *Mentha spicata* EO and coated on the surface of strawberries prevented growth of *L. monocytogenes* and retarded changes in physicochemical and organoleptic properties [119]. Chitosan with *Origanum vulgare* L. EO reduced the incidence of black mold and soft rot triggered by *R. stolonifer* and *Aspergillus niger* in cherry tomato fruit [127]. Chitosan with thymol EO prevented weight loss, retarded the rate of respiration, maintained TSS and the ratio of TSS to TA, lowered fungal decay incidence, and retained firmness, TA, anthocyanin, and sensory characteristics of fresh fig (*Ficus carica L.*) under low temperature storage [128]. Chitosan with *Mentha piperita* L. EO delayed changes in peel and pulp color and retained the catechins, procyanidins B1 and B2 in mango cultivar 'Tommy Atkins' during cold storage [129]. Chitosan applied with cinnamon EO reduced weight loss and preserved physical and biochemical quality of jujube fruits during 60 days of cold storage [130]. Clove EO fortified in chitosan inhibited activity of enzymes corresponding to browning of freshly cut lemons [131]. Chitosan–pullulan (50:50) edible coating prepared with pomegranate peel extract (0.02 g/mL) reduced weight loss and maintained TSS, pH, firmness, phenolic content, and antioxidant activity of mango fruits during 18 days of postharvest storage at 4 °C [132]. Chitosan coating incorporated with olive oil residues extracts (2% *w*/*v*) showed higher inhibition of *Penicillium expansum* compared with *Rhizopus stolonifer* in vitro and *in vivo*, thereby maintained the fresh quality of apple and strawberry fruits during postharvest storage [133]. Chitosan (1.5% *w*/*v*) enriched with hairy fig (*Ficus hirta* Vahl.) fruit extract coating applied to "Newhall" navel orange showed the lowest

decay rate (5.2%), weight loss (5.16%), and malondialdehyde content while enhancing the activities of protective enzyme such as superoxide dismutase, peroxidase, chitinase, and β-1,3-glucanase during 120 days of cold storage [134]. Additionally, chitosan (1% *w*/*v*) and alginate (2% *w*/*v*) coatings in combination with pomegranate peel extract (1% *w*/*v*) recorded reduced losses in ascorbic acid (29%), total phenolics (8%), total flavonoids (12%), and antioxidant activity measured by DPPH (12%) and FRAP (9%) in coated guavas (cv Allahabad *safeda*) for 20 days at 10 °C [135]. Different chitosan-based coatings with bioactive properties applied to fruits are presented in Tables 2 and 3.

4.3. Pectin-Based Active Coatings

Pectin is a complex network-forming biopolymer consisting of high molecular weight glycanogalacturonans in which 1,4-linked α-D-galacturonic acid molecules are linked to a small number of rhamnose and arabinose residues in the main chain and galactose and xylose in the side chains. Pectin is extracted from fruit peels and apples and is widely used as fruit coating material alone or in combination with other polysaccharides and EOs or plant extracts [136]. Apple pectin, cellulose nanocrystals, and lemongrass EO were documented to minimize weight loss and physiological and chemical attributes in coated strawberries (*Fragaria Ananassa*) [123]. Pectin coatings enriched with citral and eugenol EOs reduced microbial spoilage and maintained sensory attributes of raspberries [137]. Pectin enriched with lemon EO reduced loss of weight and retained higher antioxidant activity of strawberry fruit. Oregano (*Lippia graveolens*) EO added with pectin delayed the growth of *A. alternata* under in vitro conditions with an increase in total phenols and antioxidant activity in coated tomatoes [138]. Pectin-based coating incorporated with EO extracted from orange peel showed higher antibacterial and antifungal properties, reduced weight loss, and maintained TSS and ascorbic acid levels in coated oranges [139]. Pectin coating effectively delayed respiration and ripening processes, reduced weight loss, and restricted color change in coated lime (*Citrus aurantifolium*) [140]. Pectin-coated sapota fruits also recorded minimum weight loss and maintained acidity, TSS, pH, color, ascorbic acid content, and firmness up to 11 days of postharvest storage at room temperature [141].

4.4. Alginate-Based Active Coatings

Alginate is a natural polysaccharide commonly obtained from algae and consists of unbranched, linear binary copolymers of β-D-mannuronic acid and α-L-guluronic acid residues linked by 1–4 glycosidic bonds [142]. Alginate combined with citral and eugenol EOs revealed lower microbial and higher sensory acceptability in coated raspberries [143]. Shirazi thyme EO incorporated into alginate increased phenolic content and antioxidant activity and reduced mold and yeast growth in fresh pistachio (*Pistacia vera* L.) [144]. Alginate mixed with thyme, cinnamon, and oregano EOs in which thyme EO with alginate effectively inhibited the microbial growth, respiration rate, weight loss, firmness, and browning of fresh cut 'Red Fuji' apples [145]. Lemon (*Citrus lemon* L.), orange (*Citrus sinensis* L.), and grapefruit (*Citrus paradisi* L.) coated with sodium alginate edible coating lowered rates of O_2 consumption and CO_2 production and yeast and mold counts. Lemon and orange EOs improved firmness and ascorbic acid content during storage of kiwifruit [146]. *Ficus hirta* fruit extract with alginate coating retarded the growth of blue mold increased antioxidant content, and activity of defense enzymes in Nanfeng mandarin [147]. Alginate coating incorporated with cinnamon EO effectively reduced the rate of respiration and weight loss, retained original color, increased lightness, and inhibited polyphenoloxidase and peroxidase activity in fresh-cut apple cv Golden Delicious [148]. Rhubarb extract with alginate inhibited *Penicillium expansum* and preserved the physiological and sensory attributes in coated peaches (*Prunus persica*) [149]. Sodium alginate with cinnamon EO (0.9%, *v*/*v*) inhibited the growth of *A. carbonarius* on coated sliced apples and pears [150]. Different alginate-based coatings with bioactive properties applied on fruits are presented in Tables 2 and 3.

4.5. Starch-Based Active Coatings

Starch is the main component of plant crops such as maize, wheat, edible cassava, potato, amaranth, and quinoa mainly constituted of linear amylose and branched amylopectin fractions amounting to 98–99% of the dry weight [151]. The linear structure of amylose tends to orient itself in a parallel direction to facilitate the hydrogen bonding between hydroxyl groups that increases hydrophobicity in coating films [152]. Starches with higher amylose content have better film-forming properties, i.e., better mechanical strength, elongation, and gas barrier properties [153]. To produce starch-based coatings with a higher amylose content, it can be extracted via selective leaching of starch in hot water (50–70 °C) [154]. Different starches from pea (61–88%), corn (50–85%), potato (21–30%), and tapioca (17%) have been reported with higher amylose content for functionality, barrier, mechanical, and sorption properties of the starch-based coatings [10]. During the retrogradation of starch, the dissociated amylose and amylopectin chains in a gelatinized starch dispersion reunite to form more ordered structures that affect the permeability, solubility, and mechanical properties of starch coating films [155,156]. Additionally, starch-based edible coatings are odorless, tasteless, colorless, non-toxic, act as a good barrier to gases (carbon dioxide, oxygen), and show adequate durability and cohesive strength in coated foods [157]. Rice starch coated on apple (*Malus* L.) retained color, firmness, total soluble solids, titratable acidity, antioxidant activity, and reduced weight loss, respiration rate, and fruit greasiness [155]. Corn starch with *Moringa oleifera* extract decreased weight loss and retained firmness and ascorbic acid content in orange (*Citrus sinensis* L. Osbeck) [158]. The various starch-based coatings incorporated with EOs and plant extracts on the quality of fresh fruits during storage are presented in Tables 1 to 3.

Polysaccharide-based edible coating films added with bioactive compounds from plants have been documented to show excellent barrier, optical, and mechanical properties that play an important role in the postharvest shelf-life of fruits. Barrier properties of polysaccharide coating films include water vapor transmission rate (WVTR) and oxygen or carbon dioxide gas transmission rate (GTR). Chitosan films containing essential oils or other plant extracts addition of carvacrol (0.5, 1.0, and 1.5% v/v) significantly decreased the WVTR of chitosan film [159]. Several reports of decreased WVTR using EOs and plant extracts such as tea tree essential oil, carvacrol, cinnamon essential oil, and turmeric EO were attained in chitosan coating films, possibly due to the hydrophobicity of the EO particles and their ability to occupy the amorphous regions of the films [160–163]. A gellan gum-chitosan multilayer coating film incorporated with thyme essential oil (TEO) nanoemulsion showed improved elongation at break (EB) and UV blocking ability and increased the water vapor permeability (WVP) of the films with the addition of TEO [163]. The incorporation of turmeric essential oil in chitosan film notably inhibited *Aspergillus flavus* and prevented biosynthesis of aflatoxin [159]. Generally, the chitosan network interacts with essential oil components via hydrogen and covalent bonds, limiting the accessibility of hydrogen groups in forming hydrophilic bonds with water, which leads to a consequent reduction in affinity of chitosan film to water. The color and opacity of the coating films are important indices regarding the appearance and consumer acceptability of the coated fruits. The opacity of films has also been of interest, as an increase in opacity can be positively related to an improved light barrier property. In addition, the incorporation of rosemary essential oil reduced the light transmission in UV light of the chitosan films by more than 25% [164]. The introduction of thyme essential oil nano-emulsion obviously enhanced the UV blocking property and the yellowness index of chitosan films [165].

Mechanical properties of chitosan coating films have been directly related to the type of essential oil contained in the chitosan matrix. The Young's modulus, strength, and maximum elongation of chitosan increased with higher olive oil concentrations (5, 10, and 15%, w/w) [166]. The tensile strength (TS) of chitosan composite film significantly increased with the incorporation of cinnamon essential oil (CEO) at levels ranging from 0.4%, to 2% (v/v). CEO generated a strong cross-linked effect with chitosan, which reduced the free volume and the molecular mobility of the polymer that forms a compact sheet-like structure

resulting in increased TS and decreased elongation in break (EB) [167]. Additionally, intermolecular interaction and molecular compatibility between the functional group of citronella essential oil and cedarwood oil ingredients and hydroxyl and amino groups in the CH matrix could influence the mechanical properties of the films [163]. Therefore, organic compounds in essential oils consist primarily of hydrocarbon molecules such as alcohols, esters, terpenes, ketones, and phenols are categorized as benzene derivatives and terpenes [168]. The most common functional group in essential oils is aromatic that can interact with polysaccharides to exhibit efficient mechanical properties [169].

5. Conclusions

BECs fortified with EOs and plant extracts as active coating materials could extend the postharvest shelf life of coated fruits to achieve longer storage periods. This review compiled data from recent studies on active edible coatings in which the dipping method was the most reliable on both rough and smooth fruit surfaces compared to other coating methods. The dipping method is an inexpensive manual method and was recommended for small-scale or batch processes in industries for coating of fruits. Polysaccharides like alginate, pectin, CMC, and chitosan added with EOs and plant extracts have been employed over the past decade in fruits and have shown promising results related to the preservation of quality attributes such as firmness, weight loss, delayed ripening, and retardation of the biochemical and microbial changes in coated fruits. EOs and plant extracts containing bioactive compounds are safe additives compared to chemicals additives to be incorporated in BECs. Therefore, this review concludes that polysaccharides fortified with bioactive compounds from plant sources could be a potential means to extend shelf life of fresh fruits during postharvest storage.

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