coatings

Review

Bio-Coatings for Preservation of Fresh Fruits and Vegetables

Camelia Ungureanu, Grațiela Tihan *, Roxana Zgârian * and Georgica Pandelea (Voicu)

Faculty of Chemical Engineering and Biotechnologies, University "Politehnica" of Bucharest, Gheorghe Polizu Street 1-7, 011061 Bucharest, Romania; camelia.ungureanu@upb.ro (C.U.); voicu_georgica@yahoo.com (G.P.)
* Correspondence: gratiela.tihan@upb.ro (G.T.); roxana.zgarian@upb.ro (R.Z.)

Abstract: In response to increasing concerns over food waste and safety, and the environmental impacts of traditional conservation methods, this review aims to explore the potential of bio-coatings in preserving the freshness of fruits and vegetables. Our primary objective is to provide a comprehensive analysis of recent advancements in bio-coating technologies, detailing their benefits in terms of enhancing food safety, prolonging shelf life, and reducing waste. This paper delves into various forms of bio-coatings, their applications, and their effectiveness in maintaining post-harvest quality. We further elucidate the underlying mechanisms that govern their preservation efficacy. This review is intended for researchers, industry professionals, and policy makers who are interested in sustainable preservation alternatives and their implications for food security and environmental sustainability. By the end of this review, the audience will gain a thorough understanding of the current state of bio-coating technology and its prospects in the food preservation industry.

Keywords: edible coating; food safety; post-harvest technology; prolonged shelf life; biodegradable coatings

check for updates

Citation: Ungureanu, C.; Tihan, G.; Zgârian, R.; Pandelea, G. Bio-Coatings for Preservation of Fresh Fruits and Vegetables. *Coatings* **2023**, *13*, 1420. https://doi.org/10.3390/coatings13081420

Academic Editors: Maria Jose Fabra and Stefano Farris

Received: 16 July 2023
Revised: 9 August 2023
Accepted: 11 August 2023
Published: 13 August 2023

1. Introduction

Consuming fresh food is undoubtedly the best way to enjoy various flavors and nutrients, but their preservation helps to enjoy all these even out of season [1]. Food production and supply are not always in balance with the needs of the population. In the case of surplus production of fresh fruits or vegetables, which are perishable or semi-perishable, it is important to store and preserve them to ensure a continuous food supply. Some fruits and vegetables cannot be grown in every type of soil and climate, so preserving food will aid importing them abroad. After harvest, the ripening and aging process can be delayed by different preservation methods [2], maintaining the taste and quality, and extending the sale/consumption ratio of food out of season. Preservation makes the product available on the market in a wide variety, and when there is no discrepancy between supply and demand, stabilization of food prices can also be observed. In broad terms, the preservation of fresh fruits and vegetables consists of handling and treating them to stop or slow down their decay or spoilage (contamination by microorganisms, loss of nutritive value, loss of flavor, change in texture, microbial and enzymatic decomposition) while ensuring a longer shelf life for the food. Fruits are susceptible to a variety of post-harvest diseases caused by bacteria and fungi. These diseases can lead to visible decay and a loss of quality [3]. The loss of fruit quality during ripening and post-harvest is also influenced by several physiological changes. These changes can be categorized under factors such as maturity, respiration, ethylene production, and enzymatic reactions [4,5]. The stage of maturity at which fruits are harvested affects their quality and shelf life. When fruits are harvested too soon or too late, they may not have the flavor or texture that they should, and their shelf life may be shortened [6]. The process by which the fruit's stored organic elements are transformed into energy is called respiration. After the fruit is harvested, this process continues, causing it to lose weight and nutritional content. In general, juicy fruits respire more quickly, and as respiration continues, the quality of the fruit weakens [7]. Some fruits, such as apples and bananas, produce much more ethylene as they mature. Fruits naturally release ethylene, a plant hormone that encourages ripening. Increased ethylene production frequently results in increased respiration rates, which might accelerate fruit ripening and lower fruit quality [8]. The conversion of starches to sugars, the softening of the fruit due to the breakdown of pectin, and the growth of flavor and aroma compounds are just a few of the enzymatic events that take place throughout the ripening process. While these responses are essential for the fruit to reach its maturity peak, if they continue too far, they can cause over-ripening and a loss of fruit quality [9]. After harvesting, fruits continue to lose water through their skin, which can lead to shriveling and weight loss, impacting the fruit's appearance and texture [10]. Additionally, damage caused by handling can cause bruising and create openings for disease organisms, further accelerating deterioration and quality loss.

Post-harvest management strategies aim to minimize these physiological changes and maintain fruit quality for as long as possible. These strategies might include appropriate temperature management, humidity control, careful handling to avoid physical damage, and the application of post-harvest treatments to slow respiration, reduce ethylene production, or control disease [11].

Bio-coating technologies hold great promise for the future of food preservation, offering a more sustainable and healthy way to keep fruits and vegetables fresh for more extended periods [12]. Additionally, bio-coatings offer an attractive option as they reduce the need for plastic-based packaging materials, thereby minimizing waste and environmental impact. When implementing bio-coatings for commercial applications, it is important to consider factors such as scalability, cost-effectiveness, and regulatory considerations [13].

There is an important demand for natural preservatives instead of synthetic ones to avoid health problems caused by their use. Promising preservatives are natural antimicrobials extracted from plants, animals or microorganisms that suppress bacteria and fungi growth [14]. There are food preservatives of chemical origin that do not represent any risk to health (e.g., $CaCl_2$ and sorbates). In fact, many bio-based coatings contain these ingredients. However, we must consider, for example, the use of synthetic chemical fungicides and sodium hypochlorite as potential hazards [15,16]. Synthetic fungicides are widely used in agriculture to control fungal diseases. Chronic exposure to synthetic fungicides has been linked to various health issues in humans, including skin and eye irritation, neurological effects (such as headaches and dizziness), and more severe conditions such as cancer, endocrine disruption, and damage to the liver and kidneys. The risks depend on the specific fungicide and level of exposure. If not properly managed, fungicide residues can remain on food crops, potentially posing a consumer risk [17]. Sodium hypochlorite is a common bleaching agent and disinfectant often used to sanitize fruits and vegetables and other food products to eliminate bacteria, viruses, and other pathogens that could cause illness. While this process helps ensure the food supply's safety, there are potential risks if residues of sodium hypochlorite remain on the food and are ingested [18]. The residue could be directly consumed if fruits and vegetables have been improperly washed or rinsed after being treated with sodium hypochlorite. While the concentrations used for food sanitation are typically low, ingesting higher concentrations can be harmful [19]. Sodium hypochlorite can react with certain organic compounds on fruits and vegetables to form disinfection byproducts (DBPs) such as trihalomethanes and haloacetic acids. Some of these byproducts have been associated with potential health risks, including an increased risk of certain types of cancer [20]. Additionally, some individuals may have or develop an allergy or sensitivity to sodium hypochlorite. In such cases, consuming treated produce could lead to an allergic reaction [15].

In both cases, these substances should be used responsibly and following safety guidelines to minimize risks. Alternatives, including biological control methods for fungal diseases and non-chemical disinfection methods, are also being increasingly explored as safer and more sustainable options.

A bibliometric analysis of the data that were retrieved from the ISI Web of Science database (www.webofscience.com, accessed on 16 July 2023) using the keywords "Bio Coatings for Preservation of Fresh Fruits" and "Bio Coatings for Preservation of Vegetables" is presented in Figure 1. We are using the VOS viewer tool [21] that allows the realization and visualization of bibliometric elements to acquire a general understanding of the subject area. As seen below, several clusters are related directly or indirectly to the bio-coatings keyword, which shows the complexity of the research field. By visualizing clusters in different colors, VOS viewer allows users to identify related items and understand the overall structure of the network quickly and easily. Each color (green and red) represents a different cluster in the network. These clusters are created based on the similarities or relationships between the items within a specific group.

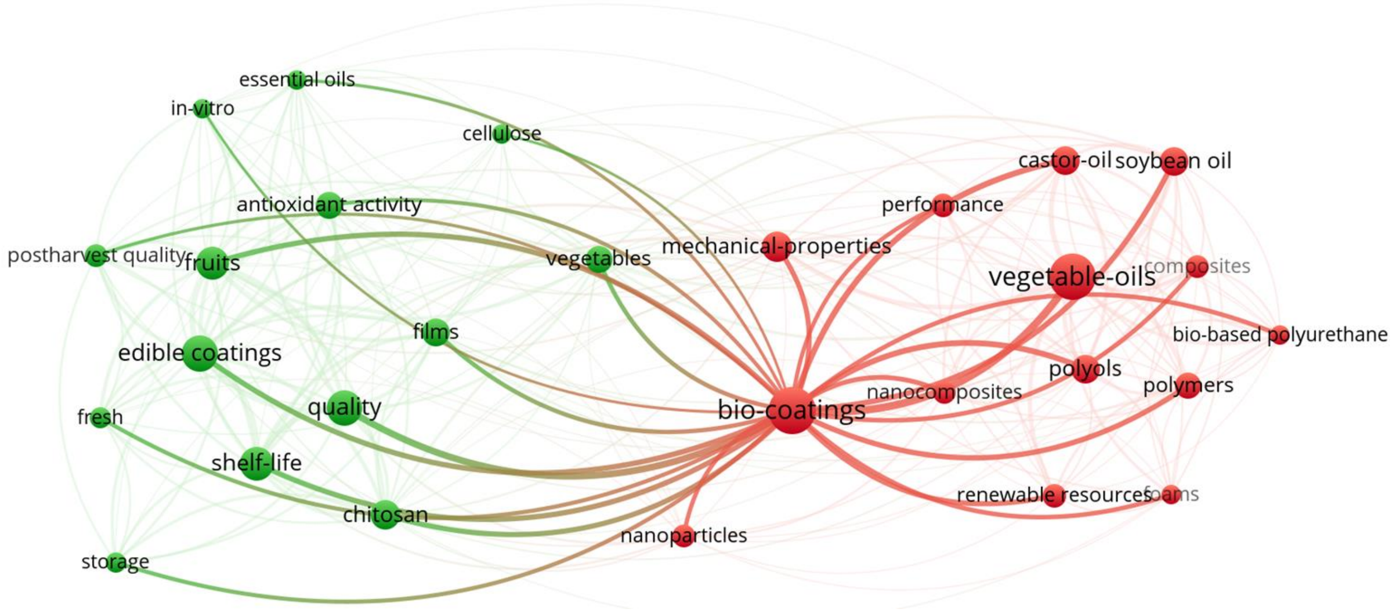

Figure 1. Bibliometric analysis of data extracted from the ISI Web of Science database (2000–2022).

Figure 2 displayed the publication trend of scientific articles that were published on the topic of "Bio Coatings for Preservation of Fresh Fruits and Vegetables" (data were taken from the ISI Web of Science database, which can be found at www.webofscience.com, accessed on 16 July 2023). The scientific community's heightened interest in the field is reflected in the significantly increased number of publications written on the subject that have been published for the past decade.

Given the contemporary challenges in food preservation and the emergent promise of bio-coating technology, this review seeks to provide a comprehensive update on the research and applications of bio-coatings in preserving fresh fruits and vegetables. Our primary objectives are as follows:

(a) We aim to collate and analyse the most recent studies in this field to understand the current landscape of bio-coating technology, detailing the specific types of bio-coatings used and the types of fruits and vegetables they are applied to.

(b) We plan to elucidate the underlying mechanisms that make these bio-coatings effective in preserving the freshness of fruits and vegetables, including their impact on moisture control, ripening processes, and microbial growth.

(c) Considering the increasing importance of sustainability, we aim to assess the environmental impacts of these bio-coatings, including their production, usage, and disposal, as compared to traditional preservation methods.

(d) Beyond the laboratory, we seek to evaluate the practical implications of bio-coating technology, such as its commercial viability, regulatory aspects, and consumer acceptance.

(e) Finally, we aim to identify gaps in the current research and suggest potential opportunities for future studies in the field.

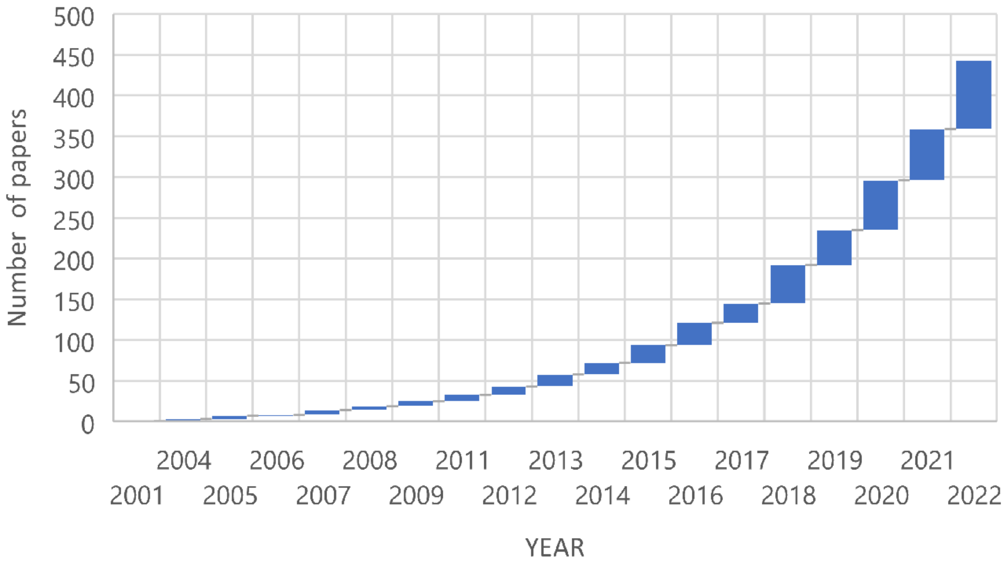

Figure 2. Publication trend (2000–2022) in the application of "Bio Coatings for Preservation of Fresh Fruits and Vegetables" field. (Source of raw data: ISI Web of Science; search keywords: "Bio Coatings for Preservation of Fresh Fruits" and "Bio Coatings for Preservation of Vegetables").

In achieving these aims, we hope to offer researchers, industry professionals, and policy makers a robust understanding of the present and potential future of bio-coatings in preserving fresh fruits and vegetables.

2. Bio-Coatings: Materials and Properties

2.1. Materials

Bio-coatings can be enriched with essential nutrients, vitamins, or bioactive compounds that contribute to the nutritional value of fresh fruits and vegetables. These nutrients can be derived from natural sources or encapsulated within the bio-coating material, ensuring their controlled release and preservation over time [22–24]. To protect spoilage-causing microorganisms the coating composition may incorporate natural antimicrobial compounds such as plant extracts or essential oils (EO). This minimises the possibility of microbial contamination and deterioration, maintaining the freshness and quality of the packaged fruits and vegetables for a longer amount of time [23]. Due to volatile molecules that can cover up the original flavor of the treated fresh fruit or vegetable, bio-coatings based on essential oils can significantly impact sensory characteristics. Alternatives to conventional techniques could include combining numerous preservation systems or using an EO compatible with specific kinds of food [25–30].

The ability of bio-coatings to tailor their composition and functionality opens new possibilities for developing innovative packaging solutions that address the dual goals of food preservation and quality enhancement [31].

Figure 3 illustrates advantages of bio-coatings on shelf life, quality, and nutritional content of fresh fruits and vegetables:

(1) Bio-coatings can help reduce the rate of moisture loss reduce the moisture loss rate and microbial growth rate, thereby extending its shelf life [31].
(2) Bio-coatings can help to preserve the appearance, texture, and flavor of produce during storage and transport. This can be particularly beneficial for high-value produce, such as berries, tomatoes, and citrus fruits [32].
(3) Bio-coatings can help to preserve the nutritional content of produce, such as vitamins and antioxidants, by reducing the rate of oxidation and degradation [33].

(4) By increasing the shelf life and preserving the quality of food products, bio-coatings can reduce waste and increase the availability of fresh products for consumption [34].

Figure 3. Main advantages of bio-coatings used in the preservation of fresh fruits and vegetables.

By addressing these advantages and safety considerations, we can maximize the potential benefits of using bio-coatings on fresh fruits and vegetables while ensuring the safety and satisfaction of consumers. All materials used in coatings must be food-grade and safe for human consumption. Any additives, such as antimicrobials or antioxidants, must also be deemed safe. The potential allergenicity of the coating materials should be considered. If allergenic substances are used, these should be clearly labelled to prevent allergic reactions. Coating materials and processes should comply with all relevant local, national, and international food safety and labelling regulations. Despite their potential to carry antimicrobial agents, incorrect formulation or application of coatings could create an environment conducive to microbial growth. Ensuring that coatings are correctly applied under sanitary conditions is essential. Coatings should not adversely affect the taste, texture, or overall sensory quality of the produce. Any potential impact on sensory attributes should be thoroughly tested [35–37].

Typically, biomolecules such as polysaccharides, proteins [38], and lipids are used to create edible bio-coatings (Figure 4), which are then applied as a thin film to the surface of the product to regulate moisture transfer, gas exchange, or the oxidation process, thereby increasing the product's shelf life [39,40].

Due to their low-cost, high stability, non-toxicity and biodegradability, polysaccharides [41] such as chitosan (CHI) [42–44], alginate, gums, starch, pectin and cellulose [45,46] or its derivates are already studied as part of the edible coating (Table 1).

Table 1. Bio-coatings for preserving fruits and vegetables.

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Alginate	Green Mango	Dipping	Alginate (2%, *w*/*w*), Glycerol (1.5%, *w*/*w*), Ascorbic acid (1%), Citric acid (1%), $CaCl_2$ (2%, *w*/*v*), N-acetylcysteine (1%, *w*/*v*)	Preserved the color of fresh-cut mangoes and increased the antioxidant potential of cubes	[47]
Alginate	Carrots	Dipping	Sodium alginate (2%, *w*/*v*), α-tocopherol acetate (1%, *w*/*v*), Glycerol (20%), $CaCl_2$ (2%, *w*/*v*)	Preservative tool to enhance the shelf life	[48]
Alginate	Apples	Dipping	Sodium alginate (1%, *w*/*v*), Glycerol (1.5%, *v*/*v*), $CaCl_2$ (1%, *w*/*v*), Citric acid (1%, *w*/*v*), Ascorbic acid (0.5%, *w*/*v*)	Changes in eating quality parameters, appearance acceptance, and textural properties	[49]
Alginate	Pineapple	Dipping	Sodium alginate (1%, *w*/*v*), Glycerol (0.5%, *w*/*v*), Ascorbic acid (0.1%, *w*/*v*)	Preservation	[50]
Alginate and Cassava starch	Pineapple	Dipping	Cassava starch (1.5%), Alginate (0.5%), Glycerol (0.5%) and Ascorbic acid (0.18%)	Extending the post-harvest life	[51]
Alginate with Lemongrass essential oil	Apples	Dipping	Sodium alginate (1%, *w*/*w*), Lemongrass essential oil (0.5–5%, *w*/*w*), Tween 80 (5%, *w*/*w*)	Preserving the quality of fresh-cut apple	[52]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Alginate with Gellan gum or Pectine	Apples	Dipping	Sodium alginate (2 g/100 mL), Gellan gum (0.5 g/100 mL) or Pectine (2 g/100 mL), Apple fiber, Glycerol (0.6 or 1.5 g/100 mL), Ascorbic acid (1 g/100 mL), $CaCl_2$ (2 g/100 mL)	Increasing the nutritional value of fresh-cut apple	[53]
Alginate with Pectine	Blueberries	Dipping	Sodium alginate (10 g/kg), Pectine (10 g/kg), Glycerol (15 g/kg) and Tween 20 (2 g/kg)	Positive effect mainly on firmness and microbial growth of treated blueberry	[54]
Alginate with Carvacrol	Blueberries	Dipping	Sodium alginate (2%, *w*/*v*), Carvacrol (0.09%), Glycerol (30%, *w*/*v*)	Delaying post-harvest spoilage	[55]
Alginate with Chitosan	Blueberries	Dipping	Chitosan solution (3%):Sodium alginate solution (2%) at 1:1, Glycerol (25%) and Tween 20 (0.15%, *w*/*v*)	Extending shelf life and maintaining quality	[56]
Chitosan	Papaya	Dipping	Chitosan (1.0%, *w*/*v*), Ascorbic acid (5%, *w*/*v*), Tween 80 (1:1, *v*/*v*)	Maintaining the post-harvest storage quality	[57]
Chitosan	Mandarin	Spreading	Chitosan (0.5, 1 and 1.5 g/L)	Maintaining fruit quality parameters	[58]
Chitosan	Banana	Spraying	Chitosan nanoparticle (0.2%, *v*/*v*) in acetic acid (0.5% *v*/*v*), Tween 80 (0.1%, *v*/*v*), Tripolyphosphate (1 mg/mL)	Slower skin discoloration	[59]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Chitosan	Banana	Dipping	Chitosan nanoparticle (2%) and *Moringa oleifera* (10%)	Increase the storage life	[60]
Chitosan	Zucchini	Dipping	Chitosan (1%, *w*/*v*) with/without Glycerol (1.5%, *v*/*v*)	Extending post-harvest life and enhancing the overall quality	[61]
Chitosan with Rice starch	Walnut	Dipping	Rice starch (4%, *w*/*v*), Chitosan (1%), Glycerol (2%, *w*/*v*)	Extend the shelf life of walnut	[62]
Chitosan with Lemongrass essential oil	Green bell pepper	Dipping	Chitosan (1.0%), Lemongrass essential oil (0.5%)	Maintaining the fruit quality	[63]
Chitosan with Eugenol and Aloe vera	Pineapple	Spraying	Chitosan (1.5%, *w*/*v*), Eugenol nanoemulsion (20%, *v*/*v*), Aloe vera gel (25%, *w*/*v*)	Preserved its quality and prolonged their shelf life	[64]
Chitosan with Beeswax and Pollen grain	Pears	Dipping	Beeswax (0.5 g), Glycerol (0.2 g), Pollen grains (0.5 g), Tween 80 (0.2 g), Chitosan in acetic acid (1%), $CaCl_2x2H_2O$ (0.4%)	Decrease in weight loss, decay and rate of softening	[65]
Beeswax	Mandarin	Spreading	Beeswax (5, 10 and 15 g/L)	Maintaining various fruit quality parameters and sensory attributes	[58]
Beeswax with Sodium caseinate and Guar gum	Strawberries	Dipping	Sodium caseinate (8%), Glycerol:Sodium caseinate at 1:10, Beeswax (2%, *w*/*v*), Guar gum (0.2%, *w*/*v*), Tween 80:Span 80 (1:3, 1:1, 3:1)	Reduce the respiration and transpiration rates of strawberries	[66]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Wax with Bavistin	Mandarin	Dipping	Wax (10%), Bavistin (0.1%)	Prolongation of shelf life, as well as the quality of mandarin fruit	[67]
Carnauba wax	Sweet potatoes	Dipping	Carnauba wax (35 g), Oleic acid (5.6 g), Myristic acid (1.4 g) with/without Glycerol monolaurate (1.0g)	Preserve food quality and extend shelf life of sweet potato roots	[68]
Carnauba wax	Tomatoes	Dipping	Carnauba wax nanoemulsion (150 g), Oleic acid (30 g), Dimethylpolysiloxane (0.1 mL), Ammonium hydroxide 8% (20 g), Deionized water (775 mL)	Increased fruit gloss and improved tomatoes appearance	[69]
Carnauba wax and Grapefruit seed extract	Mandarin	Dipping	Carnauba wax (18.1%, *w*/*w*), Grapefruit seed extract (1%, *w*/*w*)	Can extend the post-harvest shelf life of mandarins	[70]
Cassava starch with Cinnamon essential oil	Guava	Dipping	Cassava starch (2%), Cinnamon essential oil (0.01%)	Maintaining the quality of guava at room temperature and modified atmosphere, extending the useful life	[71]
Rice starch with Coconut oil and Green tea leaf extract	Tomatoes	Dipping	Starch (1.5g/100 mL) and Glycerol (0.4 mL), Additional, Coconut oil (2 mL) and green tea extract (4 mL) (*v*/*v*)	Delayed ripening effects on tomatoes	[72]
Arabic gum	Persimmon fruits	Dipping	Arabic gum (10%), Glycerol (1.5%)	Higher total phenolics, ascorbic acid, antioxidant activity, and titratable acidity	[73]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Arabic gum African baobab pulp extract	Blueberries	Dipping	Arabic gum (10%, *w*/*v*), Glycerol (1%, *v*/*v*), African baobab extract (1.5 or 2.5%, *v*/*v*)	Better preservation of total phenols and total anthocyanins delayed the increase in total soluble solids better	[74]
Tragacanth gum with Eremurus extract	Sweet cherries	Dipping	Tragacanth gum (7.5 or 12.5 g/L) Eremurus extract (10 or 12.5 g/L)	Reducing post-harvest losses and increasing the shelf life	[75]
Guar gum with Ethanolic extract of *Spirulina platensis*	Mango	Dipping	Guar gum (1%), Tween 80 and Glycerol (10%) and Ethanolic extract of *Spirulina platensis* (1%)	Increasing the shelf life of mango fruit	[76]
Guar gum with Aloe vera	Mango	Dipping	Guar gum (1%), Tween 80 and Glycerol (10%) and Aloe vera gel (40%)	ncreasing the shelf life of mango fruit	[76]
Aloe vera	Grapes	Spraying and Dipping	Salicylic acid (3 mM), Aloe vera gel (25% or 33%), Glycerol (1%, *v*/*v*), Tween 80	Prolong the storage life of table grapes and maintain their quality	[77]
Whey protein nanofibrils	Apples	Dipping	Whey protein nanofibrils (5%, *w*/*v*), Glycerol (4%, *w*/*v*), Trehalose (3%, *w*/*v*)	Protective action toward retarding the total phenolic content, browning, and product weight loss	[78]
Dextrin	Zucchini	Dipping	Dextrin (1%, *w*/*v*) and extra-virgin olive oil (0.2%, *v*/*v*)	Extending post-harvest life and enhancing the overall quality of zucchini fruit	[61]
Locust bean gum with Carboxycellulose nanocrystal	Strawberries and cherry tomatoes	Dipping	Locust bean gum (4%), Carboxycellulose nanocrystal (1.0%)	Extending the shelf life of strawberries and cherry tomatoes	[79]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Carboxymethyl cellulose	Mandarin	Spreading	Carboxymethyl cellulose (2 g/L)	Extending cold storage life, significantly reducing weight loss, spoilage, firmness loss, the activity of fruit softening enzymes besides maintaining higher levels of juice content	[58]
Carnauba wax	Papaya	Spreading	18% Carnauba wax nanoemulsion	Reduced over three times the loss of firmness; formed a gas barrier that slowed fruit respiration	[80]
Ethylene scavenger films combined with zein-Artemisia sphaerocephala Krasch (ASKG)	Banana	Electrospraying	Positively charged zein and negatively charged ASKG precursor solutions mixed in various ratios by volume (5Z:1A, 5Z:2A, and 5Z:3A).	A lower browning rate, higher hardness, and longer shelf life	[81]
Chitosan combined with alginate	Pear	Layer-by-layer	Chitosan coating solution was prepared at 0.5% (*w*/*v*) in 0.4% (*w*/*v*) acetic acid. The alginate coating solution (0.5% [*w*/*v*]) was prepared by first dissolving alginic acid in deionized water	Minimized fruit respiration and ethylene production rates, inhibited flesh firmness loss, and prevented peel color change	[82]
Alginate/Oil nanoemulsion	Sweet cherries	Cross-linked coating	Alginate solution (1.0%, *w*/*v*) Tween 80 (1.0% v/v) and soybean oil (0.5% v/v) w	Increased cracking tolerance by 53% and increased firmness. Exhibited a 10% increase in water loss	[83]
Alginate/chitosan	Mandarine fruits	Layer-by-layer	1% (*w*/*v*) chitosan, and polyelectrolyte complexes such as 1.5% (*w*/*v*) alginate/chitosan, 1% (*w*/*v*) hydroxypropyl methylcellulose/chitosan, and 0.2% (*w*/*v*)	The preservation of bioactive compounds and organic acids in fruits	[84]

Table 1. *Cont.*

Bio-Coatings	Fresh Fruits and/or Vegetables	Coating Method	Composition of Bio-Coatings (Concentration)	Main Results	Ref.
Xanthan gum (XG)	Apple	3D food printing	0.4% in proportion 2:1, 1:1, and 1:2 addition of xanthan gum (XG) and basil seed gum (BSG)	Higher hardness, gumminess, stiffness and self-supporting ability	[85]
Carboxymethyl cellulose (CMC) combined with chitosan	Citrus fruit	Layer-by-layer	1.5% CMC and 1.0% chitosan solutions	Enhanced fruit glossiness and appearance	[86]
Protein/guar gum and mango puree/calcium chloride	Fresh-cut mango	Cross-linked coating	for coating solution-A, 400 mL of denatured protein solutions and 100 mL of guar gum solutions were mixed. As a plasticizer, 10% of glycerol (on a protein basis) was added to all the solutions. For coating solution-B, 500 mL of 2% calcium chloride (*w*/*v*) solution, which contains 30% of fresh mango puree (*v*/*v*)	Decreasing deterioration of fresh-cut mangoes, enhancing shelf life, and keeping quality during low-temperature storage	[87]
Water-in-oil (w/o) emulsions maltodextrin and whey protein isolate (WPI)	Strawberries	Electrospraying	The dispersed phase of the emulsion was prepared with maltodextrin (MD), WPI, or 50:50 (*w*/*w*) mixture of MD and WPI at 16% (*w*/*w*) concentration	Moisture loss of strawberries significantly reduced	[88]

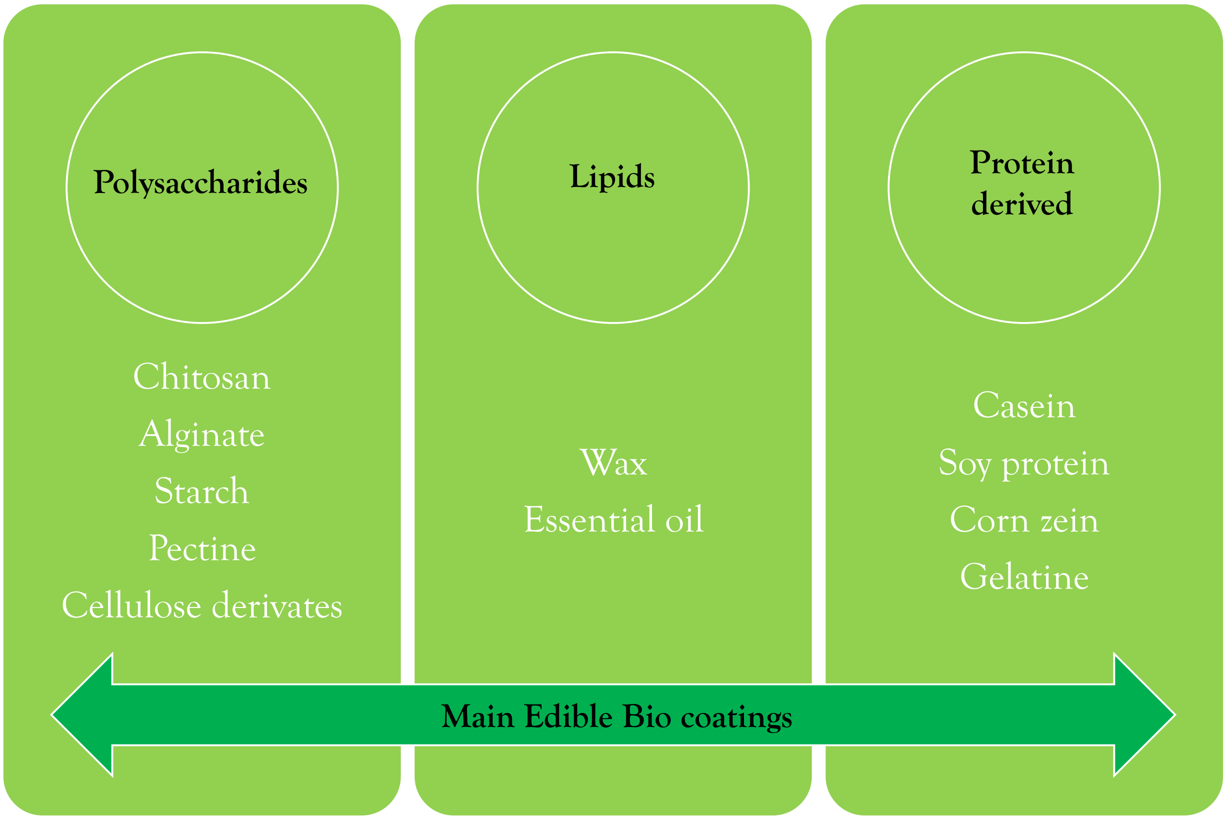

Figure 4. Main edible bio-coatings derived from different sources.

2.2. Properties

Fresh vegetables and fruits are frequently coated with polysaccharide-based materials to extend their shelf lives. Their organized structure, which contains a hydrogen network, is why they are regarded as an efficient oxygen blocker. Starch, a polysaccharide that is abundant in nature and inexpensive, is made up of the linear polymer amylose and the highly branched polymer amylopectin. Aiming to achieve three essential objectives, namely: preserving physico-chemical and sensory properties, improving microbial stability, and increasing the post-harvest shelf life of fresh strawberries during storage, Aryou Emamifar and Sudabeh Bavaisi considered obtaining edible coating based on polysaccharide and nano-zinc oxide (nano–ZnO). They combined sodium alginate (SA) with nano–ZnO as antimicrobial agents and used low temperature storage. Similar to alginate in terms of applications, gellan gum is an anionic polysaccharide that is easily processed into transparent gels and has low water vapour permeability [89].

According to Petriccione et al. [90], strawberries stored at 2 °C that had been coated with a 1% or 2% chitosan solution had a much lower degradation rate than untreated strawberries of the same cultivar. Due to research by Jongsri et al. [91], high molecular weight Chitosan (HM–CTS) applied during post-harvest storage of 'Nam Dok Mai' mango can slow down deteriorative processes, keep the fruit's quality intact, and lengthen its storage life.

Ma et al. (2013) studied the effects of CHI and oligoCHI on the resistance of peach fruit against brown rot brought on by *Monilinia fructicola* (*M. fructicola*) [92]. They demonstrated the effectiveness of these natural substances in controlling disease and maintaining peach fruit quality.

Several reports indicated a suitable way to improve the effectiveness of CHI-based coatings by adding plant extracts [93–95]. In 2003, Bautista-Banos et al. [96] investigated the in vitro fungicidal effect of CHI and plant extracts, alone and combined, on *Colletotrichum gloeosporioides* (*C. gloeosporioides*), which causes anthracnose on papaya fruits. They considered CHI an important natural product with good capacity in control of anthracnose on papaya fruit. It acts as a barrier that limits the penetration of *C. gloeosporioides* without maintaining a great firmness of fruit. They also observed a trend towards better firmness in the case of fruits treated only with papaya seed extract or with papaya seed extract combined with CHI. The same action was observed at the grapefruit seed extract (GSE). GSE is one of several bioactive chemicals generally recognized as safe for use in food. GSE is widely utilized as an antibacterial in the food industry, and its effectiveness as a coating material or in edible packaging films has been discovered very recently [97].

Van Thi Tran et al. [98], obtained in 2021 CHI-based coatings with different concentrations of tea seed oil (TSO) and monitored their antifungal capacity on Japanese pears (*Pyrus pyrifolia Nakai*) inoculated with a spore suspension of *B. cinerea*. The results demonstrated that incorporating different concentrations of TSO improved the in vitro and in vivo antifungal capacity of chitosan coatings.

Treatments with CHI particles combined with *Zataria multiflora* and *Cinnamomum zeylanicum* essential oils revealed a strong capacity to inhibit gray mold proliferation on strawberries, especially that of *B. cinerea* [99]. In 2022, Chun Yang et al. [100] studied CHI-based coatings with high phenolic extracts such as turmeric (TU) and green tea (GT) for strawberry preservation. Their study demonstrated that the post-harvest treatment of strawberries by coating with CHI and TU inhibited the proliferation of *B. cinerea* during 7 days of storage at 20 °C, and the one based on CHI and GT prolonged the antioxidant properties of strawberries post-harvest to 8 days at 20 °C, without significantly affecting the aroma and taste.

Natália Ferrão Castelo Branco Melo et al., in 2018 [101], prepared and evaluated coatings with edible CHI nanoparticles as possible treatment to improve the post-harvest quality of grapes. As a result, grapes were cleaned with sodium hypochlorite (1%), washed in drinking water, dried for two hours, and then submerged for three minutes in coating solutions containing chitosan nanoparticles the day after they were harvested. Grapes with and without CHI nanoparticle coating were kept either at ambient temperature (25 °C/12 days) or in the refrigerator (12 °C/24 days). Coatings with edible CHI nanoparticles delayed the ripening process of grapes, and implicitly decreased weight loss.

Recent studies showed that *Aloe vera* gel (AVG) having film-forming properties is easy to apply, has antifungal and antimicrobial actions and acts as a natural barrier to humidity and air [102–106]. AVG delays browning and ripening, delays firmness and weight loss and preserves phenolic content.

The world's most popular and delicious fruit, strawberries, are susceptible to microbial and fungal infection during storage. Coatings of banana starch–CHI with different concentrations of AVG show that AVG presence significantly reduces fungal decay, increasing the shelf life of strawberries up to 15 days of storage, a 5% lower weight loss compared to uncovered fruits, maintaining at the same time their color and firmness. The positive results are attributed to the cross-linking process between AVG molecules and starch [103]. Additionally, the effect CHI coatings with beeswax, such as CHI–beeswax–CHI coatings on the quality of *Fragaria ananassa* cv *Camarosa strawberries*, was studied in 2013 by Velickova et al. The authors showed a significant decrease in fruit senescence and weight loss while preserving the produce color and texture [107].

Cellulose derivatives are successfully used in obtaining coatings [108]. For example, the hydroxypropyl methylcellulose (HPMC) coating exhibits excellent properties, acting as effective lipid, oxygen, and carbon dioxide barriers, while having high water vapour permeability. Roberta Passafiume et al. [109], in 2020, analysed the effect of three types of edible coatings based on AVG, AVG with HPMC, and AVG with lemon essential oil (LEO) on the quality of fresh-cut kiwifruit. In the case of coatings based on AVG, respectively AVG with LEO, the quality of the Hayward kiwis was very well maintained, because the coatings functioned as a barrier to gas and slowed the growth of bacteria. However, the coatings based on AVG with LEO give the fruit a taste characteristic of LEO, and AVG used alone give the fruit an herbaceous taste, so that the coatings based on AVG with HPMC come with the advantage of not altering the natural taste of kiwi slices. Essentially, AVG combined with HPMC or LEO has demonstrated the ability to preserve the quality of freshly cut kiwi. For the preservation of cherry tomatoes and grapes, edible coating based on soy protein isolate (SPI), HPMC, and glycerine (GLY) shown much lower weight loss rates [110]. Additionally, for tomatoes preservation, in 2020, Stefania Frassinetti et al. [111] prepared bio-coatings based on gelatine (G) or G enriched with blueberry juice (GB) showing that GB preserved the nutritional quality of tomatoes. Poveronov et al. [112], in 2014, combined G and CHI in edible films or coatings and demonstrated inhibition of microbial proliferation on fresh-cut melon. Strawberries coated with CHI had a longer shelf life and preserved its qualitative qualities for a longer period than uncoated strawberries, according to a study published in the "Foods" journal [113]. In this investigation, different concentrations of CHI were applied to strawberries, and they were kept at 2 °C for nine days. The findings demonstrated that CHI coatings extended fruit shelf life by slowing weight loss, microbial development, and degradation. The study also discovered that the CHI coatings had no detrimental impact on the sensory characteristics of the strawberries, proving that the coating had no impact on the fruit's flavor or texture. The tomatoes were coated with alginate that had been enhanced with oregano essential oil (OEO) and stored at room temperature for two weeks, according to Pirozzi et al. [114]. They demonstrated how alginate coatings may extend the shelf life of tomatoes and improve their quality while being transported and stored. Moreover, to inhibit foodborne pathogens' growth and to prolong the shelf life of tomatoes, Das et al., prepared coatings based on carboxymethyl cellulose and cardamom oil [115]. The findings revealed the antibacterial effect of these coatings against *Escherichia coli* and *Listeria monocytogenes* and demonstrated the shelf life extension of tomatoes during storage. These coatings are being designed as an ecologically friendly and sustainable alternative for synthetic coatings and traditional preservation methods [116,117]. According to the authors, using alginate coatings in combination with natural additives can be a successful strategy for maintaining the quality and increasing the shelf life of apples.

Dordevici et al. [118] produced κ-carrageenan films by incorporating spent coffee grounds oil. κ-Carrageenan is a naturally derived biopolymer extracted from certain species of red seaweeds. It is widely used in the food industry for its gelling, thickening, and stabilizing properties. In the context of bio-coatings for preserving fresh fruits and vegetables, κ-carrageenan has shown promising results. Being derived from natural sources and biodegradable, using κ-carrageenan as a bio-coating aligns with the current shift towards more sustainable and environmentally friendly food packaging and preservation solutions. Despite these benefits, challenges remain. For instance, the functionality of κ-carrageenan coatings can be influenced by the type of fruit or vegetable, storage conditions, and the specific formulation of the coating [119].

These examples illustrate the potential and the properties of bio-coatings to lengthen the shelf life of produce and maintain its quality in commercial and research settings. The continuous conduct of research and development in this field has the potential to assist in the discovery of novel coating materials and formulas that are superior, leading to an even higher level of success in the use of bio-coatings for the preservation of fresh fruits and vegetables.

Below, based on what we discussed above, we present a suggestion for classifying and integrating the mechanisms of different bio-coatings in inhibiting the deterioration of fruits and vegetables:

(a) Bio-coatings can act as an effective barrier against moisture loss, a common cause of deterioration in fruits and vegetables. This can help maintain the firmness and prolong the produce's shelf life.

(b) Bio-coatings can also control the exchange of gases, such as oxygen and carbon dioxide, slowing down the respiration rate and ripening process in fruits and vegetables.
(c) Certain bio-coatings can incorporate antimicrobial agents that inhibit the growth of spoilage and pathogenic microorganisms, further enhancing the shelf life and safety of the produce.
(d) Some bio-coatings can also contain antioxidants, preventing oxidative browning and off-flavor development in fruits and vegetables.
(e) Bio-coatings can slow down ethylene production and perception, effectively delaying the ripening and senescence of fruits.
(f) By providing a protective barrier, bio-coatings can help in preserving the nutritional quality of fruits and vegetables, preventing the loss of vitamins and other essential nutrients during storage.
(g) By maintaining freshness and reducing blemishes or discoloration, bio-coatings can also help in preserving the visual appeal of fruits and vegetables, which is an essential factor in consumer acceptance.

By classifying the mechanisms in this way, we can better understand how different bio-coating's function, and it allows us to design and formulate coatings that are best suited to specific types of fruits and vegetables, considering their unique post-harvest handling and storage requirements. This integrated approach will ensure the most effective use of bio-coatings in preserving the freshness, quality, and safety of fruits and vegetables.

3. Bio-Coatings Methods for Fruits and Vegetables Preservation

The choice of a coating method may depend on the type of fresh fruits and vegetables, the coating material, and the desired coating thickness. The application method should be carried out under hygienic conditions to prevent contamination and ensure the effectiveness of the coating. It is also essential to apply the coating evenly and that it adheres properly to the surface of the produce, maximizing its effectiveness. The coating material can be applied in its pure form or mixed with other ingredients such as antioxidants, preservatives, or antimicrobial agents, thus enhancing its effectiveness [120].

3.1. Methods to Prepare the Bio-Coatings

3.1.1. Nanoencapsulation

As mentioned before, for the food industry, as an alternative to synthetic preservatives, researchers have paid attention to the use of natural preservatives such as EO [121,122]. However, there are also some limitations, such as its volatility or its rapid oxidation. In this regard, for bio-efficacy in terms of antifungal, antimycotoxigenic and antioxidant capacity, new studies have applied nanotechnology for incorporating the EOs into the polymer matrix. By nanoencapsulation, the polymer matrix will capture the EO and act as a carrier matrix improving thus the efficacy of the EO [123].

Nanoemulsions can be used as edible coatings, creating a barrier on the surface of fruits and vegetables, reducing water loss, controlling respiration rate, and inhibiting microbial growth. Additionally, the small droplet size of the nanoemulsion allows for a more complete coverage of the surface, including small crevices and pores, and enhances the adhesion of the coating [124]. The composition of the nanoemulsion can be optimized to include bioactive compounds such as antioxidants, antimicrobials, or enzymes, which can enhance the preservation of fruits and vegetables. For example, nanoemulsions containing plant extracts, essential oils, or CHI have effectively inhibited the growth of pathogens and spoilage microorganisms, and delay senescence and ripening of fresh produce [125,126]. Nanoemulsions as edible coatings can be applied through various methods, such as spray coating or dip coating. The choice of the method will depend on factors such as the type of fruit or vegetable being coated, the desired shelf life, and the properties of the nanoemulsion [12]. Nanoemulsions represent a promising strategy for the preservation of fresh fruits and vegetables, and they have the potential to reduce food waste, enhance food quality, and provide added nutritional value. However, further research is needed to optimize the composition and application of nanoemulsions as edible coatings, and to evaluate their safety and consumer acceptance.

In general terms, this nanotechnology offers protection over a long period, ensuring maintenance of firmness and nutritional and organoleptic characteristics. In 2015, M. Sessa et al. [127] concluded in their research that the modified CHI with nanoencapsulated LEO prolong the shelf life of rucola leaf with no significant effect of the organoleptic characteristics of the vegetable in comparison to CHI coating or EO alone.

In-Hah Kim et al., in 2013 [128], developed highly stable nanoemulsions—solutions based on *Carnauba wax* and LEO for coating plums. The results revealed their ability to inhibit *Salmonella typhimurium* (*S. typhimurium*) and *Escherichia coli* (*E. coli*) O157:H7 contamination, maintaining the firmness of coated fruits and reducing respiration rates during storage.

3.1.2. Microemulsion Formulation

Formulation of the microemulsion involves mixing the coating materials in a suitable solvent system to form a microemulsion. This typically involves using an emulsifier (a surfactant or co-surfactant) to ensure stability of the microemulsion. The properties of the microemulsion and the final coating will depend on the emulsifier used and the proportion of the oil-to-water phase. To ensure the stability of the microemulsion, an emulsifier (a surfactant or co-surfactant) is often used [129]. Microemulsion is applied to the surface of the fresh fruits or vegetables. Several techniques, such as dipping, spraying, or brushing, can be used to accomplish this. Following application, the fruit or vegetable is typically let too dry at a specified temperature and relative humidity [130].

3.1.3. Microspinning (Electrospinning)

Is a flexible method for producing ultra-thin fibers from a variety of materials. Electrospinning is used to create nanofibers, which are then used to coat fruit through dipping, spraying, painting, etc. Electrospun nanofibers have a very high surface area-to-volume ratio, making them perfect for thinly and uniformly coating fruits and legumes [131]. Because the fibers are so fine, they can go inside the fruit or legume's surface pores and provide a more thorough coating than other techniques. One benefit of electrospinning is that depending on the number of layers used, coatings can be made with various thicknesses, from a few nanometres to several microns [132,133]. This method requires specialized equipment, making it more expensive and difficult to scale up for commercial production. Although electrospinning has significant potential for use in food applications, it also comes with several difficulties. Electrospun mats are sensitive and may not fully respond to unusual shapes, making applying them directly on fruits or vegetables difficult. Some edible polymers might also need particular electrospinning settings or solvents that are not always food-grade or may present other difficulties [134].

Less common but still used are the following briefly mentioned methods:

3.1.4. Melt Extrusion

In this method, the biopolymer is heated until it melts and then extruded or pressed into a thin film. This method is often used with lipid-based coatings, such as waxes or resins [135].

3.1.5. Coacervation

This method is often used to encapsulate active ingredients within a bio-polymer coating. In coacervation, the polymer is dissolved in a liquid, and then a second, immiscible liquid is added. The polymer separates from the solution and forms tiny droplets, which can be collected and dried to form a coating [136].

3.1.6. Phase Inversion Method

The phase Inversion method is used to produce porous coatings. The biopolymer is first dissolved in a solvent, and then a non-solvent is added. This causes the polymer to precipitate out of the solution and form a porous structure [137].

3.2. Methods of Coating Application in Fresh Fruits and Vegetables

Some standard methods for applying bio-coatings (Figure 5) to fresh fruits and vegetables are presented below:

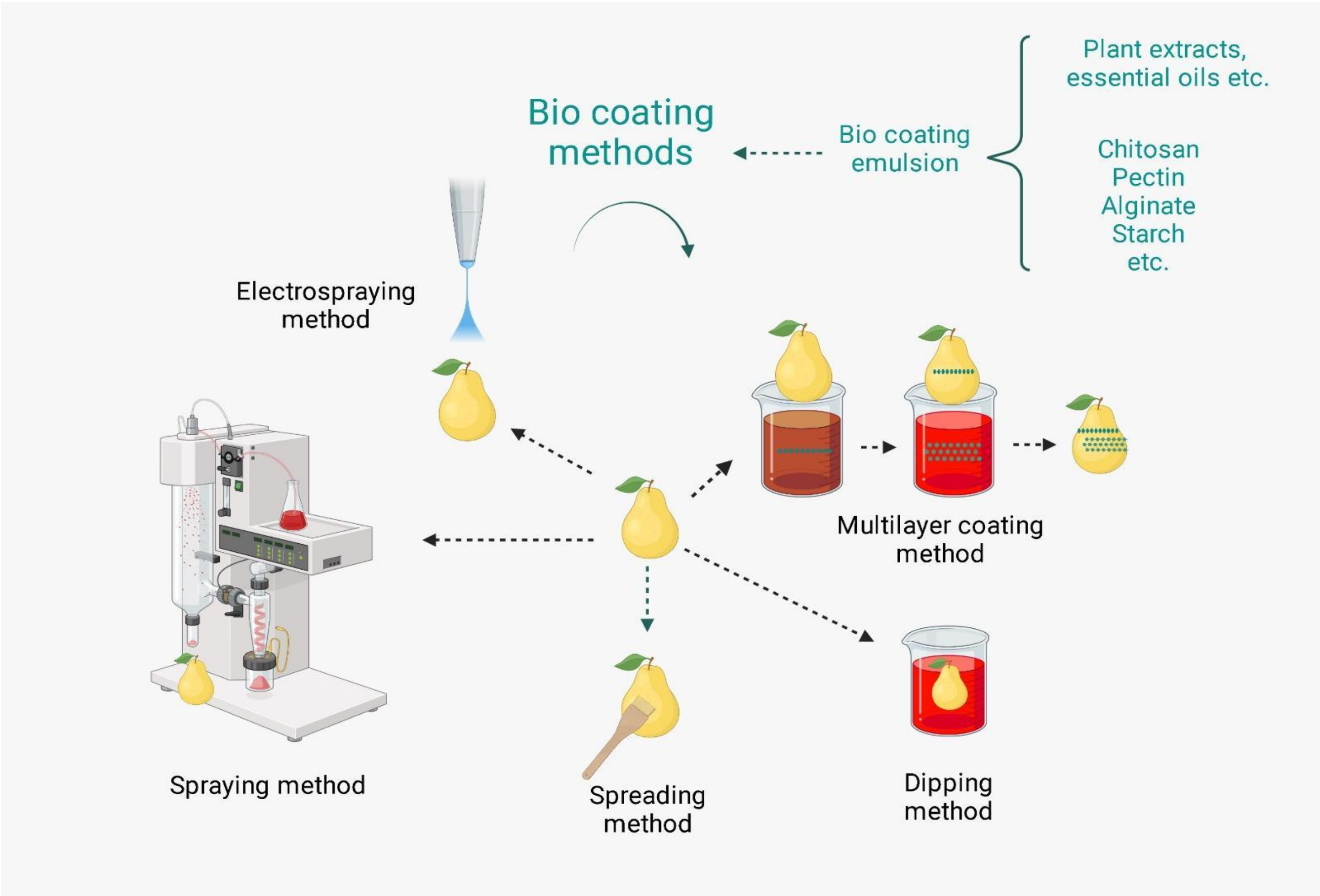

Figure 5. Examples of some bio-coating methods for fresh fruits and vegetables (the graphical representation was made using the BioRender program by the Toronto-based BioRender Corporation).

3.2.1. Dipping (Dip Coating) Method

In the Dipping (Dip coating) method the fruit and/or vegetable is immersed in a solution of the coating material for a predetermined amount of time, then removed and allowed to dry. The fruit or legume is then removed from the solution and excess solution drains off. Dip coating is commonly used for fruits and vegetables that have a relatively smooth surface [31]. It may not be suitable for fruits or legumes with delicate skins or membranes, as they may be damaged during immersion. Dip coating it is a simple and inexpensive method that can be easily scaled up for commercial production [138]. Adding antimicrobial and/or antioxidants extract to the biopolymer solution can help extend the shelf life of the coated fruit and/or vegetable [139].

3.2.2. Spraying Method

The bio-coating material it can also be applied to the surface of the fruits and/or vegetables using a spray nozzle by Spraying method [140]. Spraying (using spray nozzles) is the standard method used by the industry in packing lines to coat fruit in many different types of fruit (citrus, apples, tomatoes, pears, etc.). The biopolymer is dissolved into a suitable solvent to create a solution. The solution is then atomized into a fine mist using a spray nozzle, which is directed onto the surface of the fruit or vegetable [141]. One of the advantages of spraying is that it is a fast and efficient method that can be easily scaled up for commercial production. Adding antimicrobial agents or antioxidants to the biopolymer solution can help extend the coated produce's shelf life. However, spraying method also has some limitations [142].

3.2.3. Spreading Method

Another method for applying bio-coatings is the Spreading method. This method is used for producing with a small surface area, such as mushrooms or grapes [143]. The coating material is applied to the surface of the fruits and/or vegetables using a brush.

3.2.4. Vacuum Infusion

Vacuum infusion is used for the fresh fruits and vegetables with a porous structure, such as melons or cucumbers [144]. The biopolymer solution is introduced into the vacuum chamber, where it is absorbed into the pores of the fruits and vegetables [145] but applying this method to food such as carrots or eggplants, could improve the organoleptic characteristics and nutritional values, increasing the storage time and preserving their tissue hardness. This can be particularly useful for preserving fruits and legumes with thick skins or membranes that require a deeper coating [146]. The vacuum infusion is not suitable for fruits or vegetables with delicate structures, as they may be damaged during the vacuum process [147].

3.2.5. Solution Casting Process

Solution casting for applying bio-coatings involves dissolving the biopolymer in a suitable solvent and then casting it onto the surface of the fruit or vegetable [148]. Solution casting is used to obtain stand-alone films in a Petri dish or similar. Dipping and spraying are the most common application methods in fruits, and the solvent (mostly water) evaporates as the fruit dries. Care should be taken when choosing the solvent to dissolve the biopolymer since it must be compatible with both the biopolymer and the fruit or vegetable that will be coated. The solvent evaporates once the solution is thrown over the fruit or legume's surface, leaving behind a thin layer. By varying the biopolymer solution's concentration or the number of coating layers used, the coating's thickness can be managed [141,148]. Solution casting has the benefit of being an easy, inexpensive process that is simple to scale up for commercial production [149]. Additionally, depending on the application technique, the coating's thickness and uniformity could vary, which may impact the coating's effectiveness [150]. In conclusion, solution casting is a promising method for obtaining bio-coatings for the preservation of fruits and vegetables, and it has the potential to improve food quality and reduce food waste [151].

3.2.6. Multilayer Coating (Layer by Layer)

Another process for applying bio-coatings is Multilayer coating (Layer by layer) method. The procedure consists of applying a thin layer of edible bio-based coating to the fruits' and vegetables' surfaces [152]. The fruits and vegetables are coated with multiple layers of coating using the multilayer coating method. Each layer has a specific purpose, such as preventing infectious agents from penetrating the fruit and vegetables or limiting the amount of oxygen that reaches [153]. The coatings are typically made from natural materials, such as CHI, cellulose, and pectin that are safe for human consumption. The multilayer coating method has been shown to be effective in extending the shelf life of a variety of fresh fruits and vegetables, including apples, strawberries, tomatoes, and cucumbers. The method is also environmentally friendly, as it reduces the need for chemical preservatives and packaging materials [154].

3.2.7. Cross-Linked Coating Method

Cross-linking is a process in which polymer chains are linked together via chemical bonds, creating a three-dimensional network of interconnected chains. This technique is used in the formulation of coatings to improve their performance, as the cross-linked structure typically provides improved mechanical strength, water resistance, and stability [83]. In the context of preservation of fresh fruits and vegetables, the Cross-linked coating method can offer several advantages. Cross-linked coatings have tighter polymer networks which can reduce the permeability of gases (such as oxygen and carbon dioxide) and water vapor, slowing down the ripening process and moisture loss in fruits and vegetables. These coatings typically have greater mechanical strength and resistance to abrasion or damage, ensuring that the protective layer remains intact during handling and transportation. Cross-linked coatings are less likely to dissolve or degrade, making them more stable and durable for longer storage periods. Cross-linked coatings can also be used as a matrix for encapsulating and releasing active agents, such as antimicrobial and antioxidant compounds. The cross-linked structure can provide controlled release of these compounds, enhancing the shelf life and safety of the produce. For instance, chitosan, a naturally derived biopolymer commonly used in edible coatings, can be cross-linked using agents such as genipin [155].

However, it's important to note that the safety of the cross-linking agents and the potential migration of substances from the coating to the food should be thoroughly assessed to ensure food safety. The coatings should always comply with relevant food safety regulations and standards.

3.2.8. D Food Printing Method

3D food printing is a burgeoning technology that has the potential to revolutionize the food industry. It involves the use of a 3D printer to deposit materials layer by layer to create a food product with a specific structure, texture, and potentially, nutritional profile [156]. 3D printing technology could be used to create precise, uniform edible coatings on fruits and vegetables, enhancing their shelf life and quality. 3D food printing allows for the incorporation of various ingredients into the food structure. This could potentially be leveraged to include natural preservatives or antimicrobials in the printed food, helping to extend the shelf life of fresh produce. 3D printing can help in reducing food waste by allowing for the creation of food products from produce that would otherwise be discarded due to aesthetic imperfections. This does not preserve fresh produce per se, but it can help in maximizing the utility of harvested fruits and vegetables. While still a relatively new concept, there is potential for 3D printing to create biodegradable packaging for fruits and vegetables. This could be designed to provide protection and potentially incorporate preservation techniques (e.g., modified atmosphere packaging) [85].

4. Innovations in the Development and Application of Edible Bio-Coatings for Fresh Fruits and Vegetables

The food processing industry is part of what concerns the world economy. Innovations in developing and applying edible bio-coatings for fresh fruits and vegetables are in continuous evolution (Figure 6).

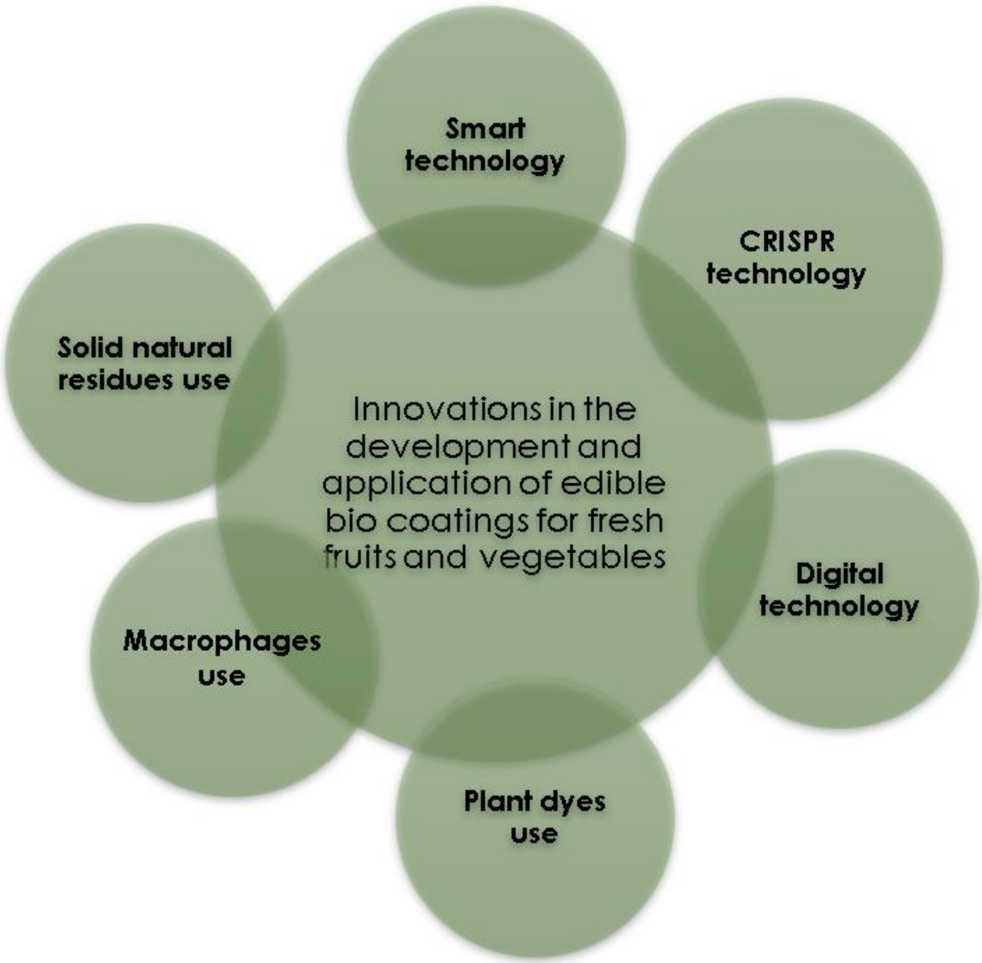

Figure 6. Directions followed for innovation of edible bio-coatings for fresh fruits and vegetables.

4.1. Smart Technology (Artificial Intelligence (AI))

Many organizations in the food industry recognized the need for smart technology such as Artificial Intelligence (AI) [157] to solve fruits and vegetable supply problems, maintain food quality and safety, increase profits, and reduce food waste. Research studies [158,159] demonstrated that AI-assisted drying process of fruits and vegetables can extend the freshness period as well as their nutritional values. To check for internal rot or pesticide residues, and to determine the shelf life of a product, Software can be used [160]. It will detect defects in the fresh products, even when they appear perfect to the human eye. The food industry is known to have a slow transition to Industry 4.0 [161] that aims [162] to achieve efficiency between supply chain members, to enhance the connectivity between human and physical systems, to improve traceability, quality, and food safety, following the impact on the environment. Therefore, it is expected that green technologies such as harvesting, extraction, processing, and pasteurization to be applied in the coming years in combination with Industry 4.0 technologies such as AI [163], smart sensors or robotics [164] to ensure a healthier food future [165,166]. AI technology can always be improved to detect specific causes of disease in fruits and vegetables, helping producers to increase production and profits. Moreover, Society 5.0, which the Japanese government introduced, is also in progress [167].

4.2. Digital Technology

As a digital technology, 3D printing [168,169] has applications in various industries, including food processing. Additionally, 4D [170] printing is applied. There are new challenges involving the use of materials based on plants for 3D food printing by extrusion. With the advancement of 3D printing technology, it might be possible to create custom bio-coatings with precise thickness and uniformity, or even multiple layers of different biopolymers. For example, a 3D printer could be programmed to apply a thin, even layer of chitosan coating onto fresh fruits or vegetables, potentially reducing microbial growth and prolonging shelf life. As mentioned before alginate coatings [45,46] can help to maintain the structural integrity of fruits and vegetables, reducing mechanical damage and water [171]. A 3D printer could be used to apply this coating in a controlled and uniform manner. As in the case of pectin, a complex carbohydrate found in the cell walls of fruits and vegetables [172], a 3D printer could apply a precise layer of bio-coating to the fresh fruits and vegetables. These are only some examples of the bio-based materials that could potentially be used in 3D printed coatings for fresh fruits and vegetables. The exact composition of the coating could be customized based on the specific needs of the produce, including its ripeness level, the environmental conditions it will be stored in, and how long it needs to be preserved.

4.3. Solid Natural Residues Use

Current research studies focus on finding innovative models in the circular economy, including the use of edible coatings in the food processing industry. For this purpose, it is necessary to inform consumers [173] about the advantages of eating food preserved by edible bio-coatings in reducing waste and pollution by optimizing the resources needed and reusing them [174]. There are concerns regarding the processing of solid residues remained after squeezing fruits, vegetables or plants into fibrillated cellulose that can be used to obtain edible bio-coatings for fresh fruits. Luana Amoroso et al. [175] studied the use of waste resulted from squeezing fresh or stale carrots to produce cellulose nanofibers. These nanofibers suspension films sprayed on the surface of bananas led to an important delay in enzymatic browning of the peels, so this research could be considered significant in achieving sustainable food materials.

4.4. Plant Dyes Use

Bio-coatings for preserving fresh fruits and vegetables using plant dyes can also offer potential preservation benefits. Plant dyes, derived from natural sources, can provide color and additional functional properties to bio-coatings [176].

Plant-based dyes that are safe for consumption, derived from sources such as fruits, vegetables, or herbs, can be chosen. Examples include beetroot extract (for red/pink color), turmeric extract (for yellow color), spinach extract (for green color), or purple cabbage extract (for purple color) [177]. A bio-coating formulation would be prepared using a suitable edible matrix, such as starch, pectin, or alginate. The plant dyes would be integrated into the matrix during the formulation process. These would give the produce vibrant colors, enhancing its aesthetic appeal and maybe enhancing consumer preference. Natural antioxidants are present in many plant colors, which can help lower oxidative damage and delay spoiling processes. These antioxidants may extend the shelf life and freshness of the fruits and vegetables. Together with the plant pigments, the bio-coating creates a layer of defence on the surface of the produce that serves as a physical barrier against outside contaminants, moisture loss, and light exposure. By performing so, you can preserve quality and stop microbial growth [178,179]. In addition to controlling gas exchange, the bio-coating made of plant pigments can also control respiration rates and ethylene generation. By doing so, the ripening process can be slowed and the fruits and vegetables' shelf life can be increased [180]. To achieve the expected preservation effects, maximizing both the bio-coating formulation and the amounts and combinations of plant pigments would be necessary. Additionally, it's essential to confirm that the plant dyes used comply with food safety regulations and are safe for consumption [135].

4.5. Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) Technology

Another innovative method to create bio-coating for preserving fresh fruits and vegetables is the use of clustered regularly interspaced short palindromic repeats (CRISPR) technology. Using CRISPR technology, probiotic microorganisms with improved antibacterial capabilities could be created [181]. These could be incorporated into a bio-coating for fresh fruit preservation resistance in crops [182]. Researchers could use CRISPR to precisely edit the genes of a crop plant to enhance its resistance to specific diseases or pathogens. Targeting and modifying key genes associated with disease susceptibility can potentially make the plant more resistant to infections. The edited genes or CRISPR components could be incorporated into a bio-coating formulation. The bio-coating would act as a protective layer applied to the surface of the seeds or plant tissues. The bio-coating would adhere to the seeds or plant surfaces and gradually release the CRISPR components into the plant cells over time. This controlled release would allow for the plant to efficiently uptake of the CRISPR machinery. Once inside the plant cells, the CRISPR components would activate or deactivate specific genes involved in disease resistance. For example, the CRISPR system could target and suppress favourable genes for pathogen invasion or activate genes that enhance the plant's defence mechanisms. By introducing these genetic modifications using CRISPR, the crop plant would potentially exhibit enhanced resistance against specific diseases or pathogens, thereby reducing crop losses and improving overall yield and quality. The specific implementation of CRISPR technology in bio-coatings for disease resistance is still an area of ongoing research [183,184].

4.6. Macrophages Use

Additionally, the application of macrophages such as CRISPR technologies is constantly evolving. Macrophages are immune cells that are typically associated with the immune response and tissue repair in living organisms. Using macrophages for preserving fresh fruits and vegetables is not a commonly explored approach. Their application in food preservation is not well-established, but macrophages cell membrane-based nanoparticles is a new promising platform for novel bio-coatings development [185].

Due to the food industry's significant adverse effects on the environment, adopting more sustainable practices that boost both productivity and sustainability has become necessary. Bio-based edible coatings, which are essential to meeting the demands of the market today, are a prime illustration of this. PolyNatural is an outstanding example of how the food industry is now driven fundamentally differently because of the agricultural sector and new technologies. Given the rising demand for organic products every year, this scale-up is essential to the Agtech industry. In 2021, the value of organic goods sold in the United States alone exceeded USD 9 billion, an increase of 5.5% from the previous year. Additionally, 12% of the nation's overall agricultural product market comprised organic goods, reflecting an increasing trend [186].

Many scale-ups and start-ups are working on non-chemical methods of extending the shelf life of fruits and vegetables. The Global Startup Heat Map indicates that 289 companies are now leading the way in the food industry with their ground-breaking and environmentally friendly solutions. Five scale-ups from this limited group deserve special attention for their natural bio-coating advances. StartUs Insight [187] has helped to make this list of the best innovative firms in natural preservatives and coatings possible. More than 2 million startups and scale-ups worldwide are analysed by this platform using big data and artificial intelligence. We are discussing important developments that will help the fruit export business grow and adopt a sustainable approach to food production, a market where maintaining product shelf life is essential to protect investments and maintain positive bilateral relations.

Chinova Bioworks is developing a natural preservative called Chiber derived from white mushroom fibers [188] Chiber's applications are not limited to fresh fruits and vegetables; it may also be utilized in beverages and dairy products that originate from vegetables, so organically increasing the shelf life of a wider variety of food kinds.

The level of innovation of Mori [189] that has been applied to the company's flagship product, which is a coating for fresh fruits and vegetables produced from silk protein, makes it, without a doubt one of the most appealing scales-ups now available.

Because it prevents microbial development, dehydration, and the oxidation of food, this solution can double the amount of time that fruits and vegetables can be stored at room temperature before going bad.

An Israeli startup company [190] has developed a coating for fresh fruits and vegetables that is entirely comprised of natural ingredients and improve the period they may be preserved without using any chemicals. Since the solution offered by Sufresca is derived from plants and is odourless, colorless, and tasteless, it does not change the flavor of the products, nor does it affect the color of the items when it works to protect them from dehydration and fermentation.

Encapsulation of natural flavors in all natural materials is the product of a Swiss company [191] that just recently started. It is a powder that encapsulates the flavors of food and then releases them once the meal is consumed in an environmentally responsible manner. This is a significant advancement for the food industry since it raises overall product quality, reduces the amount of money spent on processing, and, as a result, enhances the profitability of businesses operating in the area.

With its Shel-Life® solution [192], a food-grade organic coating that increases the shelf life of fruits and vegetables, it is currently one of the top scale-ups. Shel-Life® is a 100% organic coating that stops fruits and vegetables from drying out, preserving their freshness for longer while being kind to the environment. It is built of natural polymers and vegetable lipids. In other words, food that is fresher and of greater quality is obtained, maintaining its integrity, and promoting consumer health. Since PolyNatural's Shel-Life® was implemented in January 2022, it has helped save more than 840 tons of fruit from going to waste. This shows how valuable this solution is for reducing the carbon footprint of food production.

With these innovations in the development and application of edible bio-coatings for fresh fruits and vegetables it is now possible to extend the shelf life these without adding chemicals or petroleum derivatives. This helps the food industry advance onto a more sustainable way of accomplishing issues.

5. Challenges and Limitations of Bio-Coatings for Produce Preservation

Despite their numerous benefits, bio-coatings pose challenges that need to be addressed to ensure their wide adoption. One of the major factors hindering their broad-scale implementation is the cost of manufacturing and raw materials. Compared to conventional coatings, the production and formulation of bio-coatings can be more expensive, thereby limiting their cost-effectiveness. The industry must focus on the development of more cost-efficient production processes and sourcing strategies for bio-coating materials. Another aspect affecting the use of bio-coatings is their availability. The raw materials needed for these coatings may not be readily available in certain regions or countries. This lack of access can serve as a barrier to their widespread use. Strategies need to be developed to ensure that these materials can be sourced or substituted locally to facilitate their use in different parts of the world. If the bio-coatings have a short shelf life, they may not be as effective as other methods in maintaining the freshness of food over extended periods. The efficacy of bio-coatings in maintaining the quality of food may be interdependent on a few elements, including the kind of product, the features of the fruit or vegetables, the storage circumstances, as well as the formulation and surface properties of the coating [31,141,193]. The successful application of bio-coatings also relies heavily on controlling storage conditions, composition of the covering film, and the process of its deposition. When these elements are optimized, food preservation can be significantly enhanced. While commercial applications of bio-coatings are currently limited, ongoing research into integrating multiple naturally occurring components is expected to improve their functionality and suitability [194]. Bio-coatings have the potential to reduce waste, contributing to environmental protection significantly. However, certain criteria must be met to fulfil their intended purpose of enhancing food quality, functionality, and safety over extended periods. These include cost-effectiveness, stability, non-stickiness, the inclusion of functional ingredients, good adhesion, and no impact on sensory properties. They should also control moisture content without affecting the appearance of the fruits and vegetables. They must easily obtained and inexpensive; uniform and stable during production and storage; non-sticky when handling the fruit or vegetable; to contain functional ingredients such as antimicrobial and antioxidant agents; to have good adhesion to surface; to not affect the smell, aroma, taste, and texture of fruit and vegetable; to maintain a desired moisture content by controlling the water migration in the fruit and vegetable; and to not affect the appearance of the fruit and vegetable [195].

Finally, the role of surface characteristics cannot be overlooked in the development and application of bio-coatings. Understanding these characteristics is essential to enhance food preservation and film adhesion. While wetting is necessary for appropriate adhesion, it is not sufficient. The coating should be designed to maximize surface contact with the product for optimal wettability. However, achieving good wettability does not automatically translate into good adhesion, suggesting that other factors also play a role in this process. Further studies are needed to understand and optimize these factors It [196,197].

6. Conclusions

In conclusion, our comprehensive review of the current research shows that bio-coatings present an innovative and environmentally friendly approach to preserving the freshness of fruits and vegetables. These sustainable solutions extend the shelf life of these products and reduce dependency on traditional packaging, which often contributes to environmental pollution. By enhancing food safety, bio-coatings could also play a pivotal role in reducing foodborne diseases, a significant concern worldwide.

While the application of bio-coatings is promising, more research is necessary to understand their long-term impacts and their interaction with different types of food products. Specifically, further research should optimize bio-coating compositions to cater to a wide range of fruits and vegetables with different preservation needs. Additionally, studies should investigate consumer acceptance of bio-coatings, as public perception and acceptance will significantly influence the adoption rate of this technology.

Looking towards the future, we predict a growth in bio-coating technologies integrated with smart and active packaging solutions. These might include indicators for freshness or ripeness, or even release of antimicrobial agents over time. Additionally, the future might see bio-coatings that preserve the fruits and vegetables and enhance their nutritional content. Commercial scalability of these technologies, while maintaining cost-effectiveness, will be crucial for widespread adoption.

The exploration and implementation of bio-coatings are a testament to our continual strive for sustainable solutions in the food industry, reflecting our growing awareness of and responsibility towards our environment. With the ever-present challenge of feeding an increasing global population, bio-coatings stand at the frontier of innovative, sustainable, and effective food preservation methods.

Author Contributions: Conceptualization, C.U. and R.Z.; methodology, C.U. and G.T.; software, C.U.; validation, C.U., R.Z. and G.T.; formal analysis, G.P.; investigation, C.U., R.Z., G.P. and G.T.; resources, C.U.; data curation, R.Z.; writing—original draft preparation, C.U., R.Z., G.P. and G.T.; writing—review and editing, C.U., R.Z., G.P. and G.T.; visualization, C.U.; supervision, C.U.; project administration, C.U.; funding acquisition, C.U. All authors have read and agreed to the published version of the manuscript.

Funding: All authors gratefully acknowledge the support of a grant of the Ministry of Research, Innovation and Digitization, CCCDI–UEFISCDI, Project No. PN-III-P2-2.1-PED-2021-0042, within PNCDI III.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: All authors gratefully acknowledge the support of a grant of the Ministry of Research, Innovation and Digitization, CCCDI–UEFISCDI, project number PN-III-P2-2.1-PED-2021-0042, within PNCDI III.

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

Abbreviations

LOX	Lipoxygenase
PG	Polygalacturonase
Chlase	Chlorophyllase
SO_2	Sulfur dioxide
HPMC	Hydroxypropylmethylcellulose
GLY	Glycerine
G	Gelatine
CHI	Chitosan
SA	Sodium alginate
nano-ZnO	Nano-zinc oxide
M. fructicola	*Monilinia fructicola*
B. cinerea	*Botrytis cinerea*
C. gloeosporioides	*Colletotrichum gloeosporioides*
E. coli	*Escherichia coli*
S. typhimurium	*Salmonella typhimurium*
TU	Turmeric
GT	Green tea
EO	Essential oil
TSO	Tea seed oil
GSE	Grapefruit seed extract
AVG	Aloe vera gel
SPI	Soy protein isolate
GB	Blueberry juice
LEO	Lemon essential oil
°C	Degrees Celsius
h	Hour
min	Minute
GSE	Grapefruit seed extract
AI	Artificial Intelligence
CRISPR	clustered regularly interspaced short palindromic repeats
XG	Xanthan gum
CMC	Carboxymethyl cellulose
ASKG	Artemisia sphaerocephala Krasch

References

1. Sridhar, A.; Ponnuchamy, M.; Kumar, P.S.; Kapoor, A. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: A review. *Environ. Chem. Lett.* **2021**, *19*, 1715–1735. [CrossRef]
2. Devi, M.P.; Bhowmick, N.; Bhanusree, M.R.; Ghosh, S.K. Preparation of Value-Added Products Through Preservation. In *Value Addition of Horticultural Crops: Recent Trends and Future Directions*; Sharangi, A.B., Datta, S., Eds.; Springer India: New Delhi, India, 2015; pp. 13–41.

3. Jaya Shankar, T. Introductory Chapter: Food Processing, Preservation, and Packaging—A Brief Overview. In *Food Processing and Packaging Technologies*; Jaya Shankar, T., Ed.; IntechOpen: Rijeka, Croatia, 2023; Chapter 1.
4. Cocetta, G.; Natalini, A. Ethylene: Management and breeding for postharvest quality in vegetable crops. A review. *Front. Plant Sci.* **2022**, *13*, 968315. [PubMed]
5. Factors Affecting Ripening. Available online: http://eagri.org/eagri50/HORT381/lec04.html (accessed on 14 July 2023).
6. Basic Agricultural Study—A Resource Hub for Young Agriculturists. Available online: https://agriculturistmusa.com/maturity-indices-types-and-determination/?utm_content=cmp-true (accessed on 15 July 2023).
7. Fonseca, S.C.; Oliveira, F.A.R.; Brecht, J.K. Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: A review. *J. Food Eng.* **2002**, *52*, 99–119. [CrossRef]
8. Maduwanthi, S.D.T.; Marapana, R. Induced Ripening Agents and Their Effect on Fruit Quality of Banana. *Int. J. Food Sci.* **2019**, *2019*, 2520179. [CrossRef] [PubMed]
9. Palumbo, M.; Attolico, G.; Capozzi, V.; Cozzolino, R.; Corvino, A.; de Chiara, M.L.V.; Pace, B.; Pelosi, S.; Ricci, I.; Romaniello, R.; et al. Emerging Postharvest Technologies to Enhance the Shelf-Life of Fruit and Vegetables: An Overview. *Foods* **2022**, *11*, 3925. [CrossRef]
10. Lufu, R.; Ambaw, A.; Opara, U.L. Water loss of fresh fruit: Influencing pre-harvest, harvest and postharvest factors. *Sci. Hortic.* **2020**, *272*, 109519. [CrossRef]
11. Strategies to Reduce Post-Harvest Losses for Fruits and Vegetables. Available online: http://www.postharvestproject.com/uploads/outputs/8fa991f1-6260-45e4-95b0-438127a4deb0.pdf (accessed on 14 July 2023).
12. Odetayo, T.; Tesfay, S.; Ngobese, N.Z. Nanotechnology-enhanced edible coating application on climacteric fruits. *Food Sci. Nutr.* **2022**, *10*, 2149–2167. [CrossRef]
13. Samir, A.; Ashour, F.H.; Hakim, A.A.A.; Bassyouni, M. Recent advances in biodegradable polymers for sustainable applications. *NPJ Mater. Degrad.* **2022**, *6*, 68. [CrossRef]
14. Muhammad Sajid, A.; Syeda Ayesha, B. Natural Antimicrobials, their Sources and Food Safety. In *Food Additives*; Desiree Nedra, K., Geethi, P., Eds.; IntechOpen: Rijeka, Croatia, 2017; Chapter 4.
15. Chung, I.; Ryu, H.; Yoon, S.Y.; Ha, J.C. Health effects of sodium hypochlorite: Review of published case reports. *Environ. Anal. Health Toxicol.* **2022**, *37*, e2022006. [CrossRef]
16. Wu, P.H.; Chang, H.X.; Shen, Y.M. Effects of synthetic and environmentally friendly fungicides on powdery mildew management and the phyllosphere microbiome of cucumber. *PLoS ONE* **2023**, *18*, e0282809. [CrossRef]
17. Kori, R.K.; Singh, M.K.; Jain, A.K.; Yadav, R.S. Neurochemical and Behavioral Dysfunctions in Pesticide Exposed Farm Workers: A Clinical Outcome. *Indian J. Clin. Biochem.* **2018**, *33*, 372–381. [CrossRef]
18. Sun, S.H.; Kim, S.J.; Kwak, S.J.; Yoon, K.S. Efficacy of sodium hypochlorite and acidified sodium chlorite in preventing browning and microbial growth on fresh-cut produce. *Prev. Nutr. Food Sci.* **2012**, *17*, 210–216. [CrossRef]
19. Raffo, A.; Paoletti, F. Fresh-Cut Vegetables Processing: Environmental Sustainability and Food Safety Issues in a Comprehensive Perspective. *Front. Sustain. Food Syst.* **2022**, *5*, 681459. [CrossRef]
20. Gadelha, J.R.; Allende, A.; López-Gálvez, F.; Fernández, P.; Gil, M.I.; Egea, J.A. Chemical risks associated with ready-to-eat vegetables: Quantitative analysis to estimate formation and/or accumulation of disinfection byproducts during washing. *EFSA J.* **2019**, *17*, e170913. [PubMed]
21. Perianes-Rodriguez, A.; Waltman, L.; van Eck, N.J. Constructing bibliometric networks: A comparison between full and fractional counting. *J. Informetr.* **2016**, *10*, 1178–1195. [CrossRef]
22. Zabot, G.L.; Schaefer Rodrigues, F.; Polano Ody, L.; Vinícius Tres, M.; Herrera, E.; Palacin, H.; Córdova-Ramos, J.S.; Best, I.; Olivera-Montenegro, L. Encapsulation of Bioactive Compounds for Food and Agricultural Applications. *Polymers* **2022**, *14*, 4194. [CrossRef]
23. Muñoz-Tebar, N.; Pérez-Álvarez, J.A.; Fernández-López, J.; Viuda-Martos, M. Chitosan Edible Films and Coatings with Added Bioactive Compounds: Antibacterial and Antioxidant Properties and Their Application to Food Products: A Review. *Polymers* **2023**, *15*, 396. [CrossRef] [PubMed]
24. Dordevic, S.; Dordevic, D.; Sedlacek, P.; Kalina, M.; Tesikova, K.; Antonic, B.; Tremlova, B.; Treml, J.; Nejezchlebova, M.; Vapenka, L.; et al. Incorporation of Natural Blueberry, Red Grapes and Parsley Extract By-Products into the Production of Chitosan Edible Films. *Polymers* **2021**, *13*, 3388. [CrossRef] [PubMed]
25. Khalifa, I.; Barakat, H.; El-Mansy, H.A.; Soliman, S.A. Enhancing the keeping quality of fresh strawberry using chitosan-incorporated olive processing wastes. *Food Biosci.* **2016**, *13*, 69–75. [CrossRef]
26. Khan, I.; Tango, C.N.; Chelliah, R.; Oh, D.H. Development of antimicrobial edible coating based on modified chitosan for the improvement of strawberries shelf life. *Food Sci. Biotechnol.* **2019**, *28*, 1257–1264. [CrossRef]
27. Zhang, W.; Lin, M.; Feng, X.; Yao, Z.; Wang, T.; Xu, C. Effect of lemon essential oil-enriched coating on the postharvest storage quality of citrus fruits. *Food Sci. Technol.* **2022**, *42*, e125421. [CrossRef]
28. Sun, X.; Narciso, J.; Wang, Z.; Ference, C.; Bai, J.; Zhou, K. Effects of Chitosan-Essential Oil Coatings on Safety and Quality of Fresh Blueberries. *J. Food Sci.* **2014**, *79*, M955–M960. [CrossRef] [PubMed]

29. Zhang, X.; Ismail, B.B.; Cheng, H.; Jin, T.Z.; Qian, M.; Arabi, S.A.; Liu, D.; Guo, M. Emerging chitosan-essential oil films and coatings for food preservation—A review of advances and applications. *Carbohydr. Polym.* **2021**, *273*, 118616. [CrossRef]
30. Maurya, A.; Prasad, J.; Das, S.; Dwivedy, A.K. Essential Oils and Their Application in Food Safety. *Front. in Sustain. Food Syst.* **2021**, *5*, 133. [CrossRef]
31. Pham, T.T.; Nguyen, L.L.P.; Dam, M.S.; Baranyai, L. Application of Edible Coating in Extension of Fruit Shelf Life: Review. *AgriEngineering* **2023**, *5*, 520–536. [CrossRef]
32. Jafarzadeh, S.; Mohammadi Nafchi, A.; Salehabadi, A.; Oladzad-abbasabadi, N.; Jafari, S.M. Application of bio-nanocomposite films and edible coatings for extending the shelf life of fresh fruits and vegetables. *Adv. Colloid Interface Sci.* **2021**, *291*, 102405. [CrossRef]
33. Khan, M.R.; Di Giuseppe, F.A.; Torrieri, E.; Sadiq, M.B. Recent advances in biopolymeric antioxidant films and coatings for preservation of nutritional quality of minimally processed fruits and vegetables. *Food Packag. Shelf Life* **2021**, *30*, 100752. [CrossRef]
34. Versino, F.; Ortega, F.; Monroy, Y.; Rivero, S.; López, O.V.; García, M.A. Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. *Foods* **2023**, *12*, 1057. [CrossRef]
35. Fruit and Vegetable Safety. Available online: https://www.cdc.gov/foodsafety/communication/steps-healthy-fruits-veggies.html (accessed on 4 August 2023).
36. Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards of Fresh-Cut Fruits and Vegetables. Available online: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-guide-minimize-microbial-food-safety-hazards-fresh-cut-fruits-and-vegetables (accessed on 4 August 2023).
37. Commission Notice on Guidance Document on Addressing Microbiological Risks in Fresh Fruits and Vegetables at Primary Production through Good Hygiene. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017XC0523(03)&rid=1 (accessed on 4 August 2023).
38. Shendurse, A.; Gopikrishna, G.; Patel, A.C.; Pandya, A.J. Milk protein based edible films and coatings–preparation, properties and food applications. *J. Nutri. Health Food Eng.* **2018**, *8*, 219–226. [CrossRef]
39. do Evangelho, J.A.; da Silva Dannenberg, G.; Biduski, B.; El Halal, S.L.M.; Kringel, D.H.; Gularte, M.A.; Fiorentini, A.M.; da Rosa Zavareze, E. Antibacterial activity, optical, mechanical, and barrier properties of corn starch films containing orange essential oil. *Carbohydr. Polym.* **2019**, *222*, 114981. [CrossRef]
40. Díaz-Montes, E.; Castro-Muñoz, R. Edible Films and Coatings as Food-Quality Preservers: An Overview. *Foods* **2021**, *10*, 249. [CrossRef]
41. Hmmam, I.; Ali, M.A.-S.; Abdellatif, A. Alginate-Based Zinc Oxide Nanoparticles Coating Extends Storage Life and Maintains Quality Parameters of Mango Fruits “cv. Kiett”. *Coatings* **2023**, *13*, 362.
42. Shiekh, R.A.; Malik, M.A.; Al-Thabaiti, S.A.; Shiekh, M.A. Chitosan as a Novel Edible Coating for Fresh Fruits. *Food Sci. Technol. Res.* **2013**, *19*, 139–155. [CrossRef]
43. Bautista-Baños, S.; Ventura-Aguilar, R.; Correa Pacheco, Z.; Corona-Rangel, M. Chitosan: A versatile antimicrobial polysaccharide for fruit and vegetables in postharvest—A review. *Rev. Chapingo Ser. Hortic.* **2017**, *23*, 103–121. [CrossRef]
44. El-Naggar, N.E.-A.; Saber, W.I.A.; Zweil, A.M.; Bashir, S.I. An innovative green synthesis approach of chitosan nanoparticles and their inhibitory activity against phytopathogenic Botrytis cinerea on strawberry leaves. *Sci. Rep.* **2022**, *12*, 3515. [CrossRef]
45. Resende, N.S.; Gonçalves, G.A.S.; Reis, K.C.; Tonoli, G.H.D.; Boas, E.V.B.V. Chitosan/Cellulose Nanofibril Nanocomposite and Its Effect on Quality of Coated Strawberries. *J. Food Qual.* **2018**, *2018*, 1727426. [CrossRef]
46. Pop, O.L.; Pop, C.R.; Dufrechou, M.; Vodnar, D.C.; Socaci, S.A.; Dulf, F.V.; Minervini, F.; Suharoschi, R. Edible Films and Coatings Functionalization by Probiotic Incorporation: A Review. *Polymers* **2020**, *12*, 12. [CrossRef]
47. Robles-Sánchez, R.M.; Rojas-Graü, M.A.; Odriozola-Serrano, I.; González-Aguilar, G.; Martin-Belloso, O. Influence of alginate-based edible coating as carrier of antibrowning agents on bioactive compounds and antioxidant activity in fresh-cut Kent mangoes. *LWT-Food Sci. Technol.* **2013**, *50*, 240–246. [CrossRef]
48. Keshari, D.; Tripathi, A.D.; Agarwal, A.; Rai, S.; Srivastava, S.K.; Kumar, P. Effect of α-dl tocopherol acetate (antioxidant) enriched edible coating on the physicochemical, functional properties and shelf life of minimally processed carrots (*Daucus carota* subsp. sativus). *Future Foods* **2022**, *5*, 100116. [CrossRef]
49. Najafi Marghmaleki, S.; Mortazavi, S.M.H.; Saei, H.; Mostaan, A. The Effect of Alginate-Based Edible Coating Enriched with Citric Acid and Ascorbic Acid on Texture, Appearance and Eating Quality of Apple Fresh-Cut. *Int. J. Fruit Sci.* **2021**, *21*, 40–51. [CrossRef]
50. López-Córdoba, A.; Aldana-Usme, A. Edible coatings based on sodium alginate and ascorbic acid for application on fresh-cut pineapple (*Ananas comosus* (L.) Merr). *Agron. Colomb.* **2019**, *37*, 317–322. [CrossRef]
51. Guimarães, G.; Dantas, R.; Sousa, A.; Soares, L.; Raylson, D.; Rosana, S.; Lima, R.; Rejane, M.; Beaudry, R.; Silva, S. Impact of cassava starch-alginate based coatings added with ascorbic acid and elicitor on quality and sensory attributes during pineapple storage. *Afr. J. Agric. Res.* **2017**, *12*, 664–673.
52. Cofelice, M.; Lopez, F.; Cuomo, F. Quality Control of Fresh-Cut Apples after Coating Application. *Foods* **2019**, *8*, 189. [CrossRef] [PubMed]
53. Moreira, M.R.; Cassani, L.; Martín-Belloso, O.; Soliva-Fortuny, R. Effects of polysaccharide-based edible coatings enriched with dietary fiber on quality attributes of fresh-cut apples. *J. Food Sci. Technol.* **2015**, *52*, 7795–7805. [CrossRef] [PubMed]

54. Mannozzi, C.; Cecchini, J.P.; Tylewicz, U.; Siroli, L.; Patrignani, F.; Lanciotti, R.; Rocculi, P.; Dalla Rosa, M.; Romani, S. Study on the efficacy of edible coatings on quality of blueberry fruits during shelf-life. *LWT-Food Sci. Technol.* **2017**, *85*, 440–444. [CrossRef]
55. Medina-Jaramillo, C.; Quintero-Pimiento, C.; Díaz-Díaz, D.; Goyanes, S.; López-Córdoba, A. Improvement of Andean Blueberries Postharvest Preservation Using Carvacrol/Alginate-Edible Coatings. *Polymers* **2020**, *12*, 2352. [CrossRef]
56. Chiabrando, V.; Giacalone, G. Quality evaluation of blueberries coated with chitosan and sodium alginate during postharvest storage. *Int. Food Res. J.* **2017**, *24*, 1553–1561.
57. Zhou, Y.; Hu, L.; Chen, Y.; Liao, L.; Li, R.; Wang, H.; Mo, Y.; Lin, L.; Liu, K. The combined effect of ascorbic acid and chitosan coating on postharvest quality and cell wall metabolism of papaya fruits. *LWT* **2022**, *171*, 114134. [CrossRef]
58. Baswal, A.K.; Dhaliwal, H.S.; Singh, Z.; Mahajan, B.V.C.; Kalia, A.; Gill, K.S. Influence of carboxy methylcellulose, chitosan and beeswax coatings on cold storage life and quality of Kinnow mandarin fruit. *Sci. Hortic.* **2020**, *260*, 108887. [CrossRef]
59. Esyanti, R.R.; Zaskia, H.; Amalia, A.; Nugrahapraja, d.H. Chitosan Nanoparticle-Based Coating as Post-harvest Technology in Banana. *J. Phys. Conf. Ser.* **2019**, *1204*, 012109. [CrossRef]
60. Odetayo, T.; Sithole, L.; Shezi, S.; Nomngongo, P.; Tesfay, S.; Ngobese, N.Z. Effect of nanoparticle-enriched coatings on the shelf life of Cavendish bananas. *Sci. Hortic.* **2022**, *304*, 111312. [CrossRef]
61. Castro-Cegrí, A.; Ortega-Muñoz, M.; Sierra, S.; Carvajal, F.; Santoyo-Gonzalez, F.; Garrido, D.; Palma, F. Application of polysaccharide-based edible coatings to improve the quality of zucchini fruit during postharvest cold storage. *Sci. Hortic.* **2023**, *314*, 111941. [CrossRef]
62. Aghazadeh, M.; Karim, R.; Sultan, M.T.; Paykary, M.; Johnson, S.K.; Shekarforoush, E. Comparison of starch films and effect of different rice starch-based coating formulations on physical properties of walnut during storage time at accelerated temperature. *J. Food Process Eng.* **2018**, *41*, e12607. [CrossRef]
63. Ali, A.; Noh, N.M.; Mustafa, M.A. Antimicrobial activity of chitosan enriched with lemongrass oil against anthracnose of bell pepper. *Food Packag. Shelf Life* **2015**, *3*, 56–61. [CrossRef]
64. Basumatary, I.B.; Mukherjee, A.; Katiyar, V.; Dutta, J.; Kumar, S. Chitosan-based active coating for pineapple preservation: Evaluation of antimicrobial efficacy and shelf-life extension. *LWT-Food Sci. Technol.* **2022**, *168*, 113940. [CrossRef]
65. Sultan, M.; Hafez, O.M.; Saleh, M.A.; Youssef, A.M. Smart edible coating films based on chitosan and beeswax–pollen grains for the postharvest preservation of Le Conte pear. *RSC Adv.* **2021**, *11*, 9572–9585. [CrossRef]
66. Miele, N.A.; Volpe, S.; Torrieri, E.; Cavella, S. Improving physical properties of sodium caseinate based coating with the optimal formulation: Effect on strawberries' respiration and transpiration rates. *J. Food Eng.* **2022**, *331*, 111123. [CrossRef]
67. Joshi, P.; Ojha, B.R.; Kafle, A. Effect of Different Postharvest Treatments on Prolonging Shelf life of *Citrus reticulata* Blanco. *Nepal. Hortic.* **2020**, *14*, 1–8. [CrossRef]
68. Yang, H.; Li, X.I.A.; Lu, G. Effect of Carnauba Wax–Based Coating Containing Glycerol Monolaurate on Decay and Quality of Sweet Potato Roots during Storage. *J. Food Prot.* **2018**, *81*, 1643–1650. [CrossRef] [PubMed]
69. Miranda, M.; Ribeiro, M.D.M.M.; Spricigo, P.C.; Pilon, L.; Mitsuyuki, M.C.; Correa, D.S.; Ferreira, M.D. Carnauba wax nanoemulsion applied as an edible coating on fresh tomato for postharvest quality evaluation. *Heliyon* **2022**, *8*, e09803. [CrossRef] [PubMed]
70. Won, M.Y.; Min, S.C. Coating Satsuma mandarin using grapefruit seed extract–incorporated carnauba wax for its preservation. *Food Sci. Biotechnol.* **2018**, *27*, 1649–1658. [CrossRef]
71. Botelho, L.N.S.; Rocha, D.A.; Braga, M.A.; Silva, A.; de Abreu, C.M.P. Quality of guava cv. 'Pedro Sato' treated with cassava starch and cinnamon essential oil. *Sci. Hortic.* **2016**, *209*, 214–220. [CrossRef]
72. Das, D.K.; Dutta, H.; Mahanta, C.L. Development of a rice starch-based coating with antioxidant and microbe-barrier properties and study of its effect on tomatoes stored at room temperature. *LWT-Food Sci. Technol.* **2013**, *50*, 272–278. [CrossRef]
73. Saleem, M.S.; Ejaz, S.; Anjum, M.A.; Nawaz, A.; Naz, S.; Hussain, S.; Ali, S.; Canan, İ. Postharvest application of gum arabic edible coating delays ripening and maintains quality of persimmon fruits during storage. *J. Food Process. Preserv.* **2020**, *44*, e14583. [CrossRef]
74. Tahir, H.E.; Zhihua, L.; Mahunu, G.K.; Xiaobo, Z.; Arslan, M.; Xiaowei, H.; Yang, Z.; Mariod, A.A. Effect of gum arabic edible coating incorporated with African baobab pulp extract on postharvest quality of cold stored blueberries. *Food Sci. Biotechnol.* **2020**, *29*, 217–226. [CrossRef] [PubMed]
75. Esmaeili, A.; Jafari, A.; Ghasemi, A.; Gholamnejad, J. Improving Postharvest Quality of Sweet Cherry Fruit by Using Tragacanth and Eremurus. *Int. J. Fruit Sci.* **2022**, *22*, 370–382. [CrossRef]
76. Ebrahimi, F.; Rastegar, S. Preservation of mango fruit with guar-based edible coatings enriched with *Spirulina platensis* and *Aloe vera* extract during storage at ambient temperature. *Sci. Hortic.* **2020**, *265*, 109258. [CrossRef]
77. Ehtesham Nia, A.; Taghipour, S.; Siahmansour, S. Effects of salicylic acid preharvest and *Aloe vera* gel postharvest treatments on quality maintenance of table grapes during storage. *S. Afr. J. Bot.* **2022**, *147*, 1136–1145. [CrossRef]
78. Feng, Z.; Wu, G.; Liu, C.; Li, D.; Jiang, B.; Zhang, X. Edible coating based on whey protein isolate nanofibrils for antioxidation and inhibition of product browning. *Food Hydrocoll.* **2018**, *79*, 179–188. [CrossRef]
79. Li, T.; Liu, R.; Zhang, C.; Meng, F.; Wang, L. Developing a green film from locust bean gum/carboxycellulose nanocrystal for fruit preservation. *Future Foods* **2021**, *4*, 100072. [CrossRef]

80. Miranda, M.; Gozalbo, A.M.; Sun, X.; Plotto, A.; Bai, J.; de Assis, O.; Ferreira, M.; Baldwin, E. *Effect of Mono and Bilayers of Carnauba Wax Based Nano-Emulsion and HPMC Coatings on Popst-Harvest Quality of 'Redtainung' Papaya*; Simposio Nacional de Instrumentação-Agropecuaria (SIAGRO): São Paulo, Brazil, 2019.
81. Fan, X.; Rong, L.; Li, Y.; Cao, Y.; Kong, L.; Zhu, Z.; Huang, J. Fabrication of bio-based hierarchically structured ethylene scavenger films via electrospraying for fruit preservation. *Food Hydrocoll.* **2022**, *133*, 107837. [CrossRef]
82. Hira, N.; Mitalo, O.W.; Okada, R.; Sangawa, M.; Masuda, K.; Fujita, N.; Ushijima, K.; Akagi, T.; Kubo, Y. The effect of layer-by-layer edible coating on the shelf life and transcriptome of 'Kosui' Japanese pear fruit. *Postharvest Biol. Technol.* **2022**, *185*, 111787. [CrossRef]
83. Gutiérrez-Jara, C.; Bilbao-Sainz, C.; McHugh, T.; Chiou, B.-S.; Williams, T.; Villalobos-Carvajal, R. Effect of Cross-Linked Alginate/Oil Nanoemulsion Coating on Cracking and Quality Parameters of Sweet Cherries. *Foods* **2021**, *10*, 449. [CrossRef]
84. Jurić, S.; Bureš, M.S.; Vlahoviček-Kahlina, K.; Stracenski, K.S.; Fruk, G.; Jalšenjak, N.; Bandić, L.M. Chitosan-based layer-by-layer edible coatings application for the preservation of mandarin fruit bioactive compounds and organic acids. *Food Chem. X* **2023**, *17*, 100575. [CrossRef] [PubMed]
85. Qiu, L.; Zhang, M.; Bhandari, B.; Chitrakar, B.; Chang, L. Investigation of 3D printing of apple and edible rose blends as a dysphagia food. *Food Hydrocoll.* **2023**, *135*, 108184. [CrossRef]
86. Arnon, H.; Zaitsev, Y.; Porat, R.; Poverenov, E. Effects of carboxymethyl cellulose and chitosan bilayer edible coating on postharvest quality of citrus fruit. *Postharvest Biol. Technol.* **2014**, *87*, 21–26. [CrossRef]
87. Sharma, L.; Saini, S.C.; Sharma, K.H. Biocomposite edible coatings based on cross linked-sesame protein and mango puree for the shelf life stability of fresh-cut mango fruit. *J. Food Process Eng.* **2019**, *42*, e12938. [CrossRef]
88. Cakmak, H.; Kumcuoglu, S.; Tavman, S. Electrospray coating of minimally processed strawberries and evaluation of the shelf-life quality properties. *J. Food Process Eng.* **2019**, *42*, e13082. [CrossRef]
89. Emamifar, A.; Bavaisi, S. Nanocomposite coating based on sodium alginate and nano-ZnO for extending the storage life of fresh strawberries (*Fragaria* × *ananassa* Duch.). *J. Food Meas. Charact.* **2020**, *14*, 1012–1024. [CrossRef]
90. Petriccione, M.; Mastrobuoni, F.; Pasquariello, M.S.; Zampella, L.; Nobis, E.; Capriolo, G.; Scortichini, M. Effect of Chitosan Coating on the Postharvest Quality and Antioxidant Enzyme System Response of Strawberry Fruit during Cold Storage. *Foods* **2015**, *4*, 501–523. [CrossRef]
91. Jongsri, P.; Wangsomboondee, T.; Rojsitthisak, P.; Seraypheap, K. Effect of molecular weights of chitosan coating on postharvest quality and physicochemical characteristics of mango fruit. *LWT* **2016**, *73*, 28–36. [CrossRef]
92. Ma, Z.; Yang, L.; Yan, H.; Kennedy, J.F.; Meng, X. Chitosan and oligochitosan enhance the resistance of peach fruit to brown rot. *Carbohydr. Polym.* **2013**, *94*, 272–277. [CrossRef] [PubMed]
93. Chaudhary, S.; Kumar, S.; Kumar, V.; Sharma, R. Chitosan nanoemulsions as advanced edible coatings for fruits and vegetables: Composition, fabrication and developments in last decade. *Int. J. Biol. Macromol.* **2020**, *152*, 154–170. [CrossRef]
94. Hesami, G.; Darvishi, S.; Zarei, M.; Hadidi, M. Fabrication of chitosan nanoparticles incorporated with *Pistacia atlantica* subsp. kurdica hulls' essential oil as a potential antifungal preservative against strawberry grey mould. *Int. J. Food Sci. Technol.* **2021**, *56*, 4215–4223. [CrossRef]
95. Martínez, K.; Ortiz, M.; Albis, A.; Gilma Gutiérrez Castañeda, C.; Valencia, M.E.; Grande Tovar, C.D. The Effect of Edible Chitosan Coatings Incorporated with *Thymus capitatus* Essential Oil on the Shelf-Life of Strawberry (*Fragaria* × *ananassa*) during Cold Storage. *Biomolecules* **2018**, *8*, 155. [CrossRef] [PubMed]
96. Bautista-Baños, S.; Hernández-López, M.; Bosquez-Molina, E.; Wilson, C.L. Effects of chitosan and plant extracts on growth of Colletotrichum gloeosporioides, anthracnose levels and quality of papaya fruit. *Crop Prot.* **2003**, *22*, 1087–1092. [CrossRef]
97. Roy, S.; Zhang, W.; Biswas, D.; Ramakrishnan, R.; Rhim, J.-W. Grapefruit Seed Extract-Added Functional Films and Coating for Active Packaging Applications: A Review. *Molecules* **2023**, *28*, 730. [CrossRef]
98. Tran, V.T.; Kingwascharapong, P.; Tanaka, F.; Tanaka, F. Effect of edible coatings developed from chitosan incorporated with tea seed oil on Japanese pear. *Sci. Hortic.* **2021**, *288*, 110314. [CrossRef]
99. Mohammadi, A.; Hashemi, M.; Hosseini, S.M. The control of Botrytis fruit rot in strawberry using combined treatments of Chitosan with *Zataria multiflora* or *Cinnamomum zeylanicum* essential oil. *J. Food Sci. Technol.* **2015**, *52*, 7441–7448. [CrossRef]
100. Yang, C.; Lu, J.-H.; Xu, M.-T.; Shi, X.-C.; Song, Z.-W.; Chen, T.-M.; Herrera-Balandrano, D.D.; Zhang, Y.-J.; Laborda, P.; Shahriar, M.; et al. Evaluation of chitosan coatings enriched with turmeric and green tea extracts on postharvest preservation of strawberries. *LWT* **2022**, *163*, 113551. [CrossRef]
101. Castelo Branco Melo, N.F.; de MendonçaSoares, B.L.; Marques Diniz, K.; Ferreira Leal, C.; Canto, D.; Flores, M.A.P.; Henrique da Costa Tavares-Filho, J.; Galembeck, A.; Montenegro Stamford, T.L.; Montenegro Stamford-Arnaud, T.; et al. Effects of fungal chitosan nanoparticles as eco-friendly edible coatings on the quality of postharvest table grapes. *Postharvest Biol. Technol.* **2018**, *139*, 56–66. [CrossRef]
102. Nourozi, F.; Sayyari, M. Enrichment of Aloe vera gel with basil seed mucilage preserve bioactive compounds and postharvest quality of apricot fruits. *Sci. Hortic.* **2020**, *262*, 109041. [CrossRef]
103. Pinzon, M.I.; Sanchez, L.T.; Garcia, O.R.; Gutierrez, R.; Luna, J.C.; Villa, C.C. Increasing shelf life of strawberries (*Fragaria* ssp.) by using a banana starch-chitosan-Aloe vera gel composite edible coating. *Int. J. Food Sci. Technol.* **2020**, *55*, 92–98. [CrossRef]

104. Nicolau-Lapeña, I.; Colàs-Medà, P.; Alegre, I.; Aguiló-Aguayo, I.; Muranyi, P.; Viñas, I. Aloe vera gel: An update on its use as a functional edible coating to preserve fruits and vegetables. *Prog. Org. Coat.* **2021**, *151*, 106007. [CrossRef]
105. Alberio, G.R.A.; Muratore, G.; Licciardello, F.; Giardina, G.; Spagna, G. Aloe vera extract as a promising treatment for the quality maintenance of minimally-processed table grapes. *Food Sci. Technol.* **2015**, *35*, 299–306. [CrossRef]
106. Chrysargyris, A.; Nikou, A.; Tzortzakis, N. Effectiveness of Aloe vera gel coating for maintaining tomato fruit quality. *New Zealand J. Crop Hortic. Sci.* **2016**, *44*, 203–217. [CrossRef]
107. Velickova, E.; Winkelhausen, E.; Kuzmanova, S.; Alves, V.D.; Moldão-Martins, M. Impact of chitosan-beeswax edible coatings on the quality of fresh strawberries (*Fragaria ananassa* cv Camarosa) under commercial storage conditions. *LWT-Food Sci. Technol.* **2013**, *52*, 80–92. [CrossRef]
108. Ortega-Toro, R.; Jiménez, A.; Talens, P.; Chiralt, A. Effect of the incorporation of surfactants on the physical properties of corn starch films. *Food Hydrocoll.* **2014**, *38*, 66–75. [CrossRef]
109. Passafiume, R.; Gaglio, R.; Sortino, G.; Farina, V. Effect of Three Different Aloe vera Gel-Based Edible Coatings on the Quality of Fresh-Cut "Hayward" Kiwifruits. *Foods* **2020**, *9*, 939. [CrossRef]
110. Zhang, T.; Yun, Y.; Chu, M.; Bai, X.; Sun, J.; Zhang, Y.; Wang, L. Coating of fruit with an edible soybean protein isolate film doped with hydroxypropyl methyl cellulose for improved preservation. *BioResources* **2022**, *17*, 2563–2575. [CrossRef]
111. Frassinetti, S.; Castagna, A.; Santin, M.; Pozzo, L.; Baratto, I.; Longo, V.; Ranieri, A. Gelatin-based coating enriched with blueberry juice preserves the nutraceutical quality and reduces the microbial contamination of tomato fruit. *Nat. Prod. Res.* **2021**, *35*, 6088–6092. [CrossRef] [PubMed]
112. Poverenov, E.; Rutenberg, R.; Danino, S.; Horev, B.; Rodov, V. Gelatin-Chitosan Composite Films and Edible Coatings to Enhance the Quality of Food Products: Layer-by-Layer vs. Blended Formulations. *Food Bioprocess Technol.* **2014**, *7*, 3319–3327.
113. Liu, T.; Li, J.; Tang, Q.; Qiu, P.; Gou, D.; Zhao, J. Chitosan-Based Materials: An Overview of Potential Applications in Food Packaging. *Foods* **2022**, *11*, 1490. [CrossRef] [PubMed]
114. Pirozzi, A.; Del Grosso, V.; Ferrari, G.; Donsì, F. Edible Coatings Containing Oregano Essential Oil Nanoemulsion for Improving Postharvest Quality and Shelf Life of Tomatoes. *Foods* **2020**, *9*, 1605. [CrossRef]
115. Das, S.K.; Vishakha, K.; Das, S.; Chakraborty, D.; Ganguli, A. Carboxymethyl cellulose and cardamom oil in a nanoemulsion edible coating inhibit the growth of foodborne pathogens and extend the shelf life of tomatoes. *Biocatal. Agric. Biotechnol.* **2022**, *42*, 102369. [CrossRef]
116. Agyei, D.; Pan, S.; Acquah, C.; Danquah, M.K. Chapter 3—Bioactivity Profiling of Peptides From Food Proteins. In *Soft Chemistry and Food Fermentation*; Grumezescu, A.M., Holban, A.M., Eds.; Academic Press: Cambridge, MA, USA, 2017; pp. 49–77.
117. Mendes-Oliveira, G.; Gu, G.; Luo, Y.; Zografos, A.; Minas, I.; Nou, X. Edible and water-soluble corn zein coating impregnated with nisin for Listeria monocytogenes reduction on nectarines and apples. *Postharvest Biol. Technol.* **2022**, *185*, 111811. [CrossRef]
118. Dordevic, D.; Dordevic, S.; Abdullah, F.A.A.; Mader, T.; Medimorec, N.; Tremlova, B.; Kushkevych, I. Edible/Biodegradable Packaging with the Addition of Spent Coffee Grounds Oil. *Foods* **2023**, *12*, 2626. [CrossRef]
119. Rinaudo, M. 2.21—Seaweed Polysaccharides. In *Comprehensive Glycoscience*; Kamerling, H., Ed.; Elsevier: Oxford, MS, USA, 2007; pp. 691–735.
120. Magami, S. Functional can coatings—Part 2: Composition, attributes, applications and performance. *Surf. Coat. Int.* **2015**, *96*, 148–155.
121. Das, S.; Ghosh, A.; Mukherjee, A. Nanoencapsulation-Based Edible Coating of Essential Oils as a Novel Green Strategy against Fungal Spoilage, Mycotoxin Contamination, and Quality Deterioration of Stored Fruits: An Overview. *Front. Microbiol.* **2021**, *12*, 768414. [CrossRef]
122. Al-Tayyar, N.A.; Youssef, A.M.; Al-Hindi, R.R. Edible coatings and antimicrobial nanoemulsions for enhancing shelf life and reducing foodborne pathogens of fruits and vegetables: A review. *Sustain. Mater. Technol.* **2020**, *26*, e00215.
123. Pandey, V.K.; Islam, R.U.; Shams, R.; Dar, A.H. A comprehensive review on the application of essential oils as bioactive compounds in Nano-emulsion based edible coatings of fruits and vegetables. *Appl. Food Res.* **2022**, *2*, 100042. [CrossRef]
124. de Oliveira Filho, J.G.; Miranda, M.; Ferreira, M.D.; Plotto, A. Nanoemulsions as Edible Coatings: A Potential Strategy for Fresh Fruits and Vegetables Preservation. *Foods* **2021**, *10*, 2438. [CrossRef]
125. Tripathi, A.D.; Sharma, R.; Agarwal, A.; Haleem, D.R. Nanoemulsions based edible coatings with potential food applications. *Int. J. Biobased Plast.* **2021**, *3*, 112–125. [CrossRef]
126. Horison, R.; Sulaiman, F.O.; Alfredo, D.; Wardana, A. Physical characteristics of nanoemulsion from chitosan/nutmeg seed oil and evaluation of its coating against microbial growth on strawberry. *Food Res.* **2019**, *3*, 821–827. [CrossRef] [PubMed]
127. Sessa, M.; Ferrari, G.; Donsì, F. Novel Edible Coating Containing Essential Oil Nanoemulsions to Prolong the Shelf Life of Vegetable Products. *Chem. Eng. Trans.* **2015**, *43*, 55–60.
128. Kim, I.-H.; Lee, H.; Kim, J.E.; Song, K.B.; Lee, Y.S.; Chung, D.S.; Min, S.C. Plum Coatings of Lemongrass Oil-incorporating Carnauba Wax-based Nanoemulsion. *J. Food Sci.* **2013**, *78*, E1551–E1559. [CrossRef]
129. Tartaro, G.; Mateos, H.; Schirone, D.; Angelico, R.; Palazzo, G. Microemulsion Microstructure(s): A Tutorial Review. *Nanomaterials* **2020**, *10*, 1657. [CrossRef] [PubMed]
130. Paul, B.K.; Moulik, S.P. Uses and applications of microemulsions. *Curr. Sci.* **2001**, *80*, 990–1001.

131. Xue, J.; Wu, T.; Dai, Y.; Xia, Y. Electrospinning and Electrospun Nanofibers: Methods, Materials, and Applications. *Chem. Rev.* **2019**, *119*, 5298–5415. [CrossRef]
132. Shi, C.; Fang, D.; Huang, C.; Lyu, L.; Wu, W.; Li, W. Electrospun biopolymer material for antimicrobial function of fresh fruit and vegetables: Application perspective and challenges. *LWT* **2023**, *174*, 114374. [CrossRef]
133. Gagaoua, M.; Pinto, V.Z.; Göksen, G.; Alessandroni, L.; Lamri, M.; Dib, A.L.; Boukid, F. Electrospinning as a Promising Process to Preserve the Quality and Safety of Meat and Meat Products. *Coatings* **2022**, *12*, 644. [CrossRef]
134. Melendez-Rodriguez, B.; Castro-Mayorga, J.L.; Reis, M.A.M.; Sammon, C.; Cabedo, L.; Torres-Giner, S.; Lagaron, J.M. Preparation and Characterization of Electrospun Food Biopackaging Films of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) Derived from Fruit Pulp Biowaste. *Front. in Sustain. Food Syst.* **2018**, *2*, 38. [CrossRef]
135. Merino, D.; Quilez-Molina, A.I.; Perotto, G.; Bassani, A.; Spigno, G.; Athanassiou, A. A second life for fruit and vegetable waste: A review on bioplastic films and coatings for potential food protection applications. *Green Chem.* **2022**, *24*, 4703–4727. [CrossRef]
136. Tavares, L.; Souza, H.K.S.; Gonçalves, M.P.; Rocha, C.M.R. Physicochemical and microstructural properties of composite edible film obtained by complex coacervation between chitosan and whey protein isolate. *Food Hydrocoll.* **2021**, *113*, 106471. [CrossRef]
137. Ramos, M.; Mellinas, C.; Solaberrieta, I.; Garrigós, M.C.; Jiménez, A. Emulsions Incorporated in Polysaccharide-Based Active Coatings for Fresh and Minimally Processed Vegetables. *Foods* **2021**, *10*, 665. [CrossRef]
138. Jose, A.; Pareek, S.; Radhakrishnan, E.K. Advances in Edible Fruit Coating Materials. In *Advances in Agri-Food Biotechnology*; Sharma, T.R., Deshmukh, R., Sonah, H., Eds.; Springer Singapore: Singapore, 2020; pp. 391–408.
139. Pirozzi, A.; Ferrari, G.; Donsì, F. The Use of Nanocellulose in Edible Coatings for the Preservation of Perishable Fruits and Vegetables. *Coatings* **2021**, *11*, 990. [CrossRef]
140. Giray Tufan, E.; Akpinar Borazan, A.; Koçkar, Ö.M. A Review on Edible Film and Coating Applications for Fresh and Dried Fruits and Vegetables. *BSEU J. Sci.* **2021**, *8*, 1073–1085. [CrossRef]
141. Moncayo-Martínez, D.; Buitrago, G.; Enciso, N. The surface properties of biopolymer-coated fruit: A review. *Ing. Investig.* **2013**, *33*, 11–16. [CrossRef]
142. Ghosh, M.; Singh, A.K. Potential of engineered nanostructured biopolymer based coatings for perishable fruits with Coronavirus safety perspectives. *Prog. Org. Coat.* **2022**, *163*, 106632. [CrossRef]
143. Shiekh, K.A.; Ngiwngam, K.; Tongdeesoontorn, W. Polysaccharide-Based Active Coatings Incorporated with Bioactive Compounds for Reducing Postharvest Losses of Fresh Fruits. *Coatings* **2022**, *12*, 8. [CrossRef]
144. Senturk Parreidt, T.; Schmid, M.; Müller, K. Effect of Dipping and Vacuum Impregnation Coating Techniques with Alginate Based Coating on Physical Quality Parameters of Cantaloupe Melon. *J. Food Sci.* **2018**, *83*, 929–936. [CrossRef] [PubMed]
145. Dilucia, F.; Lacivita, V.; Conte, A.; Del Nobile, M.A. Sustainable Use of Fruit and Vegetable by-Products to Enhance Food Packaging Performance. *Foods* **2020**, *9*, 857. [CrossRef] [PubMed]
146. Aphirak, P.; Hathaitip, R.; Tri Indrarini, W. Effect of Fruit Size and Processing Time on Vacuum Impregnation Parameters of Cantaloupe and Apple. *CMU J. Nat. Sci.* **2015**, *14*, 125–132.
147. Radziejewska-Kubzdela, E.; Biegańska-Marecik, R.; Kidoń, M. Applicability of Vacuum Impregnation to Modify Physico-Chemical, Sensory and Nutritive Characteristics of Plant Origin Products—A Review. *Int. J. Mol. Sci.* **2014**, *15*, 16577–16610. [CrossRef] [PubMed]
148. Neegam, N.; Gunjan, K.K.; Sawinder, K.; Prasad, R. Recent Developments in Edible Coatings for Fresh Fruits and Vegetables. *J. Hortic. Res.* **2021**, *29*, 127–140.
149. Chawla, R.; Sivakumar, S.; Kaur, H. Antimicrobial edible films in food packaging: Current scenario and recent nanotechnological advancements—A review. *Carbohydr. Polym. Technol. Appl.* **2021**, *2*, 100024.
150. Abdullah; Cai, J.; Hafeez, M.A.; Wang, Q.; Farooq, S.; Huang, Q.; Tian, W.; Xiao, J. Biopolymer-based functional films for packaging applications: A review. *Front. Nutr.* **2022**, *9*, 1000116. [CrossRef]
151. Moeini, A.; Pedram, P.; Fattahi, E.; Cerruti, P.; Santagata, G. Edible Polymers and Secondary Bioactive Compounds for Food Packaging Applications: Antimicrobial, Mechanical, and Gas Barrier Properties. *Polymers* **2022**, *14*, 2395. [CrossRef]
152. Rossi-Márquez, G.; Dávalos-Saucedo, C.A.; Mayek-Pérez, N.; Di Pierro, P. Multilayered Edible Coatings to Enhance Some Quality Attributes of Ready-to-Eat Cherimoya (*Annona cherimola*). *Coatings* **2023**, *13*, 41. [CrossRef]
153. Arnon-Rips, H.; Poverenov, E. Improving food products' quality and storability by using Layer by Layer edible coatings. *Trends Food Sci. Technol.* **2018**, *75*, 81–92. [CrossRef]
154. Andriani, V.; Abyor Handayani, N. Recent technology of edible coating production: A review. *Mater. Today Proc.* **2023**, *in press*. [CrossRef]
155. Tihan, G.T.; Zgarian, R.G.; Berteanu, E.; Ionita, D.; Totea, G.; Iordachel, C.; Tatia, R.; Prodana, M.; Demetrescu, I. Alkaline Phosphatase Immobilization on New Chitosan Membranes with Mg^{2+} for Biomedical Applications. *Mar. Drugs* **2018**, *16*, 287. [CrossRef] [PubMed]
156. Cheng, Y.; Fu, Y.; Ma, L.; Yap, P.L.; Losic, D.; Wang, H.; Zhang, Y. Rheology of edible food inks from 2D/3D/4D printing, and its role in future 5D/6D printing. *Food Hydrocoll.* **2022**, *132*, 107855. [CrossRef]
157. Almeyda, E.; Ipanaqué, W. Recent developments of artificial intelligence for banana: Application areas, learning algorithms, and future challenges. *Eng. Agrícola* **2022**, *42*, e20210144. [CrossRef]

158. Chen, J.; Zhang, M.; Xu, B.; Sun, J.; Mujumdar, A.S. Artificial intelligence assisted technologies for controlling the drying of fruits and vegetables using physical fields: A review. *Trends Food Sci. Technol.* **2020**, *105*, 251–260. [CrossRef]
159. Przybył, K.; Koszela, K. Applications MLP and Other Methods in Artificial Intelligence of Fruit and Vegetable in Convective and Spray Drying. *Appl. Sci.* **2023**, *13*, 2965. [CrossRef]
160. No Bad Apples: Artificial Intelligence Checks Fruit Inside and Out. Available online: https://nocamels.com/2022/09/ai-checks-produce-inside-and-out/ (accessed on 15 July 2023).
161. Moving Food Processing to Industry 4.0 and Beyond. Available online: https://www.ift.org/news-and-publications/food-technology-magazine/issues/2021/july/columns/processing-food-processing-industry (accessed on 15 July 2023).
162. Borangiu, T.; Răileanu, S.; Anton, F.; Iacob, I.; Anton, S. A Systems Engineering-Oriented Learning Factory for Industry 4.0. In *Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future*; Borangiu, T., Trentesaux, D., Leitão, P., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 233–253.
163. AI-Based Design Method Synthesizes Polymers That Mimic Blood Plasma. Available online: https://www.news-medical.net/news/20230320/AI-based-design-method-synthesizes-polymers-that-mimic-blood-plasma.aspx (accessed on 15 July 2023).
164. Wang, Z.; Xun, Y.; Wang, Y.; Yang, Q. Review of smart robots for fruit and vegetable picking in agriculture. *Int. J. Agric. Biol. Eng.* **2022**, *15*, 33–54.
165. Režek Jambrak, A.; Nutrizio, M.; Djekić, I.; Pleslić, S.; Chemat, F. Internet of Nonthermal Food Processing Technologies (IoNTP): Food Industry 4.0 and Sustainability. *Appl. Sci.* **2021**, *11*, 686. [CrossRef]
166. Hassoun, A.; Prieto, M.A.; Carpena, M.; Bouzembrak, Y.; Marvin, H.J.P.; Pallarés, N.; Barba, F.J.; Punia Bangar, S.; Chaudhary, V.; Ibrahim, S.; et al. Exploring the role of green and Industry 4.0 technologies in achieving sustainable development goals in food sectors. *Food Res. Int.* **2022**, *162*, 112068. [CrossRef]
167. Mavrodieva, A.V.; Shaw, R. Disaster and Climate Change Issues in Japan's Society 5.0—A Discussion. *Sustainability* **2020**, *12*, 1893. [CrossRef]
168. Wang, M.; Li, D.; Zang, Z.; Sun, X.; Tan, H.; Si, X.; Tian, J.; Teng, W.; Wang, J.; Liang, Q.; et al. 3D food printing: Applications of plant-based materials in extrusion-based food printing. *Crit. Rev. Food Sci. Nutr.* **2022**, *62*, 7184–7198. [CrossRef] [PubMed]
169. Diañez, I.; Martínez, I.; Franco, J.M.; Brito-de la Fuente, E.; Gallegos, C. Advances in 3D printing of food and nutritional products. *Adv. Food Nutr. Res.* **2022**, *100*, 173–210. [PubMed]
170. Waghmare, R.; Suryawanshi, D.; Karadbhajne, S. Designing 3D printable food based on fruit and vegetable products—Opportunities and challenges. *J. Food Sci. Technol.* **2023**, *60*, 1447–1460. [CrossRef] [PubMed]
171. Duong, N.T.C.; Uthairatanakij, A.; Laohakunjit, N.; Jitareerat, P.; Kaisangsri, N. An innovative single step of cross-linked alginate-based edible coating for maintaining postharvest quality and reducing chilling injury in rose apple cv. 'Tabtimchan' (*Syzygium samarangenese*). *Sci. Hortic.* **2022**, *292*, 110648. [CrossRef]
172. Moalemiyan, M.; Ramaswamy, H.S.; Maftoonazad, N. Pectin-based edible coating for shelf-life extension of ataulfo mango. *J. Food Process Eng.* **2012**, *35*, 572–600. [CrossRef]
173. European Consumers Positive about Plant-Based Coating on Fruit and Vegetables When Its Purpose is Explained. Available online: https://www.wur.nl/en/research-institutes/food-biobased-research/show-fbr/european-consumers-positive-about-plant-based-coating-on-fruit-and-vegetables-when-its-purpose-is-explained.htm (accessed on 15 July 2023).
174. Pashova, S.; Radev, R.; Dimitrov, G.; Ivanov, Y. Edible coatings in food industry related to circular economy. *Qual. Access Success.* **2018**, *19*, 111–117.
175. Amoroso, L.; De France, K.J.; Milz, C.I.; Siqueira, G.; Zimmermann, T.; Nyström, G. Sustainable Cellulose Nanofiber Films from Carrot Pomace as Sprayable Coatings for Food Packaging Applications. *ACS Sustain. Chem. Eng.* **2022**, *10*, 342–352. [CrossRef]
176. Silva, M.M.; Reboredo, F.H.; Lidon, F.C. Food Colour Additives: A Synoptical Overview on Their Chemical Properties, Applications in Food Products, and Health Side Effects. *Foods* **2022**, *11*, 379. [CrossRef]
177. Novais, C.; Molina, A.K.; Abreu, R.M.V.; Santo-Buelga, C.; Ferreira, I.C.F.R.; Pereira, C.; Barros, L. Natural Food Colorants and Preservatives: A Review, a Demand, and a Challenge. *J. Agric. Food Chem.* **2022**, *70*, 2789–2805. [CrossRef]
178. Martins, V.; Santos, L.; Romani, V.; Fernandes, S. Bio-based Sensing: Role of Natural Dyes in Food Freshness Indicators. In *Bio-and Nano-Sensing Technologies for Food Processing and Packaging*; Royal Society of Chemistry: London, UK, 2023; Chapter 3; pp. 37–62.
179. Mondal, K.; Bhattacharjee, S.K.; Mudenur, C.; Ghosh, T.; Goud, V.V.; Katiyar, V. Development of antioxidant-rich edible active films and coatings incorporated with de-oiled ethanolic green algae extract: A candidate for prolonging the shelf life of fresh produce. *RSC Adv.* **2022**, *12*, 13295–13313. [CrossRef]
180. Saleem, M.S.; Ejaz, S.; Anjum, M.A.; Ali, S.; Hussain, S.; Ercisli, S.; Ilhan, G.; Marc, R.A.; Skrovankova, S.; Mlcek, J. Improvement of Postharvest Quality and Bioactive Compounds Content of Persimmon Fruits after Hydrocolloid-Based Edible Coating Application. *Horticulturae* **2022**, *8*, 1045. [CrossRef]
181. de Oliveira KÁ, R.; Fernandes, K.F.D.; de Souza, E.L. Current Advances on the Development and Application of Probiotic-Loaded Edible Films and Coatings for the Bioprotection of Fresh and Minimally Processed Fruit and Vegetables. *Foods* **2021**, *10*, 2207. [CrossRef] [PubMed]
182. Liu, Q.; Yang, F.; Zhang, J.; Liu, H.; Rahman, S.; Islam, S.; Ma, W.; She, M. Application of CRISPR/Cas9 in Crop Quality Improvement. *Int. J. Mol. Sci.* **2021**, *22*, 4206. [CrossRef] [PubMed]

183. Xu, Y.; Li, Z. CRISPR-Cas systems: Overview, innovations and applications in human disease research and gene therapy. *Comput. Struct. Biotechnol. J.* **2020**, *18*, 2401–2415. [CrossRef] [PubMed]
184. Schenke, D.; Cai, D. Applications of CRISPR/Cas to Improve Crop Disease Resistance: Beyond Inactivation of Susceptibility Factors. *iScience* **2020**, *23*, 101478. [CrossRef]
185. Wu, Y.; Wan, S.; Yang, S.; Hu, H.; Zhang, C.; Lai, J.; Zhou, J.; Chen, W.; Tang, X.; Luo, J.; et al. Macrophage cell membrane-based nanoparticles: A new promising biomimetic platform for targeted delivery and treatment. *J. Nanobiotechnol.* **2022**, *20*, 542. [CrossRef] [PubMed]
186. Bio-Based Edible Coatings: 5 Startups & Scaleups. Available online: https://polynatural.com/2022/04/28/bio-based-edible-coatings-5-startups-scaleups/ (accessed on 16 May 2023).
187. Discover 5 Top Startups Developing Innovative Food Preservatives. Available online: https://www.startus-insights.com/innovators-guide/discover-5-top-startups-developing-innovative-food-preservatives/ (accessed on 16 May 2023).
188. Chiber™ for Food & Beverage. Available online: https://www.chinovabioworks.com/products-folder (accessed on 16 May 2023).
189. More Food. Less Waste. Available online: https://www.mori.com/company/ (accessed on 16 May 2023).
190. Sufresca. Available online: https://www.sufresca.com/#technology (accessed on 16 May 2023).
191. microPow. Available online: https://www.micropow.ch/ (accessed on 16 May 2023).
192. PolyNatural. Available online: https://polynatural.com/#about-us (accessed on 16 May 2023).
193. Palou, L.; Valencia-Chamorro, S.A.; Pérez-Gago, M.B. Antifungal Edible Coatings for Fresh Citrus Fruit: A Review. *Coatings* **2015**, *5*, 962–986. [CrossRef]
194. Sortino, G.; Allegra, A.; Gallotta, A.; Saletta, F.; Passafiume, R.; Gaglio, R.; Inglese, P.; Farina, V. Effects of combinational use of controlled atmosphere, cold storage and edible coating applications on shelf life and quality attributes of fresh-cut persimmon fruit. *Chem. Biol. Technol. Agric.* **2022**, *9*, 60. [CrossRef]
195. Aayush, K.; McClements, D.J.; Sharma, S.; Sharma, R.; Singh, G.P.; Sharma, K.; Oberoi, K. Innovations in the development and application of edible coatings for fresh and minimally processed Apple. *Food Control* **2022**, *141*, 109188. [CrossRef]
196. Sapper, M.; Chiralt, A. Starch-Based Coatings for Preservation of Fruits and Vegetables. *Coatings* **2018**, *8*, 152. [CrossRef]
197. Versino, F.; Lopez, O.V.; Garcia, M.A.; Zaritzky, N.E. Starch-based films and food coatings: An overview. *Starch/Stärke* **2016**, *68*, 1026–1037. [CrossRef]