# Bio-Coatings Methods for Fruits and Vegetables Preservation

Subjects: Chemistry, Applied

Contributor: Camelia Ungureanu , Grațiela Tihan , Roxana Zgârian , Georgica Pandelea (Voicu)

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. 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. 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.

food safety bio-coatings

## 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, people 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.

## 2. 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 [21].

### 2.1. Methods to Prepare the Bio-Coatings

#### 2.1.1. 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 [22][23]. 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 [24].

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 [25]. 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 [26][27]. 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. [28] 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 [29], 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.

### 2.1.2. 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 [30]. 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 [31].

### 2.1.3. 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 [32]. 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 [33][34]. 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 [35].

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

### 2.1.4. 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 [36].

### 2.1.5. 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 [37].

### 2.1.6. 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 [38].

## 2.2. Methods of Coating Application in Fresh Fruits and Vegetables

Some standard methods for applying bio-coatings (**Figure 1**) to fresh fruits and vegetables are presented below:

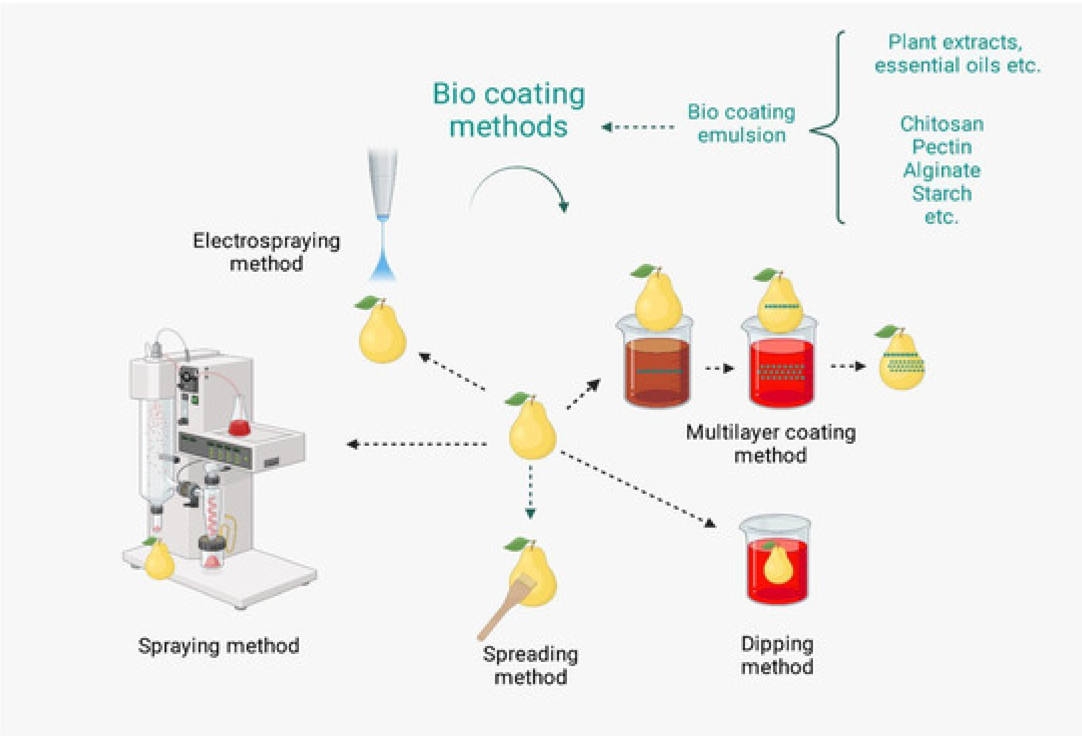


**Figure 1.** Examples of some bio-coating methods for fresh fruits and vegetables (the graphical representation was made using the BioRender program by the Toronto-based BioRender Corporation).

### 2.2.1. 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 [39]. 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 [40]. Adding antimicrobial and/or antioxidants extract to the biopolymer solution can help extend the shelf life of the coated fruit and/or vegetable [41].

### 2.2.2. 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 [42]. 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 [43]. 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 [44].

### 2.2.3. 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 [45]. The coating material is applied to the surface of the fruits and/or vegetables using a brush.

### 2.2.4. Vacuum Infusion

Vacuum infusion is used for the fresh fruits and vegetables with a porous structure, such as melons or cucumbers [46]. The biopolymer solution is introduced into the vacuum chamber, where it is absorbed into the pores of the fruits and vegetables [47] 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 [48]. The vacuum infusion is not suitable for fruits or vegetables with delicate structures, as they may be damaged during the vacuum process [49].

### 2.2.5. 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 [50]. 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 [43][50]. Solution casting has the benefit of being an easy, inexpensive process that is simple to scale up for commercial production [51]. Additionally, depending on the application technique, the coating's thickness and uniformity could vary, which may impact the coating's effectiveness [52]. 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 [53].

### 2.2.6. 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 [54]. 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 [55]. 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 [56].

### 2.2.7. 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 [57]. 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 [58].

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.

### 2.2.8. 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 [59]. 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) [60].

## 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.
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.
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.
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.

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.
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.
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.
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.
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.
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.
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.
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.
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.
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.
21. Magami, S. Functional can coatings—Part 2: Composition, attributes, applications and performance. Surf. Coat. Int. 2015, 96, 148–155.

22. 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.
23. 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.
24. 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.
25. 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.
26. 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.
27. 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.
28. 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.
29. 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.
30. Tartaro, G.; Mateos, H.; Schirone, D.; Angelico, R.; Palazzo, G. Microemulsion Microstructure(s): A Tutorial Review. Nanomaterials 2020, 10, 1657.
31. Paul, B.K.; Moulik, S.P. Uses and applications of microemulsions. Curr. Sci. 2001, 80, 990–1001.
32. Xue, J.; Wu, T.; Dai, Y.; Xia, Y. Electrospinning and Electrospun Nanofibers: Methods, Materials, and Applications. Chem. Rev. 2019, 119, 5298–5415.
33. 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.
34. 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.
35. 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.

36. 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.
37. 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.
38. 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.
39. 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.
40. 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.
41. 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.
42. 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.
43. Moncayo-Martínez, D.; Buitrago, G.; Enciso, N. The surface properties of biopolymer-coated fruit: A review. Ing. Investig. 2013, 33, 11–16.
44. 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.
45. 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.
46. 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.
47. 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.
48. 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.

49. 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.
50. 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.
51. 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.
52. 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.
53. 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.
54. 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.
55. 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.
56. Andriani, V.; Abyor Handayani, N. Recent technology of edible coating production: A review. Mater. Today Proc. 2023, in press.
57. 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.
58. 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 Mg2+ for Biomedical Applications. Mar. Drugs 2018, 16, 287.
59. 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.
60. 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.