Edible Coatings

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Edible coatings have been intensively developed and studied because of their capacity to improve the quality, shelf life, safety, and functionality of the treated products. Edible coatings can be applied through different techniques, like dipping, spraying, or coating, in order to control moisture transfer, gas exchange, or oxidative processes. Furthermore, some functional ingredients can be incorporated into an edible matrix and applied on the surface of foods, thus enhancing safety or even nutritional and sensory attributes. In the case of coated fruits and vegetables, their quality parameters, such as color, firmness, microbial load, decay ratio, weight loss, sensorial attributes, and nutritional parameters, are very specific to the type of products and their storage conditions should be carefully monitored.

edible coatings fruits vegetables shelf life functional coatings

1. Introduction

During storage, food is subjected to a process of quality degradation, this phenomenon being a major problem faced by food producers, contributing significantly to food waste. In the last years, novel and smart food processing technologies (Ultra High Pressure, Pulsed Electric Field, Modified Atmosphere Packaging, Radio Frequency, Active Packaging, and others) were developed with the aim of contributing to food preservation extension, shelf life-prolonging, and, consequently, food waste reduction [1][2][3][4]. However, not all of these novel technologies represent a real solution in the market due to their impact on consumers' attitudes [5][6].

In the last decades, the food products consumer market developed some changes in terms of sustainability and health implications of food processing and packaging [7]. Moreover, consumers are looking for less processed products or minimally processed products which have a convenient preservation period, are healthy, and present great nutritional value. These requirements are more stringent when discussing highly perishable food products, such as fruits and vegetables. This increasing demand is now a real challenge to food producers in order to develop pertinent and sustainable preservation techniques [8].

A novel way to diminish this problem is the use of edible packaging, edible coatings, or edible films, which can provide an additional protective layer(s) for fresh products, thus increasing their shelf life by delaying the microbial spoilage and providing moisture and gas barrier properties [9].

Nowadays, consumers prefer food less processed and healthier food products and so the research activity on edible packaging systems is rising every year. Edible films and coatings are designed as a primary packaging material for foodstuffs having edible components and so as to help to maintain sensorial properties such as aroma, taste, and appearance. Fruits and vegetables that are coated with edible films have longer shelf lives and their ripening processes are delayed [7][10].

Edible coatings have been used since the 12th and 13th centuries in China, where a thin coat of wax was applied on orange fruits. In the 15th century, it was discovered that Japan designed an edible coating material made from boiled soybeans, which was applied on different food products in order to improve their appearance [11].

In recent years, the market share of edible packaging has seen an increase, being valued at $697 million in 2016, and by 2023 it is expected to grow to $1097 million [12]. There are two distinct ways in which edible packaging can be used in the food industry. Edible coatings can be applied directly to the food product or can be wrapped around the food product in the form of a preformed film [13].

Although edible coatings and films can help prolong the shelf life of different food products, the food industry faces the challenge of consumer acceptance towards novel processing techniques [14]. Understanding how consumers form and perceive attitudes in relation to new technologies and products is important for food chain innovation since consumer acceptance is crucial to the development of successful food products [1][15]. Several studies regarding consumer acceptance towards novel processing technologies and techniques have been made, i.e., nanotechnology [16], radio frequency [6] food irradiation [17], and edible films and coatings [18][19].

2. Composition and Methods of Application of Edible Coatings

An edible coating is generally defined as a coating layer made from chemical or biological materials which are applied as a thin layer or layers on the product surface in order to prevent gaseous exchange, thus retarding the ripening process. Another definition for edible coatings was given by Baldwin et al. (2011) [20], defining them as a thin comestible layer that can be applied to the fruit's surface in order to create a barrier between the fruit and the environment. Jongsri et al. (2016) [21] stated that edible coatings must provide a partial barrier to water movement, so moisture loss can be reduced, and, at the same time, can modify the atmosphere around the fruit by acting as a barrier to gas exchange.

The main components used for edible coatings and films are lipids, polysaccharides, and proteins, but other materials need to be used too, such as resins, solvents, and plasticizers, in order to obtain different characteristics for the edible coatings. The flexibility and permeability of edible coatings are conferred by the use of plasticizers, tensile strength by the use of solvents, and water vapor permeability prevention is obtained with the help of resins [10][22].

Yifan et al. (2020) [23] developed self-healing coatings based on sodium alginate (SA) and l-menthol-beta-cyclodextrin-graft-chitosan for the improvement of the postharvest quality of fruits and vegetables. The developed materials presented good characteristics, showing that the addition of l-menthol led to dense, smooth, and transparent coatings with better mechanical and self-healing characteristics. Fu et al. (2021) [24] developed edible films based on waste fish scale-derived gelatin, chitosan, and $CaCO_3$ nanoparticles. The edible films presented important characteristics such as UV absorption, antimicrobial activity, great mechanical properties, and non-toxicity. Furthermore, the developed edible films were hydrophilic, which means that they can be easily removed from fruit by washing. Fan et al. (2021) [25] developed an edible composite film (PAX) based on pectin, sodium alginate (SA), and xanthan gum (XG). The film showed important properties, such as a tensile strength which could reach a maximum value of 29.65 MPa at a concentration of 4 g/L XG, 18 g/L glycerol, and 20 g/L $CaCl_2$. In addition, the elongation at break was 19.02% and the water vapor transmission rate was 18.12×10^{-11} g/(m^2·s·pa). Active films based on chitosan and gum arabic also containing cinnamon essential oil were developed by Xu et al. (2019) [26]. The analysis performed on the developed films showed that there were electrostatic interactions between chitosan and gum arabic, forming an entangled structure. In addition, the addition of gum arabic enhanced the water barrier properties and the antioxidant effectiveness of films.

The developed edible films and coatings could also meet environmental concerns due to the fact that they are generally obtained using biocompatible, biodegradable, low-toxicity, and GRAS (Generally Recognized As Safe) materials [27].

After the production of these edible coatings, they need to be applied to the desired food products. This can be done by different methods like brushing, spraying, dipping, extrusion, a fluidized bed, panning, and solvent casting. Both the food products and the edible coatings need to be examined and tested before the best method of applying the edible coating is selected. Carbon dioxide or oxygen permeability, high or low water vapor permeability, and good mechanical resistance are only some of the characteristics that need to be assessed for the coating materials [11][28].

On commercial use, extrusion and spraying processes are desired methods for food product coatings or film formation. At a laboratory scale, coating and film formation are obtained by dipping and casting processes. Despite the existence of several methods in which the edible films can be applied, the most used ones are casting (a wet process) and extrusion (a dry process) [13].

3. Edible Films and Coatings with Functional Additives for Minimally Processed Fruit Application

The next steps in this field are strongly represented by research focused on improving the effectiveness of edible films based on a polysaccharide matrix by adding functional ingredients such as [29]:

- *plasticizers* (glycerol, sorbitol, sucrose, mannitol, acetylated, monoglyceride, polyethylene glycol, and xylitol) added to coatings to increase flexibility and prevent coatings from blistering, flaking, and cracking;
- *emulsifiers* (soy lecithin, stearic acid, and Tweens) and *surfactants* (Tweens) added to improve coating adhesion;
- *antimicrobial agents* (nisin, natamycin, phenolic compounds, natural seed extracts, and essential oils—like cinnamaldehyde, eugenol) added to improve the antimicrobial activity of a coating;

- *antioxidants* (ascorbic acid, citric acid, and α-tocopherol) added to coating matrices to prevent oxidative rancidity, degradation, and discoloration;
- *nano-compounds* (like metal oxides as ZnO or TiO_2).These functional compounds are seen now as a key component of edible films/coatings for prolonging the shelf life of fruits and vegetables and testing has already started for various fruits (guava, pear, and blueberries) and vegetables (cucumber, capsicum, and mushroom) focusing also on safety and nutritional aspects [8].

Leena et al. (2020) [30] obtained an effective delivery system using nano-structured edible coating based on zein enriched with resveratrol with the possibility of using a controlled release system. An electrospinning process was used in order to encapsulate the resveratrol (in concentrations of 2%, 5%, and 10%) in the zein nanofibers. The obtained edible coating by electrospinning of resveratrol-loaded zein nanofibers was applied on apple slices. The study showed that the coated apple slices retained better color, due to the antioxidant effect of resveratrol added as a functional ingredient, and the control of moisture loss also improved.

Arnon-Rips et al. (2021) [31] conducted a study for obtaining a new structure of edible coatings using a covalent linkage mechanism. Two functional compounds (vanillin and trans-cinnamaldehyde) were bound to chitosan (polysaccharide matrix) by Schiff base reaction and reductive amination. The functionalized structure of chitosan was analyzed and tested as an edible coating in the case of fresh-cut melon samples. The results of the study showed that the tested films produced well-adhered coatings that managed to increase the fresh-cut melon quality and shelf life without altering the sensorial attributes. In order to test the antibacterial effect, mandarin juice was added to the chitosan and vanillin and trans-cinnamaldehyde mixture, and the results showed a 6 log CFU/mL microbial count reduction, which clearly demonstrates this effect.

Fresh-cut apple samples were coated with edible coatings (carboxymethyl cellulose and Aloe Vera) and anti-browning agents in different combinations, with only one active ingredient or both. The treated samples were packed in polypropylene trays and stored at 5 ± 2 °C. Multiple parameters were studied along the storage period of the samples, such as physical properties (color, physiological loss in weight, and firmness), bio-chemical properties (ascorbic acid, total antioxidant, phenol, polyphenol oxidase, and peroxidase enzymes), and microbiological indicators. The samples coated with the edible coating material along with the anti-browning agents helped preserve the quality of the samples. As for the microbiological assay, it was observed that apple slices coated with carboxymethyl cellulose and Aloe Vera had a significantly lower microbial load. The coated apple samples showed an improved firmness compared to the untreated samples. Polyphenol oxidase and peroxidase enzyme activity were also lower in the coated samples [32].

Alginate-based edible coatings enriched with Aloe Vera were developed using the Box-Behnken design in order to optimize the minimum water vapor permeability. In order to create these films, titanium oxide nanoparticles ($nTiO_2$) were incorporated in different percentages within the film. Mechanical and antimicrobial properties were improved after the incorporation of titanium oxide nanoparticles. Tomato samples were treated with these Aloe Vera and alginate-based edible coatings and shelf-life studies showed significant resistance to weight loss and spoilage when alginate/Aloe Vera film containing 5 wt% of $nTiO_2$ was applied [33].

Salas-Méndez et al. (2019) [34] investigated the effects of nanolaminate coatings incorporated with extracts of *Flourensia cernua* on tomatoes in order to extend their shelf life. The nanolaminate coating was made from polyelectrolyte solutions of alginate and chitosan that had been treated with ethanol extracts of *Flourensia cernua.* The samples were coated with this material and several parameters were tested: physicochemical analyses, ethylene production, and microbial growth. The treated samples presented weight loss and microbial growth reduction. In addition, ethylene production was slower, and the tomato firmness and color were better preserved. This shows that the nanolaminate edible coatings could improve the shelf life of tomato samples.

Lara et al. (2020) [35] studied the effect of spray-coating of fresh-cut lotus roots with xanthan gum-based edible coatings. In order to have multiple variants, the study tested several variants of edible coating solutions, consisting of three concentrations of xanthan gum solutions (0.1%, 0.3%, and 0.5%). In all of the above solutions, 2% (*w*/*w*) citric acid was added as an anti-browning agent and 1% (*w*/*w*) glycerol as a plasticizer. Fresh-cut lotus roots were then sprayed with these solutions in a 5 mm thick layer for 20 s and stored at a temperature of 5 °C for 16 days in polyethylene bags. Morphology, pH, color, and microbiological determinations were performed, and it was observed that the treated samples had a significant reduction in the total color changes compared to control samples that were not sprayed. In addition, the enzymatic browning of fresh-cut lotus root during storage was decreased. A lower microbial count was recorded to the treated samples compared to non-coated fresh-cut lotus root samples in terms of Bacillus subtilis growth rate in the first 24 h of storage.

Due to the long food chain characteristics of bananas, scientists are looking for more sustainable methods for preserving them. Alali et al. (2018) [36] studied the effects of gum arabic (GA), salicylic acid (SA), and their mixture in the form of coatings on the quality of ‘Grand Nain’ bananas during postharvest storage. Nutritional compound content (total phenols, flavonoids, and vitamin C) showed a good response in the case of GA application and less favorable responses in the case of SA application. In addition, the peel browning index was better in the case of the GA coating. According to Sinha et al. (2021) [37], pear samples coated with chitosan-enriched 2.0% and 2.0 mM salicylic acid stalled the development of internal browning throughout the storage period.

Basiak et al. (2019) [38] studied the effects of coating plums with two different starch-based edible coatings, one containing only starch and the other one containing starch and whey protein. The effects of the coating materials applied on the surface of plums on water loss were determined by studying resistances in the water vapor pathway. The dynamic behavior of two starch-based coatings both at high and low potential water losses was evaluated in the experiments. The results showed that when applying the coatings in a three-layered model, the starch and starch-whey protein coatings increased the total resistance in the water vapor pathway of individual plums by 60–75% at high transpiration potentials. An increase of 11–20% was observed at lower transpiration potentials.

Arabic gum, xanthan gum with lemongrass essential oil 1% *w*/*v,* and carrageenan edible coatings were studied by Wani et al. (2021) [39]. Postharvest quality tests were made over strawberries samples treated with the three developed edible coatings, over a period of 12 days. The result showed that the coated strawberry samples had a reduction in weight loss, retained the ascorbic acid better, had better antioxidant activity, and had improved firmness. The edible films with carrageenan gum managed to retain the anthocyanins levels and phenolic compounds during the storage period. In addition, the best results in terms of maintaining quality during storage were the coatings containing carrageenan gum.

Table 1. Effect of edible coatings/films with different functional ingredients on fruits and vegetables quality.

Film/Coating Matrix (Coating Method)	Functional Compound (Role)	Coated Fruits or Vegetables	Advantages of Coating Technology and Main Results of Study	Reference
Polysaccharides and their derivatives-based matrix (starch and its derivatives, cellulose and its derivatives, alginate, pectin, chitosan, and gums)				
Methyl cellulose (MC) (Dip coating)	Palm Oil (PO) (anti-browning agents, antioxidants, and antimicrobials)	Sapota fruits (a large berry)	Decrease PO, PPO, PME activity and discoloration; Increase anti-browning effect and retention of ascorbic acid; Delay the loss of total phenolic content; Extend the shelf life by three days	[40]
Methyl cellulose (MC) (Dip coating)	Curcumin; Limonene (antioxidants, antimicrobials)	'Chandler' strawberries	Decrease fungal growth; Increase TPC, TA	[41]
Carboxymethyl cellulose (CMC) (Dip coating)	Aloe vera (anti-browning agents, antioxidants, and antimicrobials)	Apple slices	Decrease PO and PPO activity Lower microbial load; Better firmness; Anti-browning effect.	[32]
Carboxymethyl cellulose (CMC) (Coating)	*Lactobacillus plantarum* (antimicrobials, probiotic)	Strawberries	Reduce the growth rate of molds and yeasts on the surface of strawberries; Improve functionality (as a probiotic)	[42]
Hydroxyethyl cellulose and sodium alginate (Dip coating)	Asparagus waste extract (antioxidants, antimicrobials)	Strawberries	Maintain the TFC and TPC, delay color change and weight loss	[43]
Hydroxypropyl methyl cellulose (Spraying)	Aloe vera gel and lemon essential oil (antioxidants, antimicrobials)	Hayward kiwis	Reduce weight loss and browning, maintain higher firmness, brightness, greenness, and TSS Reduce the microbial load	[44]
Chitosan solutions with a different	Chitosan (antimicrobials)	'Nam Dok Mai' mango fruits	Delay ripening; Increase TA, Fruit firmness, Reduction of weight loss,	[22]

Film/Coating Matrix (Coating Method)	Functional Compound (Role)	Coated Fruits or Vegetables	Advantages of Coating Technology and Main Results of Study	Reference
molecular weight (Dip coating)			ethylene production, and respiration rate; Maintain the ascorbic acid and AOC (the case of chitosan with high molecular weight)	
Chitosan (Dip coating)	8% and 12% blueberry (*Vaccinium spp.*) fruit and leaf extracts (BLE) (antioxidants, antimicrobials)	Blueberries (*Vaccinium spp.*)	Decrease microbial growth and decay rate; Increase the shelf life	[45]
Chitosan (Dip coating)	Acetic or Lactic acid (antimicrobials)	Blackberry	Antifungal effect over *Mucor racemosus*	[46]
Chitosan (Coating)	Vanillin and trans-cinnamaldehyde and mandarin extract (antioxidants, antimicrobials)	Fresh-cut melon	Reduce microbial load; Increase storage life; Maintain sensorial attributes	[31]
Chitosan-pullulan (Dip coating)	Pomegranate peel extract (anti-browning agents, antioxidants, and antimicrobials)	Green bell pepper	Decrease weight loss and color browning; Maintain firmness, TPC, TFC, AOC, and sensorial attributes	[47]
Chitosan and cellulose nanofibers (Dip coating)	Iron particles, curcumin (antimicrobials)	Kiwifruits	Reduce weight loss and firmness and reduce respiration rate	[48]
Chitosan and glycerol (Coating)	Whey protein isolate (antioxidants, antimicrobials)	Strawberries	Decrease weight loss, pH, color modifications, TA, TPC, and DPPH; Extend shelf life by 60%	[49]
Chitosan, Alginate (Coating)	*Flourensia cernua* ethanol extract (antimicrobials)	Tomatoes	Decrease weight loss; Decrease microbial growth and ethylene production; Maintain firmness and color	[34]
Chitin, cellulose, and chitosan (Coating)	Chitosan (antimicrobials)	Strawberries	Decrease microbial growth, decrease color changes, and weight loss	[50]
Chitosan (Coating)	Salicylic acid (antimicrobials)	Pears	Decrease PPO activity; Stalled the development of internal browning	[37]

Film/Coating Matrix (Coating Method)	Functional Compound (Role)	Coated Fruits or Vegetables	Advantages of Coating Technology and Main Results of Study	Reference
			throughout the storage period	
Chitosan (0.05%) (Coating)	Cinnamon essential oil (0.1%), trans-cinnamaldehyde (0.05%) (antimicrobials)	Cucumber	Antifungal activity (*Fusarium solani)*	[51]
Chitosan (1%) (Coating)	Nano-silica (0.05%) (anti-browning agents, antioxidants, antimicrobials)		Decrease in PPO activity and browning; Reduced weight loss and TA	[52]
Chitosan and alginate (Coating)	Pomegranate peel extract (PPE) (anti-browning agents, antioxidants, antimicrobials)	Capsicum	Decrease loss in weight, firmness, color, and ascorbic acid content	[53]
Sodium alginate (Dip coating)	Eugenol (Eug) and Citral (Cit) (anti-browning agents, antioxidants, antimicrobials)	*Arbutus unedo* fruit (red berry)	Decrease microbial growth and weight loss; Improve physicochemical and biochemical parameters: color, firmness, AOC, and sensorial attributes	[54]
Sodium alginate (Dip coating)	Essential Oil extracted from sweet orange (antimicrobials)	Tomatoes	Decrease weight loss up to 3-fold lower than uncoated samples; Decrease bacterial growth; Increase the firmness by up to 33%	[55]
Sodium alginate (Dip coating)	Citral nano-emulsions (anti-browning agents, antioxidants, antimicrobials)	Pineapples	Better color retention, low respiration rate, reduce microbial growth	[56]
Sodium alginate (Dip coating)	$CaCl_2$ (antioxidants, antimicrobials)	Rose apple	Significantly reduce the respiration rate and weight loss; Improve total phenolic content and antioxidant activity	[57]
Sodium alginate, konjac glucomannan, and	lotus leaf extract (antioxidants, antimicrobials)	Goji berries (*Lycium barbarum* L.)	Reduce decay rate and weight loss; Maintain AA, TA, TSS;	[58]

Film/Coating Matrix (Coating Method)	Functional Compound (Role)	Coated Fruits or Vegetables	Advantages of Coating Technology and Main Results of Study	Reference
starch (Dip coating)				
Modified starch from sweet potatoes (Dip coating)	Cumin essential oil (antimicrobials)	Pears	Suppress the respiration rate and delay the weight loss and maintain flesh firmness	[59]
Starch and nystose (Dip coating)	Nystose (antioxidants, antimicrobials)	Blackberries	Positive effects in delaying the increase in pH, maintaining the firmness and anthocyanin content	[60]
Arabic gum (Dip coating)	Salicylic acid (anti-browning agents, antioxidants)	'Grand Nain' bananas	Decrease weight loss; Improve firmness and peel browning index; Maintain antioxidant activity	[36]
Arabic gum, xanthan gum (Coating)	Lemongrass essential oil 1% w/v and carrageenan (antioxidants, antimicrobials)	Strawberries	Decrease weight loss; Increase AA, AOC, and firmness; Maintain TANC and TPC	[39]
Protein-based matrix (vegetable proteins as corn zein, wheat protein, soy protein, and animal proteins as keratin, collagen, gelatin, casein, fish myofibril protein, egg white protein, protein whey)				
Gelatin (5, 6, and 7%) (Dip coating)	Persian gum (3.5, 4, and 4.5%) and 9, 10, and 11% Shellac (antioxidants)	Oranges	Decrease of weight loss; Decrease TA; Increase TPC and AOC; Maintain fruit firmness and glossiness	[61]
Gelatin (Spraying)	Ethanolic Extract of Propolis (PEE) and zein nanocapsules (antimicrobials)	Raspberries (*Rubus idaeus L.*)	Antifungal activity against *P. digitatum* and *B. cinerea* strains; Increase the shelf life	[62]
The nano-structured edible coating based on zein (Controlled release coating system)	Resveratrol (anti-browning agents, antioxidants)	Apple slices	Improve color retention; Decrease moisture loss	[30]
Pectin and pullulan (Coating)	*Vitis vinifera* grape seed extract	Peanuts	Reduced lipid oxidation and antibacterial activity	[63]

ssed fruits r alginate Ds, nano- the basic , such as a positive impact on consumers. A better understanding of the mechanism of the edible functional coatings and their promotion among consumers could help to extend their application in fruit and vegetable preservation. Moreover, edible coatings and film can become a very promising method that could be applied for delivering bioactive

Film/Coating Matrix (Coating Method)	Functional Compound (Role)	Coated Fruits or Vegetables	Advantages of Coating Technology and Main Results of Study	Reference
	(antioxidants, antimicrobials)		against *E. coli* and *L. monocytogenes*	
Mixed formulations or heterogeneous coatings				
Aloe vera-based gel (Dip coating)		Papaya fruits	Decrease microbial growth rate; Increase TSS, TA, AA, TCAC, TPC, and TFC; Extend the shelf life by 25%.	[64]
Starch and starch-whey protein coatings (Coating)		Plums	Increase the total resistance in the water vapor pathway	[38]

PO-peroxidase; PPO-polyphenol oxidase; PME-pectin methylesterase; TA-titratable acidity; TPC-total phenolic content; TFC-total flavonoids content; TANC-total anthocyanin content; TCAC-total carotenoids content; AOC-antioxidant capacity/content; TSS-total soluble solid; AA-ascorbic acid.

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