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Review

Application of Polysaccharide-Based Edible Coatings on Fruits and Vegetables: Improvement of Food Quality and Bioactivities

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Abstract: Most foods derived from plant origin are very nutritious but highly perishable products. Nowadays, the food industry is focusing on the development of efficient preservation strategies as viable alternatives to traditional packaging and chemical treatments. Hence, polysaccharide-based edible coatings have been proposed because of their properties of controlled release of food additives and the protection of sensitive compounds in coated foods. Thus, this technology has allowed for improving the quality parameters and extends the shelf life of fruits and vegetables through positive effects on enzyme activities, physicochemical characteristics (e.g., color, pH, firmness, weight, soluble solids), microbial load, and nutritional and sensory properties of coated foods. Additionally, some bioactive compounds have been incorporated into polysaccharide-based edible coatings, showing remarkable antioxidant and antimicrobial properties. Thus, polysaccharide-based edible coatings incorporated with bioactive compounds can be used not only as an efficient preservation strategy but also may play a vital role in human health when consumed with the food. The main objective of this review is to provide a comprehensive overview of materials commonly used in the preparation of polysaccharide-based edible coatings, including the main bioactive compounds that can be incorporated into edible coatings, which have shown specific bioactivities.

Keywords: edible coating; antioxidant; antimicrobial; shelf life; water loss control; fruits and vegetables

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Citation: Cruz-Monterrosa, R.G.; Rayas-Amor, A.A.; González-Reza, R.M.; Zambrano-Zaragoza, M.L.; Aguilar-Toalá, J.E.; Liceaga, A.M. Application of Polysaccharide-Based Edible Coatings on Fruits and Vegetables: Improvement of Food Quality and Bioactivities. *Polysaccharides* **2023**, *4*, 99–115. https://doi.org/10.3390/polysaccharides4020008

Academic Editor: Isabel Coelhoso

Received: 9 February 2023
Revised: 8 March 2023
Accepted: 19 March 2023
Published: 27 March 2023

1. Introduction

Overall quality and shelf life of foods are reduced by several factors depending on their nature (e.g., animal, plant, solid, liquid), water loss, enzymatic reactions, auto-oxidation, texture deterioration, senescence processes, and microbial growth, among others [1]. For example, fruits and vegetables are very susceptible to mechanical damage, thermal damage, or disease, whereas foods of animal origin are more vulnerable to microbial growth [2,3]. On the other hand, in the case of some foods, these events are accelerated due to tissue lesions inflicted by some processing steps applied to particular foods, including peeling, slicing, and cutting [1]. In addition, there are some foods such as sensitive fruits (e.g., strawberries, blackberries) or vegetables (e.g., tomatoes, lettuce) that are highly perishable with a short shelf life because of their high metabolism and microbial decay [4].

Over the years, the food industry has applied some preservation techniques in order to increase the shelf life and maintain freshness of perishable foods, including the use of refrigeration and modified/controlled atmospheres (e.g., modification of the gas composition, use of noble and inert gases), chemicals (e.g., acidic electrolyzed water, ozone), thermal and non-thermal treatments (e.g., electron beam irradiation, pulsed light, ultraviolet light, cold plasma), biopreservation techniques (e.g., bacteriophages, bacteriocins, and bioprotective microorganisms), and genetic manipulation (e.g., pectinase activity modification, ethylene synthesis control) [5–7]. However, new promising technologies such as edible coatings are being applied not only for the improvement of the quality and shelf life of foods but also as potential carriers of additives (e.g., flavors, colors) and bioactive compounds (e.g., antimicrobial, antioxidant), which can improve the shelf life of food products and generate high value-added foods [8,9]. Additionally, the edible coating technology is considered a more eco-friendly and user-friendly form of packaging compared with other technologies or conventional packaging materials [10,11]. In this context, conventional packaging material generates environmental pollution, and its manufacturing processes requires non-renewable resources such as glass, metals (e.g., aluminum, foils, and laminates), paper (e.g., paperboards, paper bags) [12], and petroleum-based plastics [10]. In contrast, edible coatings are considered user-friendly packaging alternatives because they provide convenience to the consumers and generate less waste as well as show easy handling, opening, and dispensing. In terms of their eco-friendly aspect, this technology generates a lower environmental impact because it uses biodegradable and/or bio-based polymers as materials [10,13].

The most common materials used in edible coatings include polysaccharides (e.g., chitosan, alginate, cellulose, starch, pectin), lipids (e.g., wax, oil), and proteins (e.g., collagen, zein, casein) [14]. For the abovementioned materials, polysaccharides show some clear advantages. These polymeric carbohydrates unveil biodegradability and biocompatibility and are non-toxic for living organisms [15]. For example, chitosan films sourced from shrimp and edible crickets have demonstrated water resistance, mechanical, and light barrier properties, highlighting their potential to be used as bio-based packaging materials for food and pharmaceutical applications [16,17]. Furthermore, some polysaccharides have been approved by the Food and Drug Administration (FDA) of the United States of America (USA) and given generally recognized as safe (GRAS) status, including alginate, cellulose, starch, gums (e.g., guar gum, gum arabic), and carrageenan [18]. Although in Mexico there are national standards (Official Mexican Standards: NOM) that require that food products have approved additives in their formulation and that these be reported on their labeling, there is no specific regulatory framework related to the type of polysaccharides approved for their direct use on food products (i.e., as coatings). Thus, polysaccharides must be classified as GRAS substances for their use as edible coatings [19]. Currently, other polysaccharides that are in practical use, such as chitosan, are not permitted as food-contact material in the European Union (EU) [20].

In the following sections, this review provides new perspectives and current advances in the application of polysaccharide-based edible coatings towards the improvement of food quality as well as their bioactivities considering the main scientific literature available. For this purpose, a comprehensive search of published original scientific studies dating from 2018 to 2022 was carried out using Google Scholar, PudMed, and Scopus databases. In addition, the FDA databases were consulted for information on regulatory status. The main search terms used were “polysaccharides” AND “coating(s)” OR “film(s)” AND “fruit(s)” OR “vegetable(s)” AND “bioactivities” “bioactive” OR “quality” consulting scientific studies published in English. The literature collected was carefully screened based on the title, abstract, and keywords of the selected articles, and studies unrelated to the rationale of the review were excluded.

2. Improvement of Quality Parameters of Foods by Polysaccharide-Based Edible Coating

Some beneficial effects have been reported for the application of polysaccharide-based edible coating on fruits and vegetables; these include extending the shelf life period, lowering respiration rate, maintaining firmness, reducing weight/mass loss, protecting sensitive compounds (e.g., soluble solids, vitamins), protecting bioactive compounds (e.g., flavonoids, anthocyanins, phenolics), decreasing microbial growth (e.g., fungal, bacterial), maintaining sensory properties (e.g., flavor, aroma, color), maintaining the activity of antioxidant enzymes (e.g., superoxide dismutase [SOD], catalase [CAT]), imparting antioxidant activity and decreasing oxidative cellular damage (e.g., malondialdehyde [MDA]), delay browning (e.g., UV-shielding), and decrease overall food damage (e.g, chill injury indicators, disease incidence/severity) (Figure 1). According to Table 1, these polysaccharide-based coatings can provide protective effects on a diverse group of fruits and vegetables, and the protective effect will depend on various factors such as the coating material (e.g., type of material, concentration, presence of bioactive compounds) and the type of coated food. Among the materials used for coatings include chitosan, alginate, cellulose, starch, and to a lesser extent, *Aloe vera* gel, gums (e.g., guar, gum arabic, xanthan), and carrageenan.

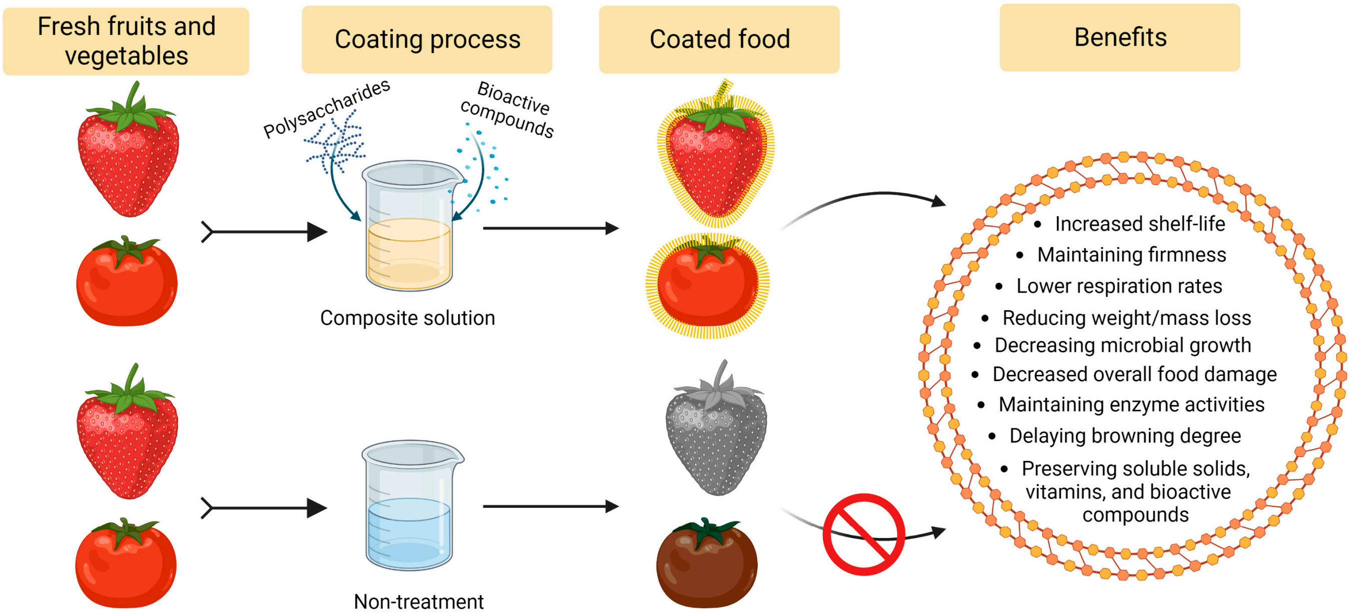

Figure 1. Beneficial effects of the application of polysaccharides-based edible coating on fruits and vegetables. Created with Biorender.com (accessed on 30 January 2023).

Table 1. Beneficial effect of polysaccharide-based edible coatings on fruits and vegetables.

Coating Material	Food Coated	Principal Effect of Coating	References
Alginate	Rose apple (*Syzygium samarangenese*) cv. Tabtimchan	↓ weight loss, respiration rate, MDA and H_2O_2 content ↓ LOX activity ↑ CAT and APX	Duong, et al. [21]
Alginate, *Aloe vera*, garlic oil	Tomatoes (*Solanum lycopersicum* L.)	↑ shelf life period ↑ UV-shielding, barrier, thermal, and mechanical properties	Abdel Aziz and Salama [22]
Alginate, chitosan, zein, potato starch, essential oil (oregano and cinnamon)	Potatoes (*Solanum tuberosum* L.) cultivars (Rio Grande Russet, Yukon Gold, and Purple Majesty)	↓ weight loss ≈ firmness ↑ sensory properties, particularly with colored skin potatoes ↑ shelf life period by sprout inhibition	Emragi, et al. [23]
Alginate, galactomannans, cashew gum, and gelatin	Table grapes (*Vitis vinifera*) cv. Italia	↓ weight loss ≈ firmness and color ↑ phenolic compound content and antioxidant potential	de Souza, et al. [24]
Alginate, hydroxyethyl cellulose, asparagus (*Asparagus officinalis* L.) waste extract	Strawberry (*Fragaria* × *ananassa*)	↓ color change, weight loss ≈ total phenolic and flavonoid contents	Liu, et al. [25]
Alginate, linseed mucilage, probiotic bacteria (*Lactobacillus casei* LC-01), fructooligosacharides	Fresh-cut yacon (*Smallanthus sonchifolius*)	↓ weight loss and browning	Rodrigues, et al. [26]
Alginate, rhubarb (*Rheum rhaponticum* L.) extract	Peaches (*Prunus persica*)	↓ weight loss, respiration rate, MDA content, and PPO activity ↑ firmness and the TSS content	Li, et al. [27]
Alginate, thyme oil	Fresh-cut cantaloupe (*Cucumis melo* L.)	≈ respiration, color, and sensory characteristics	Sarengaowa, et al. [28]
Alginate, thyme essential oil, nisin, and L-cysteine	* Mushroom (*Pholiota nameko*)	↓ weight loss, degree of browning, and MDA content ↓ PPO and POD activities ≈ soluble sugar, ascorbic acid, and soluble protein contents	Zhu, et al. [29]
Bacterial cellulose nano-fiber (*Gluconacetobacter xylinu*), chia (*Salvia hispanica*) seed mucilage	Strawberry (*Fragaria* × *ananassa*)	≈ the phenolic, flavonoids, and ascorbic acid ↓ PPO and POD activities	Mousavi, et al. [30]

Table 1. *Cont.*

Coating Material	Food Coated	Principal Effect of Coating	References
Aloe vera gel	Lychee (*Litchi chinensis* Sonn. cv. Gola)	↓ browning index, weight loss, superoxide anion, relative electrolyte leakage, H_2O_2 and MDA content ≈ total anthocyanin, total phenolic and ascorbic acid, CAT, SOD, and APX activities	Ali, et al. [31]
Aloe vera gel	Papaya (*Carica papaya* L.)	↑ shelf life period ↓ weight loss and disease severity	Parven, et al. [32]
Aloe vera gel, alginate, titanium oxide nanoparticles ($nTiO_2$)	Tomatoes (*Solanum lycopersicum* L.)	↑ shelf life period ↓ weight loss	Salama and Abdel Aziz [33]
Aloe vera gel, basil (*Ocimum basilicum* L.) seed mucilage	Apricot (*Prunus armeniaca* L. cv. Nouri)	≈ firmness, TA, total phenolic and ascorbic acid contents	Nourozi and Sayyari [34]
Aloe vera gel, *Pichia guilliermondii* BCC5389	Shogun mandarins (*Citrus reticulate* Blanco cv. Shogun)	↓ weight loss ≈ shikimic acid, total phenolics, and lignin content	Jiwanit, et al. [35]
Cassava starch, nystose	Blackberries (*Rubus* spp. cv. Tupy)	↓ increase in pH ≈ firmness and anthocyanin content ↓ counts of psychrotrophic microorganisms, molds, and yeast	Bersaneti, et al. [36]
Cassava starch, starch nanocrystals	Pear (*Pyrus pyrifolia* Nakai)	≈ color, texture, cell membrane permeability, total phenolic, TSS, and TA contents ↓ POD and PPO activities	Dai, et al. [37]
Cellulose	Kinnow mandarin fruit (*Citrus nobilis* L. × *Citrus deliciosa* T.)	↓ chilling injury symptoms, disease incidence, weight loss, MDA content, H_2O_2 and electrolyte leakage ≈ APX, POD, SOD, and CAT activities	Ali, et al. [38]
Cellulose, beeswax	Mango (*Mangifera indica* L. cv. Palmer)	↓ fruit ripening ≈ peel and pulp color and firmness ≈ TA, and TSS ↓ weight loss and the disease incidence	Sousa, et al. [39]
Cellulose, blackberry (*Morus nigra* L.) anthocyanin rich-extract	Cherry tomato (*Solanum lycopersicum* L. var. Cerasiforme)	≈ constant weight and firmness	Sganzerla, et al. [40]
Cellulose, lemon essential oil, alginate, pectin	Cucumber (*Cucumis sativus* L.)	↓ weight loss ↑ shelf life period	Zambrano-Zaragoza, et al. [41]

Table 1. *Cont.*

Coating Material	Food Coated	Principal Effect of Coating	References
Cellulose nanofiber, iron, chitosan, curcumin	Kiwifruits (*Actinidia deliciosa* cv. Hayward)	↓ mass loss, firmness loss, respiration rate, and microbial count	Ghosh, et al. [42]
Chitosan	Guava (*Psidium guajava* L.)	↓ weight loss, browning index, and respiration rate ≈ firmness and skin color were maintained ↓ PAL activity ↑ POD activity	Batista Silva, et al. [43]
Chitosan, cinnamaldehyde	Orange (*Citrus sinensis* L., Osbeck)	≈ SOD, CAT, POD, and PPO activities ↓ postharvest decay and mass loss ≈ vitamin C and TSS	Gao, et al. [44]
Chitosan and ε-polylysine	Satsuma mandarin (*Citrus unshiu* Marc.)	≈ TSS, ascorbic acid content ↓ disease incidence	Li, et al. [45]
Chitosan and montmorillonite	Tangerine (*Citrus tangerine* Hort. ex Tanaka)	↓ weight loss and decay rate ≈ TSS and TA contents	Xu, et al. [46]
Chitosan, thymol and quinoa protein	Strawberries (*Fragaria* × *ananassa* Duch. cv. Albion)	↓ mass loss and fungal decay ≈ flavor and aroma	Robledo, et al. [47]
Chitosan, zein and tocopherol	* Mushroom (*Agaricus bisporus*)	↓ weight loss, browning index, and respiration rate ↓ POD and PPO activities ≈ firmness, CAT, SOD activities, total phenolic content and DPPH radical scavenging activity	Zhang, et al. [48]
Fruit starch and phenolic stem bark extract (both from *Spondias purpurea* L.)	Mango (*Mangifera indica* L. cv. Tommy Atkins)	↓ browning index and reduced fungus attack	Rodrigues, et al. [49]
Guar gum, *Aloe vera* gel, and extracts of *Spirulina platensis*	Mango (*Mangifera indica* L.)	↓ weight loss ≈ ascorbic acid, the total phenol content, and firmness	Ebrahimi and Rastegar [50]
Gum arabic, carrageenan, xanthan gum, lemon grass essential oil	Strawberry (*Fragaria* × *ananassa*)	↓ weight loss ≈ ascorbic acid, anthocyanin, phenolic compound contents, and firmness	Wani, et al. [51]
κ-carrageenan, starch, cellulose nanofibrils	Strawberry (*Fragaria* × *ananassa*)	↓ weight loss ≈ vitamin C, TSS, hardness, TA and pH	Zhang, et al. [52]

Table 1. *Cont.*

Coating Material	Food Coated	Principal Effect of Coating	References
Moth bean starch, basil leaves extract	Eggplant (*Solanum melongena*)	↓ moisture loss and firmness ↓ increase in TSS and color changes ↑ shelf life period	Kumar, et al. [53]
Pectin, crude mulberry (*Morus alba*) leaf extract (deoxynojirimycin and chlorogenic acid)	*Capsicum annum* L.	↑ shelf life period ↓ mass loss	Shivangi, et al. [54]
Pectin, corn flour, and beetroot powder	Tomatoes (*Solanum lycopersicum* L.)	↓ weight loss and respiration	Sucheta, et al. [55]
Sweet potato starch and cumin essential oil	Pear (*Pyrus bretchneideri* Rehd.)	↓ rot lesion on infected pear caused by *Alternaria alternata* ↓ changes in color, firmness, and chlorophyll degradation	Oyom, et al. [56]
Xanthan gum, beeswax	Strawberry (*Fragaria* × *ananassa* cv. Camarosa)	↓ weight loss, firmness loss, and decay index	Zambrano-Zaragoza, et al. [57]

SOD: superoxide dismutase; CAT: catalase; POD: peroxidase; PPO: polyphenol oxidase: PAL: phenylalanine ammonia-lyase; TSS: total soluble solids; TA: titratable acidity; MDA: malondialdehyde; LOX: lipoxygenase; APX: ascorbate peroxidase. Displayed symbols indicate: ↑ increased; ↓ decreased; ≈ maintained. * Mushrooms were included in the table because they are commercially considered a vegetable, even though strictly speaking they are not plants and are classified in the Fungi kingdom.

In the majority of studies (Table 1), coatings formulated with different polysaccharides decreased the weight/mass loss of coated fruits and vegetables because they generated a semi-permeable barrier reducing the respiration and transpiration rates of coated foods. In view of the above, coatings avoid the loss of dry matter and moisture [26]. Overall, it has been reported that transpiration in fruits and vegetables is responsible for 90% of the total water loss, while respiration is responsible for less than 10% of this loss [23]. On the other hand, in practical terms, the consequences of weight/mass loss could translate into significant economic losses during postharvest and quality deterioration (e.g., texture loss), particularly in those fruits and vegetables with high water content or those with a thin skin protective layer (e.g., peaches, tomatoes), resulting in lower market value and consumer acceptability of horticultural crops [38]. In addition, edible coatings can provide weight/mass stability increases during storage [42]. At a cellular level, the structures in the epidermis of plants, called stomata, control the rate of water loss. In this context, Oyom, Xu, Liu, Long, Li, Zhang, Bi, Tahergorabi, and Prusky [56] observed a reduction in stomata density and opening in uncoated pears (*Pyrus bretchneideri* Rehd.) compared to pears coated with an edible composite of sweet potato starch and cumin essential oil. In contrast, at a molecular level, this type of polysaccharide-based edible coating decreased the weight/mass loss through the formation of hydrogen bonds with the skin (peel) of the fruit/vegetable or in the coating solution itself [55,58].

In other studies, Batista Silva, Cosme Silva, Santana, Salvador, Medeiros, Belghith, da Silva, Cordeiro, and Misobutsi [43] coated guava (*Psidium guajava* L.) with an edible coating composed of chitosan, which decreased the weight/mass loss values at 3% compared with uncoated guava (10% weight/mass loss). Similarly, Robledo, López, Bunger, Tapia, and Abugoch [47] applied an edible coating formulated with thymol nanoemulsion, quinoa protein, and chitosan to strawberries (*Fragaria × ananassa*), obtaining values of about 12–13% of weight/mass loss compared with the uncoated treatment (36%). Rodrigues, Cedran, and Garcia [26] evaluated the influence of edible coatings based on linseed mucilage, alginate, and *Lactobacillus casei* LC-01 on the shelf life of fresh-cut yacon (*Smallanthus sonchifolius*). Their results showed that the weight/mass loss value (4.09%) of the control was significantly higher than that of the coated fruit (2.7%). Duong, Uthairatanakij, Laohakunjit, Jitareerat, and Kaisangsri [21] reported that the weight loss (7%) of coated rose apple (*Syzygium samarangenese* cv. Tabtimchan) with alginate was significantly lower ($p < 0.05$) than the uncoated fruits (11%). Similar results were obtained by Shivangi, Dorairaj, Negi, and Shetty [54], reducing the weight loss from 10% (control) to 6% (treated) on *Capsicum annum* L. coated with an edible composite of pectin and crude mulberry (*Morus alba*) leaf extract (deoxynojirimycin and chlorogenic acid). On the other hand, table grapes (*Vitis vinifera* cv. Italia) coated with a composite of alginate, galactomannans, cashew gum, and gelatin showed less weight/mass loss (20%) compared with uncoated fruits (30%) [24]. Likewise, peaches (*Prunus persica*) coated with an alginate-based coating enriched with rhubarb (*Rheum rhaponticum* L.) extract exhibited a weight/mass loss of 7% compared with the control treatment (13%) [27]. In contrast, Zambrano-Zaragoza, Quintanar-Guerrero, González-Reza, Cornejo-Villegas, Leyva-Gómez, and Urbán-Morlán [41] used a combined treatment of UV-C and a cellulose-based coating enriched with lemon essential oil nanocapsules made of alginate-pectin, on fresh-cut cucumber (*Cucumis sativus* L.). Their results showed that the weight/mass loss of uncoated treatment (1.5%) was significantly higher ($p < 0.05$) than that of the coated vegetable (0.3%).

Conversely, the loss of weight/mass is considered a main factor that affects firmness in fruits and vegetables. In some studies, an association between weight/mass loss and firmness of horticultural crops has been reported; when there is less weight/mass loss, the firmness is maintained. This phenomenon was reported for mushrooms (*Agaricus bisporus*) [48], guavas (*Psidium guajava* L.) [43], potatoes (*Solanum tuberosum* L.) [23], table grapes (*Vitis vinifera*) [24], peaches (*Prunus persica*) [27], cherry tomatoes (*Solanum lycopersicum* L.) [40], kiwifruits (*Actinidia deliciosa*) [42], eggplants (*Solanum melongena*), and strawberries (*Fragaria × ananassa*) [51,57]. In this context, it is known that moisture loss is the major cause of firmness changes during postharvest of horticultural crops [59]. It is also reported that the firmness reduction can happen due to cell wall (hemicellulose and pectin) degradation caused by increased activity of endogenous autolysins by cell wall enzymes glucanases, pectin-methylesterase, and polygalacturonase [50]. Thus, edible coatings on fruits and vegetables probably slow the depolymerization of pectin due a decrease of O_2 and high CO_2 concentration, which inhibits the activity of the enzymes [13,36]. On the other hand, it also contributes to the semi-permeable barrier properties of coatings, which restrict gas exchange, including water vapor [51].

Another important effect of edible coating on fruits and vegetables is the ability to maintain compounds (e.g., soluble solids, vitamins), including bioactive compounds (e.g., flavonoids, anthocyanins, phenolic compounds). In some fruits and vegetables, soluble solids include sugars, small quantities of acids, vitamins, minerals, and soluble pectin, among others [46]. In this regard, Gao, Kan, Wan, Chen, Chen, and Chen [44] demonstrated that a cinnamaldehyde-chitosan coating applied to oranges (*Citrus sinensis* L., Osbeck) maintained vitamin C and total soluble solids at the end of the storage period (120 d). Similar results were obtained by Xu, Qin, and Ren [46], who found that vitamin C and total soluble solids were preserved during the 11 days storage period of tangerines coated with (*Citrus tangerine* Hort. ex Tanaka) a composite of chitosan and montmorillonite. Likewise, Li, Ye, Hou, and Zhang [45] reported that total soluble solids content of mandarins (*Citrus unshiu* Marc.) coated with chitosan and ε-polylysine, was maintained, while the vitamin C concentration decreased more slowly in the coated fruit than in the control treatment. In another study, Ebrahimi and Rastegar [50] found that a guar-based edible coating enriched with *Spirulina platensis* extract applied to mango was able to maintain the vitamin C content after 3 weeks of storage. This effect could be partially explained by the semi-permeable barrier properties of the coating, which inhibited the permeation of oxygen, and thus redox reactions were suppressed, leading to a lower loss of compounds [45]. The results of these studies suggested that the nutritional value of fruits and vegetables can be overall maintained when edible coatings are applied. Similar observations were reported for bioactive compounds in coated fruits and vegetables. For example, anthocyanin and phenolic compounds for strawberries [51] and lychees [31], mushrooms [48], table grapes [24], pears [37], apricots [34], shogun mandarins [35], and mangoes [50], as well as phenolic compounds and flavonoids for strawberries [25,30] and anthocyanin for blackberries [36].

Edible coatings make a significant impact on enzyme activities of fruits and vegetables. Particularly, studies have demonstrated that edible coatings maintained or increased the activity of some antioxidant enzymes. Some enzymes maintained in fruits and vegetables by the effect of edible coatings reported in the literature include SOD, which catalyzes the conversion of superoxide radicals to hydrogen peroxide, and CAT/ascorbate peroxidase (APX), which converts the H_2O_2 to H_2O and O_2. Thus, this antioxidant system is interlinked and can repair/prevent the cellular damage due to oxidative stress [60]. Other enzymes that were maintained or decreased in some studies (Table 1) are peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL). These three enzymes are related with the browning in fruits and vegetables. PPO catalyzes the oxidation of phenols to quinones that form brown pigments, while POD can also oxidize phenols to quinines in the presence of H_2O_2. On the other hand, PAL catalyzes the browning substances biosynthesis of phenolic components [61]. In this context, Gao, Kan, Wan, Chen, Chen, and Chen [44] found that the activity of SOD and CAT in oranges coated with chitosan and cinnamaldehyde was maintained. Similar results were obtained by Zhang, Liu, Sun, Wang, and Li [48], who applied an edible coating on mushrooms, preserving the activity of SOD and CAT enzymes. For their part, Ali, Khan, Nawaz, Anjum, Naz, Ejaz, and Hussain [31] reported the presence of APX in addition to SOD and CAT activities, which were maintained in lychee fruit after coating it with an *Aloe vera* gel. Batista Silva, Cosme Silva, Santana, Salvador, Medeiros, Belghith, da Silva, Cordeiro, and Misobutsi [43] observed that the PAL activity decreased in guava coated with chitosan. Similarly, POD and PPO activities were reduced after application of an edible coating on oranges (chitosan, cinnamaldehyde) [44], the mushrooms *Agaricus bisporus* (chitosan, zein, tocopherol) [48] and *Pholiota nameko* (alginate, thyme essential oil, nisin, and L-cysteine), strawberries (cellulose nano-fiber, chia seed mucilage) [30], and pears (starch) [37]. Interestingly, a relationship was observed between the increased activity of antioxidant enzymes (e.g., CAT, APX, SOD) and the decrease of malondialdehyde (MDA) values in fruits and vegetables coated with different polysaccharide-based edible coatings, including Kinnow mandarins [38], lychees [31], and rose apples [21]. The above indicates that these antioxidant enzymes may play a major role in the defense mechanism against lipid peroxidation through the delayed generation of reactive oxygen species and/or interruption of the lipid peroxidation process occurring in fruits and vegetables. This scientific evidence suggests that edible coatings contribute to increased activity of antioxidant enzymes while decreasing the activity of enzymes involved in browning.

Finally, edible coatings can offer protective effects towards food damage, namely, decreasing the chill-injury effects, postharvest decay, and disease incidence/severity. A decrease in chill-injury and disease incidence was observed by Ali, Anjum, Ejaz, Hussain, Ercisli, Saleem, and Sardar [38] after applying a cellulose-based coating on Kinnow mandarins. Likewise, postharvest decay was decreased in strawberries coated with chitosan, thymol, and quinoa protein [47] strawberries coated with xanthan gum and beeswax [57]; and tangerines coated with chitosan and montmorillonite [46]. Some studies also reported a reduction on the incidence of disease of coated citrus fruits [38,45], mangoes [39], and papayas [32]. Overall, the beneficial results listed demonstrate that the shelf life period is favorably extended. For example, the shelf life period significantly increased ($p < 0.05$) for coated tomatoes [22,33], potatoes [23], papayas [32], eggplants [53], chili peppers [54], and cucumbers [41].

The selection of the type of polysaccharide to be used to prepare an edible coating needs to be based on the coating functions/applications as well as the type of fruit or vegetable that will be coated. Table 2 summarizes the main advantages and disadvantages of polysaccharides commonly used in edible coatings. Common advantages shared by most polysaccharides used in edible coatings are that they are considered as renewable, biodegradable, biocompatible, and non-toxic. In contrast, the main disadvantages are the limiting information available for their formulation and application in fruits and vegetables. For example, some coatings exhibit poor mechanical properties (e.g., chitosan, starch, carrageenan), while others showed solubility issues (e.g., alginate, cellulose); therefore, some of these coatings may require the use of a combination with other biopolymers in order to improve their physico-chemical properties. In this context, alginate shows good gelation properties for the development of edible coatings, while it does not have anti-fungal and antioxidant activities. It also showed lower UV-protecting properties and poor water barrier, and thus it is typically combined with *Aloe vera* in order to improve the UV-protecting, antioxidant, and antimicrobial properties [22]. Others have shown that alginate combined with galactomannans improved the gas barrier properties of the developed edible coatings [24]. In contrast, cellulose shows excellent film-forming properties, but its gas permeability properties are lower, and thus it is typically combined with beeswax in order to increase its permeability to gases [39]. Similarly, chitosan was combined with cellulose in order to reinforce the network structure of the formed edible coating [42]. As observed in Table 1, this improvement of the physicochemical properties of edible coatings has a positive impact on the overall quality of coated fruits and vegetables.

Table 2. Main advantages and disadvantages and FDA regulation status of proposed polysaccharides used in edible coatings for fruits and vegetables.

Polysaccharides	Characteristics		FDA 21 CFR Regulation [1]	References
	Advantages	**Disadvantages**		
Chitosan (*N*-acetyl-D-glucosamine)	• Renewable and biodegradable • Biocompatible, biologically adhesive, and non-toxic • Antimicrobial and antioxidant properties	• Low mechanical resistance • Low solubility in neutral and alkaline pH	Not currently available [2]	Dutta, et al. [62], Sahariah and Másson [63], Garg, et al. [64]
Alginate	• Renewable, biodegradable, biocompatible, and non-toxic • Low cost • High gelation properties	• Unpleasant odor • Poor tear strength, needs combination with other biopolymers • Precipitate at low pH	184.1187	Campos, et al. [65], Pawar and Edgar [66], Gheorghita Puscaselu, et al. [67]
Cellulose	• Renewable, biodegradable, and biocompatible • Soluble dietary fiber	• Highly water sensitive • High cost of production	182.90	Hassan, et al. [68], Nešić, Cabrera-Barjas, Dimitrijević-Branković, Davidović, Radovanović, and Delattre [10]
Starch	• Biodegradable, non-toxic • Low cost and widely available • Transparent, odorless, and tasteless	• Insoluble in cold water • High viscosity • Poor resistance and mechanical properties	172.892, 182.70	Campos, Gerschenson, and Flores [65], Cruz-Romero and Kerry [69], Zarski, et al. [70]
Carrageenan	• Hydrophilic • Biodegradable	• Properties depending on the carrageenan type • Poor mechanical properties	172.620	Campos, Gerschenson, and Flores [65], Necas and Bartosikova [71], Tabernero and Cardea [72]

[1] 21CFR regulations obtained from the Select Committee on GRAS Substances (SCOGS) database: https://www.cfsanappsexternal.fda.gov/scripts/fdcc/index.cfm?set=SCOGS&sort=Sortsubstance&order=ASC&startrow=51&type=basic&search= (accessed on 3 January 2023). [2] under 21CFR216 (as Human Drug Compounding, for topical use only; not listed for food packaging or coatings).

3. Bioactivities Exhibited by Edible Coatings

Consumer demand for less use of chemicals in fruits and vegetables has led to more research efforts towards using naturally occurring compounds with antioxidant and antimicrobial properties that can be applied to produce [73]. Edible coatings can also exhibit some bioactive properties because biologically active compounds can be incorporated into composites with antioxidant and antimicrobial properties. Generally, these bioactive compounds are incorporated into edible coatings as pure compounds, essential oils, or plant extracts. The next section highlights some of main bioactive properties such as antioxidant and antimicrobial activities reported for edible coatings.

Reactive oxygen species (ROS) and other oxidant compounds can decrease the nutritional value of fruits and vegetables and change their sensory properties, triggering an overall decrease in consumer acceptance [74]. For example, ROS can react with fruit and vegetable components, producing undesirable volatile compounds, damaging essential nutrients, and changing the function of proteins, lipids, and carbohydrates, which can lead to changes in color, texture, and flavor [75]. Thus, antioxidant compounds incorporated into edible coatings can interact with coated fruits and vegetables either by trapping or neutralizing ROS and pro-oxidant compounds or releasing the antioxidants into the coated products [74]. For example, Wani, Gull, Ahad, Malik, Ganaie, Masoodi, and Gani [51] found that the antioxidant activity (22–25% DPPH inhibition) of strawberries was preserved after being coated with an edible composite compared with the uncoated fruit (18% DPPH inhibition). Similarly, Ebrahimi and Rastegar [50] reported that mangoes coated with a guar-based edible coating enriched with *Spirulina platensis* showed a higher antioxidant activity (95% DPPH inhibition) compared with the 87% DPPH inhibition observed in the control (uncoated) treatment. For their part, Nourozi and Sayyari [34] demonstrated that the application of an *Aloe vera* gel with basil seed mucilage onto apricots conserved their antioxidant properties (35% DPPH inhibition) compared with the control fruits (20% DPPH inhibition). Likewise, Shivangi, Dorairaj, Negi, and Shetty [54] developed a pectin-based edible coating enriched with mulberry leaf extract that exhibited significant antioxidant activity (IC_{50} = 2.67 mg/mL) than that of the coating with no bioactive extract added (IC_{50} = 28.46 mg/mL). Additionally, Divya, et al. [76] reported that an edible coating prepared with chitosan nanoparticles exhibited up to 50% DPPH inhibition. In contrast, the antioxidant activity of starch-coated papaya was reported to be higher than the uncoated papaya samples [77]. The authors explained that this may be due to the lower oxidation of phenolic compounds and ascorbic acid in the coated samples.

The antimicrobial activity of edible coatings is also widely studied. Antimicrobial properties of edible coatings are of great interest not only in the prevention of food-borne diseases but also towards food spoilage [28,54,56]. For example, a pectin-based coating containing mulberry leaf extract exhibited antimicrobial properties against two food-borne pathogens (*Pseudomonas aeruginosa* and *Bacillus cereus*), compared to the control coating, which did not show any antimicrobial activity against the tested pathogens [54]. On the other hand, Oyom, Xu, Liu, Long, Li, Zhang, Bi, Tahergorabi, and Prusky [56] found that an edible coating consisting of sweet potato starch and cumin essential oil exhibited in vivo antifungal efficacy by growth inhibition of *Aternaria alternata* in coated pears. Similarly, Sarengaowa, Hu, Feng, Xiu, Jiang, and Lao [28] reported that the total plate counts, total coliform counts, and yeast and mold counts on fruits treated with an alginate-based edible coating containing thyme oil were significantly lower than the fruits that had the alginate-based edible coating without bioactive (thyme) oil added. These studies demonstrate the benefit of incorporating bioactive compounds, such as those derived from essential oils, into edible coatings to impart bioactive (e.g., antioxidant, antimicrobial) properties in addition to preserving the physico-chemical features of fruits and vegetables.

4. Conclusions and Future Prospects in Polysaccharide-Based Edible Coatings

Polysaccharide-based edible coatings made with chitosan, alginate, cellulose, starch, and to a lesser extent *Aloe vera* gel, gums (e.g., guar, gum arabic, xanthan) and carrageenan have shown promising beneficial effects on coated fruits and vegetables. These beneficial effects are related with the preservation of quality attributes including increased shelf life period, lower respiration rates, maintaining firmness, reducing weight/mass loss, preserving soluble solids, vitamins, and bioactive compounds (e.g., flavonoids, anthocyanins, phenolic compounds), decreasing microbial growth (e.g., fungal, bacterial), maintaining antioxidant enzyme activities (e.g., SOD, CAT), delaying browning degree, and de-creasing overall food damage (e.g, chill-injury, disease incidence/severity). Furthermore, the addition of plant extracts and essential oils (with bioactive compounds) into polysaccharide-based edible coatings, showed remarkable antioxidant and antimicrobial properties. Thus, polysaccharide-based edible coatings with added bioactive compounds can be used not only as an efficient preservation strategy, but also may play a vital role in food safety when consumed with the food.

Emerging trends in polysaccharide-based edible coatings should be focused on the development of highly functional bioactive, nanostructured, and multilayered composite materials with different combinations. This will lead to new multifunctional edible coatings that not only contribute to the food quality but also show beneficial bioactivities towards human health. In this context, bioactive compounds that are incorporated into edible coatings as essential oils or plant extracts should be evaluated for their in vitro cytotoxicity following by their evaluation using in vivo models for their safety and efficacy for human consumption. On the other hand, another concern regarding the use of essential oils or plant extracts is that they may affect the sensory properties of produce (e.g., imparting aromas and/or flavors from the essential oils to the produce). Therefore, future studies should focus on enhancing sensory qualities by using appropriate combinations of edible coating components and/or the use of masking agents in the composite.

Furthermore, the majority of studies have focused on the development of edible coatings in early stage of development with applications at laboratory (bench) scale, as shown in Table 1. However, further studies are needed to establish trials at pilot-plant and industrial scales, which must be accompanied by an economic feasibility analysis for their commercial applications. On the other hand, studies are also needed to optimize reaction parameters in order to find the best conditions to obtain ideal mechanical and physicochemical properties of edible coatings for specific use in fruits and vegetables.

The edible coating technology is beginning to gain momentum as the industry seeks to use more user- and environmental-friendly approaches to shelf life extension of fruits and vegetables. However, there is limited information available on how the intrinsic physicochemical properties of different polysaccharides affect the mechanical and permeability properties of films and/or coatings. Additional research in this area would elucidate the potential functionality of polysaccharide-based coatings for use as a strategy to extend the shelf life period of fresh fruits and vegetables during postharvest storage. Moving forward, attention should also be paid to what is referred to as "smart edible coatings" (e.g., those that are temperature sensitive). For example, smart color-changing temperature-sensitive nanoparticles are of increasing interest for the improvement of food quality and bioactivities. These temperature nanoindicators change their color when the products are heated above or cooled below certain temperature ranges. This allows them to be used as critical reference, indicating potential food spoilage to consumers. Finally, careful consideration needs to be made on the regulatory requirements by country for the different polysaccharides being used in edible coating formulations as this limits the application of such novel polysaccharide compounds.

Author Contributions: Conceptualization, A.M.L. and J.E.A.-T.; bibliographic search, R.G.C.-M., A.A.R.-A., R.M.G.-R. and M.L.Z.-Z.; resources, A.M.L. and J.E.A.-T.; visualization, A.A.R.-A., R.M.G.-R. and M.L.Z.-Z.; writing—original draft preparation, R.G.C.-M. and J.E.A.-T.; writing—review and editing, A.M.L., J.E.A.-T. and M.L.Z.-Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the USDA National Institute of Food and Agriculture, Hatch Act formula funds project 1019794.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge the academic resources and databases provided by Purdue University and Universidad Autónoma Metropolitana.

Conflicts of Interest: The authors declare no conflict of interest.

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