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Technological Advancements in Edible Coatings: Emerging Trends and Applications in Sustainable Food Preservation

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Abstract:	This comprehensive review delves into the vital role of edible coatings in extending the shelf life of agricultural and finished food products while advancing sustainability. Such biodegradable, eco-conscious materials stand as a sustainable alternative to traditional food preservation techniques. This paper navigates through the facets of edible coatings, highlighting their origins from green sources and their evolution concerning conventional preservation, the nuanced process of their crafting, and their technological innovations. Additionally, the advantages of natural additives and nanotechnology implementation in enhancing the effectiveness of edible coatings are illustrated and discussed. A thorough exploration of their multiple applications across various foods is provided, with a peculiar focus on their multifaceted advantages. Subsequently, the commercial viability of edible coatings is addressed by detailing their current market presence, challenges in scalability, and primary determinants for their market entry. The regulatory landscape of edible coatings is critically assessed shedding light on the current scenario and potential roadblocks. At last, a brief discussion on the prospects of edible coatings in sustainable food preservation is alleged, spotlighting upcoming advancements. The overarching theme of the review emphasizes the transformative potential of edible coatings, thereby suggesting their capability to significantly influence the food sector's sustainable trajectory.
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Cover Letter

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Dear Editor,

Thank you once again for the opportunity to publish our work (***Technological Advancements in Edible Coatings: Emerging Trends and Applications in Sustainable Food Preservation - FBIO-D-24-00328R1***) in *Food Bioscience*. We have outlined all of the necessary changes regarding the format issues, using the 'track changes' feature. Hopefully, the manuscript is now acceptable for publication.

Wishing you all the best,

Dr. Slaven Jurić

Slaven Jurić

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Format issues based on R1:

Comment: (1) Line 126, 128, 130, etc.: The citation format in the main text does not meet the requirements of the journal. Please read the Guide for Authors online for references.

Response: We have checked and corrected the citation format ("&" was replaced with "and") in the main text as per the Guide.

Comment: (2) Line 1349, 1722, 1807, etc.: Genus and species should be expressed in italics.

Response: Line 1349 (new line 1079) "Shahri Balangu" is a vernacular name in Iran for the plant *Lallemantia iberica* (M.Bieb.) Fisch. & C.A.Mey. and thus should not be italicized. We also left capitalized "Argentinian" (old line 1722, new line 1456), "Iranian" etc. as adjectives derived from proper nouns are usually capitalized when they refer to the nationality of something. Additionally, we have checked and italicized all Genus and species. Please see the changes in the new manuscript.

Comment: (3) Line 1855: The citation format of journal pages in the references does not meet the requirements of the journal. Please read the Guide for Authors online for references.

Response: We apologize for this omission. A journal page was added.

Additional corrections were made for a few references (mainly books) as per the Guide, please see the changes in the manuscript marked with "track changes". Minor changes were made to tables since some of the references were not in the same font. This is now unified throughout the manuscript.

Highlights

Natural edible coatings are a sustainable solution to extend food shelf life.

Composite edible coatings offer superior performance.

Natural additives in coatings improve food quality, safety, and storage.

Nanotechnology has huge potential in formulating edible coatings.

Facing feasibility challenges, edible coatings progress with tech and sustainability.

Declaration

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Technological Advancements in Edible Coatings: Emerging Trends and Applications in Sustainable Food Preservation

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Abstract

This comprehensive review delves into the vital role of edible coatings in extending the shelf life of agricultural and finished food products while advancing sustainability. Such biodegradable, eco-conscious materials stand as a sustainable alternative to traditional food preservation techniques. This paper navigates through the facets of edible coatings, highlighting their origins from green sources and their evolution concerning conventional preservation, the nuanced process of their crafting, and their technological innovations. Additionally, the advantages of natural additives and nanotechnology implementation in enhancing the effectiveness of edible coatings are illustrated and discussed. A thorough exploration of their multiple applications across various foods is provided, with a peculiar focus on their multifaceted advantages. Subsequently, the commercial viability of edible coatings is addressed by detailing their current market presence, challenges in scalability, and primary determinants for their market entry. The regulatory landscape of edible coatings is critically assessed shedding light on the current scenario and potential roadblocks. At last, a brief discussion on the prospects of edible coatings in sustainable food preservation is alleged, spotlighting upcoming advancements. The overarching theme of the review emphasizes the transformative potential of edible coatings, thereby suggesting their capability to significantly influence the food sector's sustainable trajectory.

Keywords: Edible coatings, food packaging, food preservation, food quality, natural biopolymers, sustainable technologies.

1. Introduction

The burgeoning global population, coupled with the rising demand for fresh, nutritious, and safe food, has made food preservation an area of paramount importance. Considering the escalating global challenges associated with ensuring food security and sustainability, the development of advanced food preservation technologies has become a critical focus within the food industry (Wang et al., 2021). As efforts to mitigate the impact of traditional preservation methods on nutritional content, safety, and environmental health intensify, the limitations of existing approaches, particularly those reliant on non-biodegradable materials like plastics, have come under scrutiny (Moshood et al., 2022).

The widespread use of plastics in food packaging, despite its role in extending shelf life through barrier protection, raises significant environmental concerns due to its contribution to global plastic pollution and its long-term ecological footprint (Boone et al., 2023). This pressing environmental issue, compounded by the consumer demand for safer and more sustainable alternatives (McClements, 2020), urges a shift towards innovative preservation techniques that not only address these pain points but also align with the principles of environmental management and resource conservation (Ncube et al., 2020).

Edible coatings emerge as a direct response to this need, offering a viable, eco-friendly solution that promises to redefine the standards of food preservation (Nunes et al., 2023). Among the array of food preservation methods available, the application of edible coatings has recently gained considerable attention due to their significant potential to extend the shelf life of agricultural and finished food products (Priya et al., 2023). Beyond their utility, the relevance of edible coatings lies in their inherent alignment with the concept of sustainability, which is increasingly critically considered in modern food industry practices (Armghan Khalid et al., 2022; Soares et al., 2021). This transition highlights the industry's commitment to adopting practices that prioritize both the longevity and sustainability of food products, paving the way for a detailed examination of edible coatings as a groundbreaking advancement in the field.

Edible coating, a thin layer of edible material applied to food products forms a barrier to moisture, oxygen, and solute movement, delaying spoilage phenomena and extending product shelf life. Their composition, based predominantly on natural compounds (*i.e.*, proteins, lipids, and polysaccharides), as well as on composite materials, boosts their green credentials. By minimizing the utilization of non-renewable resources and reducing waste, edible coatings can significantly contribute to the environmental sustainability of the food industry (Guimarães et al., 2018; Miteluț et al., 2021).

The purpose of this review is to provide an updated and comprehensive exploration of edible coatings from different points of view, focusing on natural-based materials, preparation methods, the role of natural additives in enhancing their potential, and their multifaceted sustainable applications in the food sector. It further aims to analyze the selling viability of edible coatings, shedding light on their current market presence, scalability, and the key drivers and barriers that influence their commercialization. Furthermore, it critically examines the regulatory aspects dominating edible coatings, addressing its implications for the future of this promising sustainable preservation technique that could revolutionize the food industry.

2. A general overview of edible coatings

2.1. Definition of edible coatings

Edible coatings are typically characterized as thin layers composed of either chemical or biological substances that are applied to the surface of a product. Their primary function is to inhibit gaseous exchange, thereby slowing down the ripening process, enhancing product quality, and prolonging shelf life. These coatings establish a semi-permeable barrier between the food product and the external environment, mitigating moisture, gas, and solute movement, which in turn delays spoilage and maintains freshness (Miteluț et al., 2021).

Baldwin et al. (2011) reported a similar definition, describing edible coatings as thin, consumable layers that can be applied to the surface of a fruit, thereby creating a barrier between the fruit and its surrounding environment. Jongsri et al. further emphasize the role of edible coatings in providing a partial barrier to water movement (Jongsri et al., 2016). This feature reduces moisture loss and simultaneously modifies the atmosphere around the fruit by acting as a barrier to gas exchange (Miteluț et al., 2021).

Additional explanations define an edible film or coating as a material thinner than 0.3 mm, according to Díaz-Montes and Castro-Muñoz (2021), which is created from a mixture of biopolymers and various additives distributed in a water-based medium (Morales-Jiménez et al., 2020). Some researchers use the terms edible film and coating interchangeably, while others believe there is a distinction, contingent on the methods of application to the food product. Edible coatings are directly formed on the food item, while edible films are initially produced and subsequently attached to the product (Guimarães et al., 2018). Anyhow, in both instances, they result in firm matrices exhibiting comparable characteristics (Tavassoli-Kafrani et al., 2016).

Edible coatings are primarily composed of natural materials, rendering them safe for consumption and presenting a sustainable alternative for food preservation. The primary constituents of edible coatings and films are lipids, polysaccharides, and proteins. Nonetheless, additional materials such as resins, solvents, and plasticizers are also incorporated to confer special characteristics to edible coatings. In particular, plasticizers contribute to the flexibility of the coatings, solvents enhance tensile strength, whereas resins help prevent water vapor permeability (Galus, 2019; Ulusoy et al., 2018).

2.2. Rise and fall of edible coatings

The practice of applying edible coatings to food is not a modern invention since it has deep historical roots. There is evidence that as far back as ancient civilizations, Egyptians used citrus wax, a natural form of coating, to prevent the dehydration of fruits. Edible coatings are among the innovative modified atmosphere techniques that have demonstrated effectiveness in maintaining the freshness of fruits (Guimarães et al., 2018). Historical accounts indicate that the strategy of altering atmospheres to preserve fruits has been around since antiquity in places like China and Greece where fruits were stored in clay pots along with fresh leaves and grass. This unique atmosphere slowed down the ripening process by adjusting the internal gas composition and reducing the metabolic activity of the fruits, causing delayed maturation and limiting microbial growth.

In addition, the early utilization of edible coating can be traced to sausage production, where meat was preserved by packing it in animal intestines. This method was pioneered by the Sumerians in Mesopotamia around 3000 B.C., and by the Chinese around 580 B.C. (Mkandawire ~~&~~ and Aryee, 2018). During the 15th century in Japan, a specific form of an edible thin film made from the surface of boiled soy milk was used to wrap various food items (Pavlath ~~&~~ and Orts, 2009). Moreover, during the 16th century, both China and Europe used animal fat (lard) and wax as coatings for fruits and other edibles, aiding in preservation for future consumption (Teixeira-Costa ~~&~~ and Andrade, 2021).

In the 19th century, a gelatin-based coating was patented in the USA and applied to meat products (Pavlath ~~&~~ and Orts, 2009). However, the advent of synthetic plastics after the Second World War overshadowed the use of edible resources for packaging until recent times. The synthesis and advancement of various plastic materials for food packaging rapidly expanded in the 1950s, which significantly shaped the landscape of the 21st-century plastic industry. In our everyday life, one may easily notice the ubiquity of plastic. In the food industry, this growth was particularly remarkable as these materials have enhanced food preservation and lengthened the storage duration of numerous products. Numerous factors, such as cost-effectiveness, solvent resistance, processability, flexibility, lightweight, and the ability to be molded into diverse sizes and shapes, have supported the extensive adoption of plastics in food packaging (Verma et al., 2021). In the 1960s, over a quarter of bread sales involved packaging in low-density polyethylene bags (Risch, 2009). From 1950 to 2015, the total production of plastics was estimated to be over 7.5 billion metric tons and rose to 360 million tons in 2018 alone (Kamdem et al., 2019). Noteworthy, about 40% of petroleum-based plastics are employed for packaging, with almost 60% of plastic packaging being used to package food and drinks (Groh et al., 2019).

However, it is encouraging that major food and packaging companies have recently pledged to reduce plastic waste and incorporate a circular economy approach (Teixeira-Costa ~~&~~ and Andrade, 2021). Moreover, it is only in the past few decades that edible coatings have been scientifically explored, optimized, and commercialized. This has been primarily driven by increasing consumer demand for natural, safe, and sustainable food preservation methods.

The shift from traditional, natural preservation methods to synthetic plastics and the recent resurgence of interest in edible coatings highlight an ongoing struggle to balance convenience, preservation efficacy, and sustainability in food packaging. While plastic cling film offers undeniable benefits in terms of food preservation and economic efficiency, its environmental drawbacks are significant. Edible coatings, with their historical roots and modern scientific advancements, present a promising alternative that aligns more closely with sustainable practices, emphasizing the need for continued innovation and adoption of environmentally friendly packaging solutions.

2.3. Contemporary state of edible coatings technology

The current state of edible coatings technology is rapidly evolving, with recent advancements in both the materials used and the methods of application. Research has facilitated the development of a wide variety of edible coatings, designed to cater to specific food types and preservation needs. From simple solutions like beeswax or plant-derived waxes to complex formulations involving natural polymers, including polysaccharides, proteins, lipids, and composite materials, the diversity of edible coatings is vast. Furthermore, these coatings can be combined with other ingredients to enhance their stability and functionality. Advancements in nanotechnology and the incorporation of active ingredients have also expanded the possibilities of what edible coatings can achieve, from improved barrier properties to the incorporation of antimicrobial, antioxidant, or other beneficial additives (Odetayo et al., 2022). With a recent focus on enhancing food preservation by incorporating active compounds such as antimicrobials and antioxidants, the field of edible coatings has seen significant advancements. For instance, essential oils like oregano and thyme, known for their antimicrobial properties, have been successfully integrated into edible coatings to inhibit foodborne pathogens (Sánchez-González et al., 2013).

Edible coatings are typically applied to the surface of fresh or freshly cut fruits using techniques such as dipping or spraying. These coatings serve as a semi-permeable barrier, reducing moisture loss and modifying the surrounding atmosphere. This process slows down respiration and aging in the fruit, inhibits fungal development, and enhances the fruit's appearance. Coatings can improve the physical and chemical properties of whole fruits, such as enhancing firmness, increasing titratable acidity, and preserving vitamin C. Application of coatings on fresh-cut fruits can help to slow down water loss, increase soluble solid content, and maintain the color of the product (Maringgal et al., 2020).

Recent studies have shown that edible coatings can decrease the activity of enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), thus helping to prevent browning and discoloration in fruits like strawberries and sapota (Vishwasrao ~~&~~ and Ananthanarayan, 2017). Similarly, a study by Kumar et al. (2018) found that the application of an edible coating significantly reduced PPO and POD activities in coated fresh-cut apples, which was associated with a reduction in browning symptoms.

In the broader context of food packaging, innovative solutions are being developed, particularly for food products with unique characteristics such as high moisture content, modified atmosphere, and fresh foods. The goal is to design packaging that meets the specific needs of these products while aligning with environmentally friendly practices (Campos et al., 2011). Bio-based materials used in these solutions should ideally be derived from renewable sources and be recyclable, contributing to a circular economy. They should also have a low impact on greenhouse gas emissions to go hand in hand with efforts to mitigate climate change (Kamdem et al., 2019).

3. Green materials used for edible coatings fabrication

3.1. Types of green materials used for edible coatings production

A diverse array of green, bio-based materials can be used in the formulation of edible coatings (Table 1). These include polysaccharides (*e.g.*, chitosan, alginate, cellulose, pectin, and starch), proteins (*e.g.*, gelatin, zein, soy protein, and casein), lipids (*e.g.*, beeswax, carnauba wax, and vegetable oils), and composites thereof. These materials not only serve as excellent barriers to moisture, gas, and solute transfer but are also safe, biodegradable, and generally sourced from renewable resources. Furthermore, bioactive compounds can easily be incorporated into these edible coatings to improve their functionality.

Edible films and coatings share similar attributes and are often assessed based on their mechanical properties, such as elastic modulus, elongation at break, and tensile strength (Castro-Muñoz et al., 2019) These properties pertain to their elasticity, rigidity, and force required to rupture them. Moreover, they exhibit analogous mass transfer phenomena, including permeation, adsorption, and diffusion, which are associated with the movement of solutes between the food and the surrounding atmosphere. Nevertheless, as the specific material used, and the fabrication method employed dictate the structure of the biopolymeric matrices, a strong influence on both mechanical properties and mass transfer phenomena is yielded (Du et al., 2021; Ruggeri et al., 2020).

3.2. Impact of green materials for edible coatings on environmental sustainability

Leveraging green materials in the creation of edible coatings aligns with sustainable principles, offering an eco-friendly substitute to conventional synthetic food preservation techniques (Nunes et al., 2023). As these materials are biodegradable, they help decrease waste and pollution associated with packaging disposal (Moshood et al., 2022). They also come from renewable resources, reducing the strain on non-renewable assets (Matloob et al., 2023). In this way, edible coatings contribute to a circular economy, advocating environmental sustainability.

As consumer awareness about the environmental impact of household items grows, there has been a shift in perceptions toward food packaging. Heightened interest in terrestrial and aquatic plastic pollution has driven consumers to demand more eco-friendly packaging solutions from the industry (McClements, 2020). Consumer accessibility to information has transformed packaging significantly, with a growing need for packaging that minimizes waste, uses recycled materials, and is recyclable. Consumers are showing a preference for unpackaged food or traditionally packaged products, such as those in glass or paper/cardboard containers, as well as recycled and reduced packaging over plastic-packed products (Otto et al., 2021).

In response to these consumer pushes and ecological imperatives, intensive progress in the research and development of new packaging concepts has been prompted. These include edible films, bio-plastics (Rosenboom et al., 2022), intelligent packaging (Kalpana et al., 2019), and innovative recycling possibilities (Wagner et al., 2019). Consumers generally accept these novel packaging innovations. However, traditional packaging materials differ considerably in their environmental impact, such as carbon footprint, food loss, waste, biodegradability, decomposition, and lifespan. Novel concepts also vary significantly in these areas. Furthermore, consumers often feel that excessive packaging is used, especially for fresh produce, as much as they consider unpackaged food as the most sustainable option (Khodaei et al., 2021). Despite understanding the need to avoid packaging, they feel constrained in their ability to do so and hold the industry responsible for minimizing packaging.

Globally, there is a strong interest in innovative packaging solutions for various food products. These new technologies offer more than just containment and physical protection, contributing to food quality and shelf-life extension. The future of edible materials for coatings seems bright, with rapid innovations within the food industry spurred by global consumer demands. Alternatives to fossil-based packaging materials, including recyclable, biodegradable, or edible materials from renewable and sustainable sources, are sought after both by consumers and the food industry (Trajkovska Petkoska et al., 2021).

Edible packaging stands as a sustainable and biodegradable alternative, providing food-quality optimization compared to traditional packaging. Its ability to maintain food quality, prolong shelf life, and reduce waste contributes to the economic efficiency of packaging materials. The development/application of edible films has become a promising field in food science due to their versatility, potential to be generated from diverse materials, and capacity to carry active substances like antioxidants and/or antimicrobial agents (Restrepo et al., 2018).

Edible packaging is created from edible ingredients that are safe for human consumption. These materials can be processed into films and coatings with similar compositions but varying thicknesses. Films are commonly used in creating wraps, pouches, bags, capsules, and casings, while coatings are applied directly to the food surface. Unlike films, coatings are an integral part of the food product and are typically designed to remain on the food item (Trajkovska Petkoska et al., 2021). The selection of edible packaging components depends on the food product to be packaged, the material composition of the edible packaging, and the processing method. Additionally, the packaging should at least be sensory-neutral with the food (Restrepo et al., 2018).

3.3. Application of natural-based edible coatings to extend food product shelf-life

Edible coatings based on naturally derived materials have been successfully applied to preserve a variety of fruits and vegetables. In general, coatings reduced weight loss, slowed down respiration rates, delayed ripening and senescence, and minimized microbial spoilage, while effectively prolonging the shelf-life of these products. They can also enhance the appearance of the coated produce, making it more appealing to consumers. Edible coatings have also found applications in various finished food products, including dairy products, meat, and poultry. In these applications, edible coatings can prolong shelf life by preventing moisture migration, reducing fat uptake, inhibiting microbial growth, delay oxidation, and enhancing quality and sensory attributes.

Table 2 examines the latest studies dealing with the impacts of different edible coatings on a broad range of food products. For instance, chitosan-based coatings have been effective in extending the shelf life of fruits like apples and strawberries by inhibiting microbial growth and reducing the moisture transfer from the fruit. Usually, the acidity level, or pH, of strawberry juices has been observed to rise as the storage duration extends. Yet, no significant impact on this pH fluctuation during shelf-life was detected when coatings were applied. The gradual rise in pH throughout the shelf-life may be attributed to the enzymatic processes and the natural aging of the fruit, which typically results in a decrease in acidity. The rise in pH can be delayed and enzymatic processes can be mitigated through the application of edible coatings. Moreover, a significant influence on the ascorbic acid content, which plays a pivotal role in assessing the freshness and overall quality of stored strawberries, was observed when edible coatings were applied. The diminishing level of ascorbic acid in fruit is predominantly triggered by an increase in oxygen levels or storage temperature. Edible coatings, however, preserved ascorbic acid content by limiting the oxygen permeation and slowing down the fruit's respiration rate throughout storage, contributing to a longer shelf-life (Khodaei et al., 2021).

Furthermore, strawberries treated with cashew gum polysaccharide (CGP) and polyvinyl alcohol (PVA) coating (Moreira et al., 2020) exhibited reduced weight loss and inhibited fungal proliferation. Similarly, lipid-based coatings such as beeswax have been employed to maintain the quality of vegetables like cucumbers and peppers, slowing down respiration rates and reducing weight loss.

In another study, mandarins coated with different chitosan-based coatings showed improved overall preservation, with layer-by-layer coating consisting of hydroxypropyl methylcellulose/chitosan offering the best results in preserving fruit bioactive compounds and organic acids (Jurić et al., 2023a). Treatment of fruits after harvest with certain inducers can enhance the plant's natural defenses. For example, chitosan stimulates critical enzymes involved in the production of polyphenolic compounds, such as phenylalanine ammonia-lyase, leading to an increase in total polyphenols and potentially improving the antioxidant properties of fruits (Romanazzi et al., 2017). Layer-by-layer coatings are seen as highly effective in prolonging the shelf life and preserving the postharvest quality of fruit. The use of such biopolymer-based coatings positively impacts fruit preservation by reducing the fundamental metabolic processes often exacerbated by environmental stresses. Layer-by-layer edible coatings effectively reduce the respiration rate, providing a modified microgas environment that suppresses energy metabolism (Yan et al., 2019).

The application of various edible coatings to Barhi date fruits, such as gelatin, chitosan, and guar gum, also resulted in extended shelf life (Abu-Shama et al., 2020). Lime fruits coated with pectin demonstrated slower quality degradation and reduced weight loss (Maftoonazad ~~&~~ and Ramaswamy, 2019). Interestingly, the total polyphenolic content in different fruits subjected to various coating treatments demonstrated the highest levels of total phenolic content throughout the shelf-life study.

The decline in phenolic content within fruit can be associated with the disintegration of the cellular structure that occurs during natural aging. Edible coatings serve as a protective shield, obstructing the access of oxygen and moisture, which are essential for the enzymatic oxidation of phenolic compounds. This protective layer aids in maintaining the fruit's phenolic content (Khodaei et al., 2021).

Other popular foods also yielded positive outcomes when treated with edible coatings. Shiitake mushrooms coated with a combination of chitosan and guar gum maintained higher tissue firmness and a slower rate of degradation (Huang et al., 2019). When discussing firmness, the softening of the mushrooms is likely a result of cellular breakdown, and the hydrolyzation or depolymerization. Edible coatings can limit moisture loss and slow down mushroom softening. Furthermore, treating smoked herring with chitosan improved its quality and lipid stability (Abdel-Naeem~~, Sallam,~~ et al., 2021a). Meanwhile, walnuts coated with defatted walnut protein-based flour sustained better flavor and quality throughout storage, indicating the potential of utilizing the agricultural residues for industrial application (Grosso et al., 2020). The utilization of potato starch and calcium gluconate salt coating on papaya and edible coatings made from potato peel waste and beeswax on apple slices also resulted in enhanced preservation (Ruggeri et al., 2020). Notably, the edible coating on papaya helped retain the functional and nutritional quality of papaya slices during drying (Islam et al., 2019).

Edible coatings offer numerous benefits mentioned above. They also reduce the need for synthetic preservatives and packaging materials, promoting environmental sustainability. Additionally, by serving as a carrier for functional additives, edible coatings can add value to the coated product, for example, by delivering probiotics, nutraceuticals, or flavorings. Despite these benefits, the use of edible coatings requires careful formulation and application to ensure their effectiveness and consumer acceptability.

4. Preparation of edible coatings

4.1. Main processing steps

The preparation of edible coatings often starts with the selection of suitable base materials, including proteins, polysaccharides, lipids, or a combination of these (Figure 1). These are typically dissolved or dispersed in a solvent (generally water), with the addition of plasticizers to improve the flexibility and cohesiveness of the resultant coating. The concentration, pH, and temperature of the coating solution are adjusted to achieve the desired properties (Garcia et al., 2014). This represents the base formulation of the coating, to which functional additives may be incorporated, such as antimicrobial agents, antioxidants, or colorants.

The mixture is then typically heated and stirred until it reaches homogeneity. Upon cooling, it can be applied to the food product using techniques such as *dipping*, *spraying*, *fluidized bed* processing method, and *panning*, after which the coated product is left to dry, allowing the solvent to evaporate and leaving a thin layer of the edible coating material (Suhag et al., 2020).

4.1.1. Selection of materials

The selection of materials for edible coatings is a pivotal aspect of their development, underpinned by several objectives: (i) enhancing food preservation, (ii) sensory-neutral or improving sensory quality, and (iii) ensuring compatibility with environmental sustainability goals. For instance, consumer choices for fresh produce are significantly influenced by the appearance of the product, which is a key indicator of its freshness and quality (Jaeger et al., 2023). Therefore, the selection of materials for developing edible coatings should be carefully based not only on their functionality and performance but also on their impact on the final appearance of the product.

The process of material selection involves a detailed evaluation of natural compounds, such as proteins, polysaccharides, and lipids, for their ability to form effective barriers against moisture, oxygen, and solute movement. The criteria for material selection extend beyond mere functional performance as they also need to encompass considerations related to the source of materials, biodegradability, and safety for consumption (Bizymis and Tzia, 2022). For instance, polysaccharides derived from plants and seaweeds, proteins obtained from dairy or plant sources, and lipids sourced from natural oils are preferred for their renewable nature and minimal environmental impact (Rahman et al., 2024).

Edible coatings come in several varieties. Primarily, these are divided into polysaccharide-based, protein-based, lipid-based, and composite coatings (Table 1). The latter category consists of blends of more than one material, often creating a bilayer composite featuring a mix of any two elements, be they proteins, polysaccharides, or lipids (Kurek et al., 2017). The right combination of these coatings influences the final product value.

Moreover, the integration of natural additives into these coatings, such as antimicrobial agents, anti-browning compounds, texture enhancers, antioxidants, probiotics, flavors, and plasticizers, further refines their protective qualities and shelf-life extension capabilities (Khalid et al., 2022). The integration of plant-derived antimicrobial agents into these coatings is a forward-thinking approach that not only extends shelf life but also improves the safety of the product, hence promoting customer acceptance (Dhital et al., 2017). These additives not only bolster the mechanical and barrier properties of the coatings but also enhance the nutritional profile of the coated food products. The strategic selection of these materials and additives highlights the importance of a holistic approach that balances performance with consumer health and ecological considerations (Bizymis and Tzia, 2022). As research and development in this area continue to evolve, the potential for innovative combinations of materials that can address specific food preservation needs while adhering to sustainability principles presents an exciting frontier in the field of edible coatings.

Edible coatings need to be designed to be safe and robust, particularly in environments of high humidity. Ideally, edible coatings should be free from color, odor, and taste, while also demonstrating sturdy mechanical properties. Some can even serve as vehicles for nutraceuticals or texture enhancers. The core function of these coatings is to prolong the storage life of fresh produce by providing a protective barrier against environmental damage and post-harvest loss. With the right choice of materials, edible coatings can even enhance the aesthetic appeal of fresh produce, giving it a vibrant shine (Jurić et al., 2023a). They are also often used in the creation of an edible wrap, consumed with the food itself. As the demand for eco-friendly, nutritious food products grows, so does the need for advancements in edible coatings. Current trends highlight the need for the creation of environmentally sustainable packaging made from biodegradable polymers. Such packaging can contribute to waste reduction and add value to by-products (Garcia et al., 2014).

4.1.2. Preparation of edible coating solution

A variety of strategies have been established for creating edible coatings, each tailored to the specific coating material in use. Commonly used methods include the solidification of melt, solvent extraction, and thermal gelation. Edible films derived from hydrocolloids feature water-soluble polymers sourced from animal, plant, or microbial origins. Using solvent extraction, these hydrocolloid films can be developed with a structurally continuous form, with their stability bolstered by the chemical and physical interplays among molecules. Commonly used solvents include water, acetic acid, and ethanol, often combined with plasticizers, antimicrobial agents, and cross-linking agents (Dhall, 2013). Protein-based films are often fabricated through the heating of the protein solution, causing denaturation, precipitation, or gelation. This heated mixture is rapidly cooled, promoting coagulation and additional gelation. On the other hand, lipid-based films are generated through a process of melting and subsequent solidification. Each of these methods presents an effective strategy for the creation of edible coatings, contributing to the overall durability and utility of the finished product (Armghan Khalid et al., 2022).

The wetting behavior of coatings on food surfaces, especially fruits and vegetables, is pivotal in determining the effectiveness of edible coatings. This behavior is influenced by factors such as the viscosity of the coating solution, the surface characteristics of the produce, and the desired coating thickness. These elements play a significant role in how well a coating spreads and adheres, impacting both the efficiency of the coating process and the performance of the resulting edible coating. Understanding and manipulating wetting properties are key to enhancing coating designs, thereby ensuring better protection and extended shelf life for food products. Advanced techniques that modify liquid and surface properties are at the forefront of research aimed at developing new and effective edible coatings (Osorio et al., 2018; Sun et al., 2021).

In this context, the role of cohesion and adhesion is vital on surfaces with varied free energy. For instance, hydroxypropyl methylcellulose (HPMC) affects the work of cohesion, with its increased concentration leading to a decrease in cohesion value.

Additionally, glycerol, nanofibers, and κ-carrageenan within HPMC-based coatings influence the spreading work, presenting different effects based on the formulation. Surfaces with higher free energy values demonstrate a greater affinity for these coatings, suggesting enhanced application effectiveness on specific food surfaces (Osorio et al., 2018).

Surface roughness and cuticle layers also significantly impact wettability. It has been observed that fruits with smaller contact angles have larger total surface free energies. This indicates an inverse relationship between total surface free energies and contact angles, crucial for understanding how different coatings interact with food surfaces (Sun et al., 2021).

4.1.3. Adjustment of a coating solution

The preparation of the coating solution is a critical factor in the successful application of edible coatings on produce. The properties of the solution, including its viscosity, concentration, and the inclusion of additives, must be carefully adjusted to ensure the efficiency of the coating process and its subsequent performance.

Viscosity is a significant property to consider. A solution that is too viscous might not adequately adhere to the produce surface, thus leading to uneven coverage and ineffective protection. On the other hand, a solution with low viscosity might not provide adhesion or a sufficient barrier against moisture, oxygen, and microbial intrusions. The concentration of the coating material in the solution is another critical parameter. A highly concentrated solution might lead to a thick and uneven coating, which could negatively affect the product's appearance and respiration rate. Conversely, a diluted solution might not provide sufficient protection (Du et al., 2022).

The inclusion of additives in the coating solution may enhance the protective properties of the coating. Antimicrobials, antioxidants, texture enhancers, and other functional ingredients can be incorporated to improve the overall coating performance (Sharma et al., 2022). However, the concentration of these additives must be carefully calibrated to ensure they do not interfere with the coating process or adversely affect the sensory attributes of the produce. Furthermore, the pH and temperature of the coating solution may need to be adjusted depending on the specific coating material and the product being coated. Some coating materials may require specific pH or temperature conditions to ensure proper solubility and stability in the solution (Chen et al., 2023).

The adjustment of the coating solution is a complex process that requires a good understanding of the properties of the coating material, the specific requirements of the product, and the desired outcomes of the coating process. When opportunely tuned, the coating solution can effectively extend the shelf-life of the produce while preserving its freshness and quality.

4.1.4. Coating application

The application of edible coatings to fresh produce is an integral step that requires careful execution to ensure the coating's efficiency and the preservation of the product's quality. These coatings, functioning as semi-permeable membranes, are applied directly to the surface of fruits or vegetables using various methods (Resende et al., 2018). The main methods used to apply coating materials on foods are spraying, dipping, fluidized bed processing method, and panning (Table 3), each of which has its peculiarities (Suhag et al., 2020).

Spraying, a common technique for applying coatings to food, ensures uniform coverage by generating droplets across the food surface using specialized nozzles. Key aspects include regulating coating thickness and maintaining spray pressure and distance to prevent pooling (Suhag et al., 2020). The industry employs three main spraying methods:

1. *Air-Spray Atomization:* High-velocity air stream atomizes the coating fluid, ideal for cost-effective, fine droplet application (Valdés et al., 2017).

2. *Air-Assisted Airless Atomization:* Partial initial atomization with a nozzle tip, followed by fine atomization using compressed air, suitable for high-viscosity and solid coatings (Peretto et al., 2017).

3. *Pressure Atomization:* Uses high-pressure nozzles for applying coatings without air, beneficial for high surface tension and viscosity solutions (Andrade et al., 2012).

The nozzle's design and operation, such as pressure and viscosity, are crucial for effective spraying (Huber ~~&~~ and Embuscado, 2009). These techniques have proven useful in various food processes, extending shelf life and preserving the color of coated products. However, spraying highly viscous solutions can be challenging, sometimes necessitating dipping methods. Proper viscosity adjustment is essential for consistent coating applications (Suhag et al., 2020).

The dipping method for food coatings involves immersing produce in a solution, allowing for thorough soaking. This method ensures comprehensive coverage but can lead to thicker coatings, necessitating post-dipping drainage to remove excess (Fathi et al., 2021). The process includes immersion, deposition, and solvent evaporation, with the final drying step solidifying the coating (Suhag et al., 2020).

During immersion, foods are consistently soaked in the coating solution. The properties of the coating solution, such as density and viscosity, influence the resultant coating thickness. For thicker coatings, items can be dipped in denser solutions like batter or molten lipids, enhancing flavor and reducing moisture loss during frying. However, challenges arise in coating hydrophilic surfaces of cut fruits or vegetables due to poor adhesion, potentially addressed by multi-layered methods like electro-deposition. Still, dipping is popular for its simplicity and effectiveness in enhancing microbial stability and managing browning in cut fruit. Fruits and vegetables are typically immersed for 5-30 seconds in solutions containing antimicrobials or antioxidants. Despite its uniform application and cost-effectiveness, drawbacks include potential respiration inhibition in coated products, dilution, and waste accumulation in the dipping vat, microbial growth, and removal of natural wax coatings (Suhag et al., 2020).

The fluidized bed method is a widely used technique for applying thin coatings to dry, low-density particles in food processing (Aayush et al., 2022). It involves spraying solutions or suspensions onto fluidized powder to create a shell-like structure. Fluidization occurs when liquid flows upward through a bed of particles, lifting them and giving the bed fluid-like properties. The three main types are top spray, bottom spray, and rotary fluidized bed, with top spraying being the most effective in the food industry (Priya et al., 2023; Suhag et al., 2020).

For effective fluidization and to prevent excessive agglomeration, particle sizes should be over 100 µm. The fluidized bed's agglomeration characteristic aids in dispersing and solubilizing the coating material, with a liquid binder often used for stability during heat treatment before food coating. This process results in particle adhesion, aggregation, and drying, suitable for both continuous and batch processes. Pneumatic or binary nozzles are employed, with pneumatic nozzles preferred for controlling droplet size and distribution, especially at low flow rates. Atomizing air assists in solvent evaporation, increasing droplet viscosity and reducing coalescence (Zhalehrajabi et al., 2019).

The rotating fluidized bed, a variant of the standard method, uses centrifugal force to push powder samples to the wall. This method accommodates a variety of food products, including functional ingredients and flavors. It is particularly useful for encapsulating foods and additives like nuts or coating seeds with pesticides. Despite its advantages, such as reduced clustering and improved drying efficiency, the fluidized bed method faced initial hesitance in the food industry due to higher costs and larger amounts of coating solution needed, leading to potential coating imperfections (Garcia et al., 2016; Suhag et al., 2020).

The panning method, dating back to Greek Arabian society, involves rotating a bowl filled with the product to be coated and uniformly distributing a coating solution onto it. This method, which also employs heated air for drying, is known for generating heat due to friction (Dangaran et al., 2009). It is divided into three categories: hard, soft, and chocolate panning.

Hard panning applies a crystallizing sugar syrup shell, while soft panning uses a corn syrup and sugar mixture, dried with dry sugar to form a soft layer. Chocolate panning involves coating with chocolate or cocoa-based confectionery. An electrostatic dry powder pan coating, popular in pharmaceuticals for uniform powder deposition, charges the product and sprays it with an oppositely charged coating, ensuring an even layer (Suhag et al., 2020).

This method is suitable for hard, spherical particles and can apply thin or thick layers in batch processes, especially useful for extruded products like confectionery centers (*e.g.*, peanuts, almonds) coated with gum Arabic. This base layer manages moisture and fat displacement, allowing flavor addition. However, panning can be time-consuming and less economical due to water evaporation needs and product clumping prevention, but it provides a transparent, glossy coating and is convenient for batch-coating various food products (Suhag et al., 2020).

When applying coatings to food, important considerations include the viscosity of the coating solution, the surface characteristics of the produce, and the desired coating thickness. These elements greatly influence the effectiveness of the coating process and the quality of the edible coating. Future developments in application technologies like electrostatic or ultrasonic spraying are expected to improve uniformity and efficiency in edible coating applications, making this a dynamic field of current research (Resende et al., 2018).

4.1.5. Drying and curing

Edible coatings have been found to significantly enhance the quality and nutritional value of dried foods, without affecting the efficiency of the drying process or reducing water activity during drying. Moreover, these coatings contribute to a higher rate of water diffusion throughout the drying process, ensuring optimal dehydration. For example, the application of ascorbic acid during the dehydration process yields a dried food product with an increased vitamin C content. Importantly, the drying temperature tends to have a more pronounced impact on the degradation of vitamin C than the process duration. When subjected to convective drying, coated food products successfully serve as oxygen barriers, effectively preserving their nutritional content. Specifically, at higher temperatures, some coatings tend to provide better retention of vitamin C (Garcia et al., 2014).

There is an untapped research avenue in the preliminary enrichment of materials before applying edible coatings and subsequent drying stages. Using a variety of plant materials for enrichment or as functional ingredients in coatings, such as superfruit juices and extracts, presents a vast opportunity for innovation (Kowalska et al., 2021). Additionally, the combination of different technologies with edible coatings can lead to improved properties of food products. For example, osmotic dehydration is a mild processing technique, that can significantly enhance the development of novel fruit snacks, or similar products, thereby potentially benefiting consumer health. Integrating edible coatings with osmotic dehydration is designed to facilitate water removal via a semipermeable membrane, concurrently restricting solute movement from the dehydrated substance and preventing solute entry from the osmotic solution into the food. This research is essential not only for creating products that encourage more plant product consumption but also for addressing environmental challenges by reducing by-product production and energy consumption, ultimately contributing to sustainability (Kowalska et al., 2021).

Edible coatings can also aid in maintaining the color quality of food products during convective drying, resulting in a more appealing final product. Notably, the use of certain coatings leads to a slight reduction in lightness and a shift in hue from yellowness to a mild orange, adding to the product's overall color intensity (Garcia et al., 2014). Differences in optical properties of edible coatings made from hydrocolloid solutions when applied to strawberry slices were also observed when subjected to solar and oven drying. Coatings created with hydro-colloidal solutions exhibit high UV absorbance and very low transmittance, making them suitable as coatings with solar filter properties. Critically, these optical properties are affected by the thickness of the coating (López-Ortiz et al., 2021).

Furthermore, it was shown that coated foods maintain cell structures like fresh samples post-drying, with notable rupturing of cell membranes observed in dried tissues (Garcia et al., 2014; Meerasri and Sothornvit, 2023). The moisture-effective diffusion coefficients in coated foods are higher than those of uncoated counterparts, which could be associated with greater water diffusivity within the edible coating. Given the widespread use of convective drying in the food industry and considering that the application of edible coatings improves the nutritional quality of dried foods without compromising the drying efficiency, this technology presents a promising approach for enhancing the quality of dehydrated foods (Garcia et al., 2014).

The formula that could be used in the development of edible coatings for heat transfer is given (Eq. 1):

$$Q = c_p \cdot m \cdot \Delta T \qquad (1)$$

where Q is the heat transferred (in J), c_p is the isobaric-specific heat capacity (in J kg^{-1} K^{-1}), m is the mass (in kg), and ΔT is the temperature difference (in K).

This formula can be used to estimate the amount of heat needed to dry the edible coatings or to calculate the heat transfer during the cooling or heating of the coated food products.

The drying rate (Garcia et al., 2014) of the coated and uncoated products can be calculated using the following equation (Eq. 2):

$$DR = \frac{M_{t+dt} - M_t}{d_t} \qquad (2)$$

where M_{t+dt} is the moisture content at time $t + dt$ (kg$_{\text{water}}$ kg$_{\text{dry matter}}^{-1}$); M_t is the moisture content at time t (kg$_{\text{water}}$ kg$_{\text{dry matter}}^{-1}$); and t is the time (min).

4.1.6. Shrinkage of the finished edible coating

Edible coating shrinkage refers to the physical reduction in the size of the coating material as it dries and sets onto the surface of a fruit or vegetable (Islam et al., 2019). This process is influenced by a plethora of factors, including the type and concentration of the coating material, the drying conditions, and the inherent properties of the fruit or vegetable being coated. Understanding and managing shrinkage is critical as it can influence both the performance of the coating and the quality of the coated product.

Quantifying shrinkage mathematically helps predict and control how a coating will behave during and after drying. This can be achieved through the application of equations such as Fick's Second Law, which describes the diffusion of water (or other solvents) out of the coating during drying. By incorporating a shrinkage factor into these models, one can better unravel the rate and extent of drying, the final dimensions, and properties of the coating, and consequently optimize the coating process for different products (Garcia et al., 2014).

From a chemical perspective, shrinkage is largely driven by the evaporation of water (or other solvents) from the coating material during drying. This process can influence the alignment and interaction of the biopolymers making up the coating, thus leading to changes in its physical and chemical properties. For instance, as the coating shrinks, it may become denser and less permeable, improving its effectiveness as a barrier to oxygen, moisture, and microbial contamination. Moreover, shrinkage could impact the release of incorporated bioactive compounds, such as antioxidants and antimicrobials, affecting the shelf-life and nutritional value of the coated product. The biological implications of coating shrinkage primarily concern its effects on the fruit or vegetable being coated. A well-controlled shrinkage process can ensure that the coating adheres well to the surface, providing an effective barrier without damaging the underlying tissue. This can enhance the product's shelf-life by reducing moisture loss, limiting gas exchange, and protecting against microbial contamination. In contrast, uncontrolled or excessive shrinkage could result in a coating that is too tight or too brittle, potentially damaging the fruit or vegetable, affecting its appearance, and reducing its marketability.

To calculate the shrinkage of the sample, the volume variation is expressed by Eq. (3) as follows:

$$\frac{V^a - V^0}{V^0} = \left[\left(\frac{m^a}{\rho^a} - \frac{m^0}{\rho^0}\right) \times \left(\frac{m^0}{\rho^0}\right)^{-1}\right] \times 100 \tag{3}$$

where *V* stands for the volume of the sample, *m* is the mass of the sample, ρ is the density of the sample, and the apexes *0* and *a* indicate the control (fresh sample) and the sample condition as either fresh dried or coated dried, respectively (Garcia et al., 2014).

4.2. Main factors affecting the preparation of edible coatings

The preparation of edible coatings is influenced by various factors, including the type and concentration of base materials and plasticizers, the nature and quantity of functional additives, and the hygro-thermal conditions under which the coating solution is prepared and applied. Additionally, the specific properties and requirements of the food product being coated also influence the preparation of edible coatings. For instance, the coating for a high-moisture fruit might require more hydrophobic components, while a coating for a fat-rich product might require more proteins or polysaccharides to prevent lipid oxidation (Armghan Khalid et al., 2022).

Here, factors that affect the preparation of edible coatings are outlined:

- *Polymer type*: the choice of the polymer used in edible coatings can have a significant impact on its properties. Each type has different properties that affect the permeability of the coating to gases and moisture, mechanical strength, and interaction with the food surface. Different polymers offer varying degrees of wettability, which is essential for adequate coverage and adhesion;

- *Coating material concentration*: it affects coating thickness and effectiveness. Higher concentrations usually produce thicker coatings that provide better protection but also affect the appearance and sensory properties of food;
- *Inclusion of additives*: plasticizers, antioxidants, antimicrobial agents, and colorants can be included in the formula to improve the function of the coating. The type and quantity of these additives can greatly affect the coating properties;
- *Application method*: the method of application of the coating may affect its uniformity and thickness. The selected method must ensure a uniform application without damaging the food;
- *Drying conditions*: temperature, humidity, and airspeed during drying can affect coating formation and properties. These conditions must be controlled to ensure that the coating is properly dried;
- *pH and temperature of coating solution*: they can affect the solubility and interaction of coating materials with food surfaces;
- *Food surface properties*: characteristics of food surfaces, such as cleanliness, moisture content, and chemical composition, can influence the adhesion and efficiency of coatings;
- *Regulation*: in different countries, there may be regulations on substances that can be used in edible coatings, maximum permitted concentrations, and types of foods they can be applied to. Compliance with these regulations is an important aspect of the preparation of edible coatings.

5. A novel approach – enhancing edible coatings with natural additives and application of nanotechnology

5.1. Potential of natural additives in edible coatings

The incorporation of natural additives into edible coatings can significantly enhance their performance and functionality. These additives may impart antimicrobial, antioxidant, or other beneficial properties to the coating, extending the shelf-life and enhancing the safety of the food product. Additionally, natural additives can improve the sensory attributes of the coated product, such as color, flavor, or aroma, contributing to consumer acceptability (Pérez-Santaescolástica et al., 2022). A variety of natural additives can be used in edible coatings, each offering distinct benefits. For example, essential oils (such as oregano, thyme, or clove oil) and plant extracts (such as grape seed or green tea extract) can provide antimicrobial and antioxidant properties. Spices, herbs, and natural pigments can enhance color and flavor. Other additives may include natural antimicrobial agents like nisin, natamycin, and lysozyme, or natural antioxidants like ascorbic acid or tocopherols. Antimicrobial additives can inhibit the growth of spoilage and pathogenic microorganisms, extending product shelf-life and ensuring food safety. Antioxidant additives can delay oxidative rancidity in fat-rich products, preserving their quality. Sensory additives can improve the appearance, taste, or aroma of the coated product, making it more appealing to consumers (Teixeira-Costa ~~&~~ and Andrade, 2021).

Numerous case studies illustrate the benefits of using natural additives in edible coatings. This review presents an overview of various research studies exploring the potential of different edible coating materials, coupled with natural additives, on a range of food products. Each research study is presented (Table 4) in terms of the coated product, the coating material used, the natural additives incorporated, the storage conditions employed, the parameters investigated, and the results obtained. Here key developments, trends, and findings from recent studies on the implementation of natural additives in edible coatings across various food categories are showcased:

Fruits and Vegetables: The integration of zinc oxide and xanthan gum in edible coatings for tomatoes and apples has been shown to enhance antibacterial properties and reduce weight loss by minimizing moisture evaporation, demonstrating the role of viscosity and concentration in the effectiveness of these coatings (Joshy et al., 2020). An innovative coating combining alginate, aloe vera, and frankincense oil applied to green capsicums delays aging and microbial growth, leveraging the UV-shielding and antioxidant properties of its components (Salama ~~&~~ and Abdel Aziz, 2021). Pomegranate peel extract in edible coatings effectively reduces weight loss in tomatoes by providing a barrier against gas exchange and water vapor loss, highlighting the importance of controlling polyphenol oxidation and enzyme activity (Kumar et al., 2021a). Henna leaf extract, when included in Gum Arabic coatings for guava, contributes antimicrobial, antifungal, and antioxidant properties, significantly reducing fruit decay and weight loss, though the effectiveness varies with the extract's solvent properties (El-Gioushy et al., 2022). The addition of cumin essential oil to a sweet potato starch coating for pears enhances storage quality by reducing water loss, showcasing the antifungal activity and the ability to maintain chlorophyll levels (Oyom et al., 2022).

Probiotic and Prebiotic Incorporation: Investigations on edible coatings infused with probiotics, such as *Lactobacillus plantarum*, highlighting their potential to preserve the physicochemical properties of foods like strawberries without affecting cell viability (Khodaei ~~&~~ and Hamidi-Esfahani, 2019). Prebiotic-alginate coatings carrying probiotics demonstrate the capacity to maintain the microbiological and nutritional quality of fresh-cut apples, meeting health-beneficial concentration thresholds (Alvarez et al., 2021). The use of alginate-based coatings with bacteriocin-producing *Lactococcus* strains on fresh cheese suggests a method to enhance quality by preserving moisture and reducing weight loss while inhibiting pathogenic growth (Silva et al., 2022).

Meat, Eggs, and Seafood Products: A chitosan and lauric arginate coating applied to frozen chicken meat improves bacteriological quality and sensory attributes by enhancing antimicrobial activity and stabilizing the meat (Abdel-Naeem et al., 2021b). For hen eggs, chitosan-propolis extract coatings prevent moisture and bacterial penetration, improving physical properties and extending shelf life by enhancing barrier functions (Ezazi et al., 2021). Salmon fillets benefit from coatings made of salmon bone gelatine, chitosan, gallic acid, and clove oil, which offer antioxidant and antibacterial effects, extending shelf life and necessitating further research on consumer acceptance and bioactive compound migration (Xiong et al., 2021).

Overall, these studies highlight the diverse applications and benefits of natural additives in edible coatings across different food matrices. The trends indicate a growing interest in leveraging the natural properties of these additives to address specific challenges in food preservation, safety, and quality enhancement, with an emphasis on sustainability and consumer health benefits. The research studies from Table 4 highlight the significant potential of edible coatings in maintaining the quality and extending the shelf-life of a variety of food products. The combination of various coating materials and natural additives can lead to improved product quality under specific storage conditions. However, the impact of these coatings is dependent on several factors, such as the type of product, the choice of coating material and additives, and the storage conditions. While significant progress has been made, more research is required to fully understand the mechanisms underlying the performance of these coatings and to tailor them for specific applications. Future studies should also focus on scaling up these technologies for commercial implementation and evaluating their performance in real-world settings.

5.2. Nanotechnology application in the creation of edible coatings

Recent breakthroughs have introduced innovative preparation methods for edible coatings, utilizing striking materials and technologies. Among them, nanotechnology stands out, since it enables the production of nano-emulsion or nanoparticle-based coatings (Milani ~~&~~ and Nemati, 2022). The development of nanotechnology in edible coatings has become a promising strategy for enhancing the shelf-life, quality, and safety of various food products (Maria Leena et al., 2020; Shan et al., 2023). Coupled with concurrent innovations such as the creation of composite and multilayer coatings, and the utilization of advanced application techniques like electrohydrodynamic processes and atomization, nanotechnology significantly augments the scope and performance of edible coatings.

These nanostructured coatings, typically formulated with a combination of biopolymers and active ingredients, can provide a controlled release of antimicrobial, antioxidant, or other beneficial substances, thereby extending product freshness and mitigating microbial contamination (Figure 2). Additionally, nanotechnology can serve to improve the nutritional quality of edible coatings (Suhag et al., 2020). The concept of nanocomposites enables the formation of edible polymers through a process that involves spraying the solution onto the food surface. These solutions often contain bioactive agents such as antimicrobials, antioxidants, enzymes, flavorings, and coloring materials or mixtures of compounds like essential oils (Rios et al., 2022). The high hydrophobicity, reactivity, and strong aroma of essential oils present a challenge for their direct use in food and beverages (Donsì and Ferrari, 2016; Teixeira et al., 2022). Essential oils have been widely adopted not only for their antimicrobial properties in food protection but also as additives in biodegradable coatings (Rios et al., 2022). Utilizing edible coatings as carriers for essential oils has emerged as a strategy to reduce the necessary doses regarding sensory characteristics, ensuring a more controlled release and retention of active ingredients within the coating matrix. Nanoemulsion-based edible coatings loaded with essential oils are sustainable, cost-effective, and natural alternatives to synthetic food preservatives for ensuring food safety, preservation, and packaging (Pandey et al., 2022). Essential oil presence can effectively reduce the water vapor permeability of hydrophilic coatings and significantly impact their structural properties.

Nanoparticles such as zinc oxide, silver, and chitosan have been identified as effective agents for improving the postharvest quality of climacteric fruits by enhancing their physical and sensory attributes, inhibiting microbial growth, and prolonging shelf life. While some edible coatings alone have shown limitations, integrating them with nanoparticles has proven to enhance their protective capabilities (Odetayo et al., 2022). There's potential in exploring other nanoparticles like copper, cerium oxide, and titanium oxide due to their low safety concerns. Additionally, food-grade nanomaterials such as starch, cellulose, and gums offer promising, non-toxic options for fruit coatings. Combining nanoparticle-enriched coatings with existing storage technologies represents a new research frontier that could further improve fruit preservation.

The electrohydrodynamic process utilizes an electric field to disperse a polymer solution into a fine stream. This technique leads to the creation of particles *via* electrospraying or fibers through the process of electrospinning. Electrospraying represents an innovative coating technique where a material is converted into fine particles under the influence of a strong electric field. This process results in the creation of charged droplets, ranging from micrometric to sub-micrometric in size, with a remarkably uniform size distribution. Electrospraying, a technique closely related to electrospraying atomization processes (Jurić et al., 2023b), has undergone rapid development, transitioning from single-fluid systems to more intricate setups like coaxial, tri-axial, side-by-side, and tri-layer side-by-side processes. This advancement enables the integration of various fluids into electrospinning, including those not traditionally electrospinnable. Consequently, this expansion has significantly broadened the versatility and potential applications of the method (Ji et al., 2023).

For example, the development of electrospun nanofibrous membranes, particularly those infused with bioactive compounds, represents a groundbreaking advancement in food engineering and packaging (Jurić et al., 2023b). Coaxial electrospinning, a notable technique in this realm, has facilitated the creation of extremely thin, core-sheath fibrous membranes made of zein and polyethylene oxide incorporating antioxidants like ferulic acid. The unique design of these membranes enables a controlled release of active agents, providing an extended protective effect on foods. This approach has been notably effective in preserving apple slices, where it significantly reduced water loss, slowed down quality deterioration, and extended shelf life (Huang et al., 2022). This innovative strategy aligns advanced nanotechnology with traditional food engineering methods, marking a significant leap in antioxidant food packaging solutions. Nevertheless, a key obstacle in employing electrospun fibers for food packaging lies in ensuring effective adhesion between the fibers and the food items.

Nano-based edible coatings have been applied to a diverse range of products (Table 5), from fresh and fresh-cut fruits and vegetables to cheeses, meat, and fish, with innovative methods of coating production that leverage electrospinning, cross-linking, and nanoemulsion techniques (Maria Leena et al., 2020). Despite significant progress, additional research is required to optimize these technologies for broad industrial applications and consumer acceptance. The application methods of these nanoparticle-enhanced coatings and their impacts on the fruits' sensory and nutritional qualities are not very well investigated. Moreover, research into the ingestion safety and permissible levels of nanoparticles in coated products like fruits are necessary to ensure health compatibility (Odetayo et al., 2022).

The fast-growing body of research demonstrates the potential of nanotechnology in formulating innovative edible coatings to extend the shelf-life and preserve the quality of various food products. As demonstrated in the recent studies listed in Table 5, nanostructured edible coatings can effectively control moisture loss, enhance the bioavailability of nutraceutical ingredients, inhibit the growth of spoilage organisms, and suppress postharvest diseases. These advancements could revolutionize food preservation techniques, addressing challenges related to food waste, food safety, and food quality. However, while these developments are promising, further research is needed to optimize production methods, improve our understanding of the effects on food properties, and evaluate consumer perceptions of nanotechnology in food applications. As this field continues to evolve, it promises to provide exciting solutions to enhance food preservation in the near future.

6. Commercialization, scalability, quality assurance and regulations of edible coatings

In 2020, the worldwide market for edible coatings and films reached a valuation of USD 2.06 billion, with expectations to expand at a compound annual growth rate of 7.64% from 2021 to 2027. This growth is attributed to the rising adoption of edible films and coatings as sustainable alternatives to conventional plastic-based food packaging solutions (Kumar et al., 2023). In this context, the market value and projected growth rate for the combined category of edible coatings and edible films serve as a proxy for understanding the momentum of how edible coatings are translated to the real sector. It suggests that as the market for sustainable packaging solutions expands, edible coatings are likely to constitute a significant share of this growth, driven by their environmental benefits and alignment with global sustainability goals.

Currently, edible coatings and nanocomposite edible coatings are predominantly produced on a laboratory scale, despite a modest number of them reaching worldwide commercialization as food shelf-life enhancers. As mere examples, American companies like WikiFoods Inc. and BASF developed “Wikipearls” and “FreshSeal”, respectively, two polysaccharides-based coatings which preserve moisture and prevent weight loss of fresh fruits and cheese. Another example is a dutch De leye Agro company recently placed “BioFresh” on the market, a coating of sucrose ester and cellulose gum able to delay the ripening process of pears, nectarines, and apples. AgriCoat NatureSeal Ltd. From the UK launched vitamins/minerals- and oil-based coatings (“NatureSeal” and “Samperfresh”) to help prevent the oxidation phenomena of cut fruits/vegetables, and reduce the respiratory rate thereof (Kumar et al., 2022).

Notwithstanding this, the full transition to large-scale industrial production requires multiple efforts toward innovation and refining processes in terms of reduced consumption of harmful chemicals and energy (*e.g.*, reduced drying and processing times). Given a transition to large-scale industrial production, there is a need to innovate and refine production processes to diminish the use of harmful chemicals, lower production expenses, reduce drying and processing times, and cut back on energy consumption. The price point is a significant factor affecting consumer acceptance of edible coatings. At present, the cost of these films can be 10-50 times higher than conventional petroleum-based plastic films. However, considering the developmental stage of edible coatings production and the lower production quantities, the high cost should not yet be seen as a disadvantage (Jeya Jeevahan et al., 2020). Ideally, packaging costs should not exceed 10% of the total product cost. A thorough cost-benefit analysis should be conducted to assess the viability of edible coating adoption. To appeal to consumers, the price of edible coatings should be equal to or less than petroleum-derived plastics (Mihindukulasuriya ~~&~~ and Lim, 2014).

Multiple challenges need addressing for the successful commercialization and scalability of edible coatings. Technological challenges involve achieving a consistent, efficient application on an industrial scale and maintaining stability during storage and transit. Economic hurdles consist of the relatively high cost of some ingredients and the necessity for investments in novel equipment or processes. Regulatory issues related to ensuring the safety of coatings and their ingredients in line with food regulations and standards. Sustained research and development are crucial to tackling these challenges. Technological progress can enhance the efficacy of edible coatings and their application procedures. Economic feasibility can be boosted by discovering cost-effective ingredients and processes and highlighting the benefits of edible coatings, such as reduced product wastage and improved quality. Regulatory compliance can be ensured by undertaking safety evaluations, efficacy studies, and continuous engagement with regulatory bodies. Despite these obstacles, the future of commercializing and scaling up edible coatings seems promising. As the demand for sustainable food preservation methods grows, and as technology and regulations progress, it is anticipated that edible coatings will assume a more significant role in the food industry in the forthcoming years.

Quality assurance for edible coatings should involve some standard procedures designed to evaluate the safety, efficiency, and overall quality of the packaging material. There are legislations to oversee the standards of packaging quality, specifically focusing on the interaction between the packaging and the food products (the packaging-product relationship). The complexity of these regulations stems from the broad range of packaging types (Díaz-Montes and Castro-Muñoz, 2021). Quality assurance tests are critical for ensuring that the edible coatings meet regulatory standards, are safe for consumption, and effectively preserve the quality of the food product it encases. Here is an overview of available quality assurance procedures for edible coatings: (i) *physical and mechanical properties* of coatings in terms of thickness and uniformity, tensile strength and elongation, water vapor, and oxygen permeability (Chakravartula et al., 2019; Mouzakitis et al., 2022); (ii) *chemical properties* as pH and solubility, migration tests, antioxidant activity (Khalid et al., 2022; Marchiore et al., 2017); (iii) *biological properties* such as antimicrobial activity and biodegradability (Lopes et al., 2023; Torres et al., 2011~~; Lopes et al., 2023~~); (iv) *safety and toxicity* in terms of testing for heavy metals/chemicals and allergens (Arnon-Rips ~~&~~ and Poverenov, 2018; Tavassoli-Kafrani et al., 2022); (v) *sensory analysis* (Guerreiro et al., 2016; Jafarzadeh et al., 2021), (vi) *shelf-life studies* (Chettri et al., 2023) and (vii) *regulatory compliance* to ensure that the coating material complies with the relevant food safety and packaging regulations.

Quality assurance for edible coating is a comprehensive process that requires careful consideration of the material's impact on food safety, consumer health, and environmental sustainability. By conducting these tests, manufacturers can ensure that their edible coating materials are not only effective in preserving food but also safe and beneficial for consumers and the environment.

The use of edible coatings is regulated differently across countries, affecting the type and volume of data needed for approval as food packaging materials (Arnon-Rips ~~&~~ and Poverenov, 2018). In both the United States and the European Union, edible films and coatings are regulated under categories such as food ingredients, food products, food contact substances, additives, or packaging substances (Panchal et al., 2022; Raybaudi-Massilia et al., 2016). All ingredients in these coatings must meet food safety and quality regulations. Also, the production process is required to comply with Good Manufacturing

Practices (GMP). The permissible additives for these coatings vary by country; for example, the European Directive lists shellac, pectin, and beeswax as food ingredients, whereas the FDA in the United States approves additives like castor oil and cocoa butter for edible coatings (Priya et al., 2023).

Under the European Regulation (EC) No 1935/2004 (Regulation (EC) No 1935/2004, 2004), food-contact materials, including edible coatings, must meet specific criteria like not altering the food's characteristics and ensuring no harm to human health. However, this regulation lacks detailed guidelines on the safety assessment of nanoparticles in food packaging (Jeya Jeevahan et al., 2020).

In contrast, the FDA in the United States advises comprehensive research for substances containing nanomaterials, including edible coatings, under the Federal Food, Drug, and Cosmetic Act. The European Food Safety Authority (EFSA) also oversees food additives under Regulation (EC) No 1333/2008 (Regulation (EC) No 1333/2008, 2008). For a substance to be used in edible coatings, it must be classified as GRAS by the FDA or approved as a food additive. In the EU, it must be an authorized food additive (Panchal et al., 2022).

Using natural plant extracts and essential oils in edible coatings necessitates regular monitoring for safety and allergenic potential, as they can induce allergic reactions and toxic effects based on the dosage (Priya et al., 2023). In line with sustainable packaging efforts, research into pectin-based edible coatings has been extensively supported to enhance the shelf life and quality of food items. Regulations regarding synthetic resins and chemically modified resins in edible coatings are dictated by both the USFDA and European legislation. For instance, in India, wax coatings using carnauba or bee wax are permitted by the Prevention of Food Adulteration Act (PFA), with mandatory labeling and declaration of materials used (Priya et al., 2023).

The current regulatory landscape, especially concerning nanomaterials in food packaging, lacks definitive guidelines and demands a need for clear regulations. Food producers must comply with the regulations of the destination country, ensuring all edible film ingredients are listed and approved. If using edible films from external suppliers, a no-objection certificate from relevant authorities, including ingredient listings and allergenicity information, is necessary (Jeya Jeevahan et al., 2020).

7. Conclusions and prospects

Edible coatings emerge as an innovative and sustainable solution to preserve the quality and prolong the shelf-life of a wide spectrum of food items, ranging from agricultural produce to finished food products. Prepared using natural materials, these coatings may serve as effective barriers to moisture, gas, and solute transfer, and can be further enhanced. The addition of natural additives and the application of nanotechnology can improve their performance, by providing additional antimicrobial, antioxidant, or sensory benefits.

Despite the challenges concerning their commercial feasibility, scalability, and regulatory compliance, edible coatings hold significant promise for the future, given the ongoing advancements in technology, materials, and regulations, as well as the growing emphasis on sustainability in the food industry.

The findings of this review have several implications for the field. They highlight the need for continued research and development to optimize the formulation and application of edible coatings, to explore and validate the use of new materials and additives, and to address the technical and economic challenges of commercialization and scalability. They also underscore the importance of engaging with regulatory authorities to ensure the safety and compliance of edible coatings and to influence the development of supportive regulations.

Future research should focus on exploring novel green materials and natural additives for edible coatings, developing advanced coating preparation and application techniques, and investigating the performance of edible coatings under various storage and handling conditions. Studies should also aim to assess consumer acceptance of edible-coated products and to analyze the economic and environmental impacts of using edible coatings. Furthermore, efforts should be made to foster collaboration among scientists, food technologists, and regulatory authorities to facilitate the successful development, commercialization, and regulation of edible coatings.

While there is much work to be done, the prospects of edible coatings are promising. With their potential to contribute to food preservation, food quality, food safety, and sustainability, edible coatings are likely to play an increasingly significant role in the food industry in the years to come.

Author Contributions

Marina Jurić: Conceptualization; Methodology; Writing - original draft. **Luna Maslov Bandić**: Writing - review & editing. **Daniele Carullo**: Writing - review & editing. **Slaven Jurić**: Conceptualization; Methodology; Data Curation; Visualization; Writing - original draft; Writing - review & editing.

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Table 1. An overview of the materials typically employed in fabricating natural edible coatings for real food products, coupled with the latest research addressing the associated challenges.

Type of natural material	Production method	Applications	Reference
Polysaccharides (*e.g.*, chitosan, alginate, cellulose, pectin, starch)	Extraction from natural sources, often followed by dissolution in water or other safe solvents and chemical modification	Edible films and coatings for a wide range of food products, enhancing shelf-life and preventing moisture loss	(Cruz-Monterrosa et al., 2023)
Proteins (*e.g.*, gelatin, zein, soy protein, whey protein)	Extraction and purification from natural sources, such as animal tissues or plant seeds, often followed by dissolution in water	Edible films and coatings for meat, fish, fruits, and other food products, provide barriers to gases like oxygen and carbon dioxide	(Kandasamy et al., 2021)
Lipids (*e.g.*, beeswax, carnauba wax, plant oils)	Extraction and purification from natural sources, such as bees, plants, or seeds, followed	Edible coatings for fruits, candy, and other food products, providing a barrier to water vapor and enhancing gloss	(Milani ~~&~~ and Nemati, 2022)

	by possible emulsification		
Composites (any combination of proteins, polysaccharides, and lipids)	Mixing of two or more types of materials, often to combine their beneficial properties	Edible coatings for a wide range of food products, often offering superior performance due to combining the beneficial properties of the different materials involved	(Armghan Khalid et al., 2022)
Bioactive compounds (*e.g.*, antioxidants, antimicrobials)	Extraction from natural sources, such as plants, often followed by dissolution in a safe solvent	Edible coatings incorporating these bioactive compounds for fresh fruits can provide additional benefits, such as extending shelf-life by inhibiting oxidation or microbial growth	(Shiekh et al., 2021)

Table 2. List of naturally-derived edible coatings and successful applications thereof reported in the literature in the last 5 years.

Coated Product	**Edible Coating Materials**	**Storage Conditions**	**Investigated Parameters**	**Results**	**Reference**
Apples (Fresh-cut)	Silk fibroin (6%)/PVA (6%)	4°C, two weeks	Weight loss, color alteration	Diminished weight loss and color alteration	(Ruggeri et al., 2020)
Cucumbers	Lipid-based coating "*LiquidSeal*"	20°C, 65% RH, 8 days	Weight loss, elasticity, CO_2 release, chlorophyll fluorescence	Coating drastically diminished weight loss and reduced tissue stiffness, lowered CO_2 release, attenuated respirational activity, and prolonged shelf life	(Rux et al., 2023)
Garlic cloves	Zein (20%) and milk protein (15%) *Plasticizer: glycerol (35-40% w/w)*	15°C, 40% RH, 45 days	Weight loss, hardness, color, TSS, allicin content, volatiles	Milk protein coatings exhibited superior mechanical properties, while zein coatings showed better water vapor permeability; coatings effectively preserved color and reduced weight loss for up to 30 days, retained TSS, and lowered allicin loss; shelf life was extended up to 10 days with milk protein coating and 15 days with zein coating	(Torun and Ozdemir, 2022)
Starfruit (*Averrhoa carambola*)	Pectin (6%), maltodextrin (4%), and sodium chloride (100-300 ppm)	28°C, 14 days	Weight loss, pH, TSS, water activity, color, texture, microbial growth, FTIR, and sensory evaluation	Coating treatment with 100 ppm sodium chloride resulted in lower weight loss and extended shelf life	(Suhaimi et al., 2021)
Strawberries	Carboxymethyl cellulose (1%), low methoxyl pectin (2%), Persian gum (4%), tragacanth gum (0.6%)	4°C, 16 days	Weight loss, decay, ascorbic acid, total phenolic content (TPC), anthocyanins, firmness, color, and sensory attributes	Significant reduction in weight loss and decay, preservation of nutritional elements, improved sensorial attributes, carboxymethyl cellulose was most effective	(Khodaei et al., 2021)
Strawberries	Chitosan (0.5-1.5%) and Sodium alginate (0.5-1.5%)	20°C, 50% RH, 5 days	Weight loss, mechanical properties, water and oxygen transmission rates, strawberry deterioration, antioxidant capacity, total soluble solids (TSS), titratable acidity (TA), and malondialdehyde content (MDA)	Coating effectively delayed strawberry deterioration and had self-healing properties when treated with water	(Du et al., 2021)
Strawberries	Cashew gum polysaccharide (1%)/PVA (3%)	RT, 5 days	Weight loss, structural appearance, scanning electron microscopy, fungal proliferation	Reduced weight loss and inhibited fungal proliferation	(Moreira et al., 2020)

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Strawberries	Banana starch (2%)/chitosan (1%), Aloe vera gel (10-20%)	25°C, 15 days	Weight loss, TSS, TA, color, mechanical analysis, microbiological assays, and fungal decay	Extended shelf life by 15 days. Decreases water vapor loss. Reduced structural decay, firmness loss, and chemical deterioration	(Pinzon et al., 2020)
Strawberries	Chitosan (1%)/carboxymethyl cellulose (1.5%)	0°C, 8 days	Firmness, aromatic volatiles, TSS, TA, primary and secondary metabolites	Maintained fruit's firmness and aromatic volatiles without impacting TSS and TA. Decelerated primary and secondary metabolism, delaying strawberry senescence during storage	(Yan et al., 2019)
Plums	Carboxymethylcellulose (0.5-1.5%) and Pectin (0.5-1.5%) *Plasticizer: glycerol (0.3%)*	4°C, 85±5% RH, six weeks	Weight loss, firmness, TSS, TA, pH, ascorbic acid, TPC, anthocyanin and flavonoid contents, total antioxidant capacity, and activities of enzymes	Improved firmness, TPC, anthocyanins, flavonoids, antioxidant capacity, and POD activity, while reducing PPO and PG enzyme activities	(Panahirad et al., 2020)
Persimmons	Gum Arabic (5-15%) *Plasticizer: glycerol (1.5%)*	20±1°C, 80±2% RH, 20 days	Weight loss, membrane leakage, H_2O_2, MDA, enzyme activity, TPC, ascorbic acid	Lower weight loss suppressed the increase in enzyme activities. Higher TPC, ascorbic acid, antioxidant activity, and TA, but reduced total carotenoids, TSS, and ripening index throughout the storage	(Saleem et al., 2020)
Almond kernels (Peeled, fresh)	Mastic gum (0.5-2%)	25-27°C, 4 months	Moisture uptake, oil oxidation, total yeast and mold growth, *Aspergillus* species	Reduced moisture absorption, peroxide, and thiobarbituric acid indices, total yeast and mold growth, *Aspergillus* species	(Farooq et al., 2021)
Mangoes ('Palmer')	Hydroxypropyl methylcellulose (5%) and beeswax (10, 20 and 40%)	21°C, 15 days	Weight loss, ripening process, color, firmness, TSS, TA, sugars, ascorbic acid, TPC, flavonoids, β-carotene, antioxidant activity	Controlled ripening, maintaining colors, firmness, TSS, TA, sugars, AA, TPC, flavonoids, β-carotene, and antioxidant activity. Reduced weight loss, oxidative stress, and anthracnose incidence, without inducing alcohol dehydrogenase activity	(Sousa et al., 2021)
Papaya	Potato starch (1-3%) and calcium gluconate salt (0.5%)	Hot air drying at 50°C, 60°C, and 70°C	Moisture content, water activity, hardness, shrinkage, color, bioactive compounds	Improved rehydration ratio, shrinkage percentage, moisture content, water activity, hardness, and color retention	(Islam et al., 2019)
Dates (Barhi)	Gelatin (0.7-2%), chitosan (0.25-0.75%), guar gum (0.15-0.5%)	6°C, 8 weeks	Weight loss, TSS, TA, sugars, total chlorophyll and total carotenoids, vitamin C, TPC, sensory evaluation, total bacterial count	Extended shelf life with 0.5% guar gum and a combination of gelatin, guar, and chitosan being the most effective	(Abu-Shama et al., 2020)

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Mandarins	Chitosan (1%), sodium alginate (1.5%), hydroxypropyl methylcellulose (1%), locust bean gum (0.2%)	20±2°C,10 days 5°C, 28 days	Weight loss, TSS, TA, color, sensory evaluation, bioactive compounds, antioxidant activity, organic acids	Improved fruit preservation with a layer-by-layer combination of hydroxypropyl methylcellulose/chitosan showing the best performance	(Jurić et al., 2023)
Limes	Pectin (3%)	10-25°C, 40 days	Weight loss, texture, color, TSS, TA, ascorbic acid, pH, respiration rate	Slowed down quality degradation, lower respiration rates, and weight loss	(Maftoonazad ~~&~~ and Ramaswamy, 2019)
Walnuts	Defatted walnut flour (6%)	40°C, 84 days	Oxidized and cardboard flavors, walnut flavor, carotenoid, and γ-tocopherol contents, deterioration of oleic/linoleic fatty acids ratio	Maintained quality and flavor. Least deterioration, highest overall consumer acceptance, and better peroxide values after storage	(Grosso et al., 2020)
Mushrooms (Shiitake)	Chitosan (1%) and Guar Gum (5, 15, and 25%)	4±1°C, 16 days	Tissue firmness, degradation in soluble protein and ascorbic acid, TSS, reducing sugar, MDA, electrolyte leakage	Maintained higher tissue firmness and a slower rate of degradation	(Huang et al., 2019)
Herring (Smoked)	Chitosan (2%, 3%, and 4%)	-18°C, 3 months	Microbiological, physicochemical, and sensorial analyses, TPC, flavonoids, and antioxidant activity	Improved quality, stability, and sensory attributes	(Abdel-Naeem~~,~~ ~~Sallam,~~ et al., 2021a)

†Edible coating materials are expressed as % w/v, unless specified differently; RT – Room temperature; RH – Relative humidity

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Table 3. Advantages and disadvantages of the main coating methods used in the food production process.

Coating Method	Advantages	Disadvantages
Spraying	- uniform coating coverage - control of coating thickness - supports automatic continuous production	- requires careful management of spray pressure and distance - high-viscosity solutions can be challenging to spray - careful adjustment of the coating solution's viscosity is needed
Air-Spray Atomization	- cost-effective - uses air to deliver a fine spray of droplets	- requires management of disruptive and cohesive forces
Air-Assisted Airless Atomization	- handles issues related to high-viscosity and high-solids coatings	- requires special nozzle tip for atomization
Pressure Atomization	- applies to coat using pressure, omitting the use of air - suitable for high-viscosity solutions	- requires small nozzles and high-pressure energy
Dipping	- comprehensive coverage - cost-effective and simple - uniform application on complex surfaces - multilayer coating can be easily applied	- control of coating thickness can be challenging - can yield a coating that's too thick - the possibility of coating dilution and waste accumulation
Fluidized bed	- effective for applying thin coating layers to dry, low-density particles - useful for continuous and batch processes - reduces cluster formation and improves drying efficiency	- requires a larger amount of coating solution due to loss in the column wall during spraying - premature evaporation may cause imperfections in the coating - higher costs compared to other methods
Top Spray	- generally, more effective in the food industry	
Bottom Spray	- specific advantages and disadvantages depending on the application	
Rotary Fluidized Bed	- even fine particles behave differently due to high centrifugal force	
Panning	- uniform distribution of coating solution - suitable for hard, practically spherical particles - can apply either thin or thick layers in batch processes	- can be time-consuming and uneconomical due to the need for periodic water evaporation - prevention of product clumping can be challenging

Table 4. Implementation of natural additives in edible coatings for the preservation of various food products.

Coated Product	Coating Material	Natural Additive	Storage Conditions	Investigated Parameters	Results and Remarks	Reference
Fresh fruits and vegetables						
Apples	Xanthan gum (0.5%)	Zinc oxide (0.005%)	RT, 13 days	Characterization of edible coatings and cell culture studies, antibacterial, weight loss, and metabolic activity	ZnO-reinforced xanthan hybrid coating minimized weight loss compared to uncoated produce	(Joshy et al., 2020)
Avocado	Carboxymethyl cellulose (1%), hydroxypropyl methylcellulose (1%), methylcellulose (1%), chitosan (1%) in acetic acid (0.5% v/v)	Phenylalanine (4 mM) or stearic acid (0.6%)	22°C, 70 % RH, 14 days and 5°C or 2°C, 21 days followed by 22°C	Overall fruit quality, decay, volatiles, sensory evaluation, qPCR, epicatechin quantification	Chitosan and carboxymethyl cellulose with stearic acid were selected as the base for Phe addition; reduced decay from fungal pathogens like *Colletotrichum* and *Alternaria*, enhanced resistance to cold stress, minimized pitting and internal browning, and improved flavor; effectiveness linked to the upregulation of certain genes involved in the fruit's defense response	(Saidi et al., 2021)
Blackberries (Andean)	Cassava starch (3.5%), whey protein (1.16%), beeswax (0.47%), chitosan (0.75%) *Plasticizer: glycerol (9.32% v/v)*	Stearic and glacial acetic acid (1% v/v)	4°C, 10 days	Weight loss, firmness, TPC, anthocyanins, antioxidant activity, mold/yeast counts, and sensory properties	Positive effects on the physicochemical properties, conserved sensory quality, and significantly improved quality of the fruit effectively doubled the shelf life	(Cortés Rodríguez et al., 2020)
Blueberries	Gum Arabic (10%) *Plasticizer: glycerol (1.0% v/v)*	1.5% (v/v) of red or white roselle extracts (extracts obtained from 12% in 60% EtOH)	4±0.5°C, 18 days	Weight loss, decay, firmness, phytochemicals, antioxidant capacity, enzyme activities, and microbiological analyses	Inhibited the growth of microbes, reduced enzyme activities, curbed the degradation of anthocyanins and total phenolic, decreased weight loss and decay, and improved the firmness of the blueberries	(Yang et al., 2019)

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Broccoli	Chitosan (1%) in acetic acid (1% v/v)	Tea polyphenols (1%); Chitosan solution to tea polyphenols solution ratio 1:1	20±2°C, 60-70% RH, 5 days	Weight loss, decay, respiration rate, TSS, Vitamin C, amino acids, sulforaphane content, expression analysis, antioxidant capacity, phenotypic color and texture analysis, E-nose detection, chlorophyll determination, and fluorescence microscope imaging	Chitosan/tea polyphenols treatment significantly reduces decay, weight loss, and respiration compared to single chitosan and control; effectively mitigates yellowing, maintaining higher hue angles, chlorophyll levels, and red fluorescence emission, thus delaying yellowing; preserved sensory quality, vitamin C content, and antioxidant capacity; maintained higher levels of sulforaphane, by upregulating related gene expressions	(Fang et al., 2022)
Tomatoes	Whey protein isolate (5%) (*pH=9*)/xanthan gum (1% w/v on protein isolate basis) *Plasticizer: glycerol monostearate (2% w/v on protein isolate basis)*	2% (v/v) Clove oil	20°C, 85% RH, 15 days	Weight loss, decay, firmness and color, TSS, TA, pH and ascorbic acid, total sugars, reducing sugars, TPC and total flavonoid content, total plate count and sensory analysis	Improved firmness and color, with better retention of TA, ascorbic acid, TPC, total sugars, and reducing sugars; whey protein isolate/xanthan gum coating effectively prolonged shelf life by inhibiting respiration and starch conversion and sustained tomato quality over 15 days of storage	(Kumar and Saini, 2021)
Tomatoes	Chitosan (2%)/pullulan (2%) *Plasticizer: glycerol (1% v/v)*	5% of pomegranate peel extract (0.02 g/mL MetOH)	23°C and 4°C, 18 days	Weight loss, TSS, TA, color preservation, pH stabilization, TPC, flavonoid content, antioxidant activity	Significantly improved postharvest quality of tomatoes at both room and cold temperatures, extended their shelf life, and enhanced consumer acceptance	(Kumar et al., 2021a)
Tomatoes	Xanthan gum (0.5%)	Zinc oxide (0.005%)	RT, 13 days	Characterization of edible coatings and cell culture studies, antibacterial, weight loss, and metabolic activity	ZnO-reinforced xanthan hybrid coating minimized weight loss compared to uncoated produce	(Joshy et al., 2020)
Tomatoes	Candelilla wax (0.15-0.25%), whey protein (2-3%)	*Flourensia cernua* extract (500 ppm)	25±2°C, 10 days	Weight loss, firmness, pathogenic fungi growth, visual appearance, sensory evaluation	Reduced weight and firmness loss, inhibited the growth of pathogenic fungi, improved visual	(Ruiz-Martínez et al., 2020)

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	Plasticizer: glycerol (2-3%)				appearance, and accepted by consumers	
Tomatoes (Cherry)	Chitosan/Gelatine	Lemongrass oil	Cold storage for 20 days	Antimicrobial efficacy, digital imaging	Prevention of fungal contamination throughout the storage period, the potential for improving shelf life	(Erceg et al., 2023)
Tomatoes (Cherry)	Exopolysaccharide from *Weissella confusa* JCA4 *Plasticizer: glycerol (1% v/v)* *Surfactant: Tween80 (0.5% v/v)*	*Lactiplantibacillus plantarum* A6 (1%)	4°C, 30°C, 8 days	Weight loss, firmness, respiration rate, antifungal properties against *Aspergillus niger*, *Fusarium sp*., and *Rhizopus stolonifera*	Controlled weight loss, maintained firmness, and slowed the respiration rate without negatively affecting other physicochemical properties and appearance	(Álvarez et al., 2021)
Peppers (Green bell)	Chitosan (2%)/pullulan (2%) composite (50:50) *Plasticizer: glycerol (1% v/v)*	5% (v/v) pomegranate peel extract (initial conc. 25 %)	23±3°C, 40-45%, 4±3°C, 90-95% RH, 18 days	Weight loss, color browning, TSS, TA, pH, TPC, flavonoid content, antioxidant activity, firmness, and sensory attributes	Coating maintained physiochemical quality and enhanced sensory scores while effectively prolonging shelf life at room and cold storage temperatures	(Kumar et al., 2021b)
Peppers (Green capsicums)	Alginate-based coatings (100, 50, 33.3 wt%) *Plasticizer: glycerol (40%wt)*	Aloe vera (50-66.7 %wt) and Frankincense oil (2-6 v/wt%, based on total weight)	25°C, 16 days	Mechanical properties, UV-shielding, antimicrobial activity, water-barrier properties	Improved thermal stability and mechanical properties, significant UV-shielding and antimicrobial activity, and substantial reduction in water vapor permeability	(Salama ~~&~~ and Abdel Aziz, 2021)
Guava	Gum Arabic (10%) *Plasticizer: polyethylene glycol (5%)*	Cactus pear stem (10%), moringa (10%), henna leaf (3%) extracts	7±1°C, 90±5% RH, 22–24°C, 65±5% RH, 24 days	Weight loss, decay, rot ratio, fruit firmness, TSS, total sugars, total antioxidant activity	Reduced weight loss, decay, and rot ratio, and enhanced marketability, maintained fruit firmness, TSS, total sugars, and total antioxidant activity	(El-Gioushy et al., 2022)
Lychee (*Litchi chinensis* Sonn.)	Chitosan-citric acid (0.5-1%)	Pomelo extract (1-2%)	5°C, 14 days, transferred to 20°C, 3 days	Weight loss, decay, browning, and disease severity, sensory quality	Chitosan (1%) with pomelo extract (2%) improved the shelf life, reduced browning, weight loss, and disease severity while extending the shelf life by at least	(Yang et al., 2023)

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					2 days, maintaining marketability in 73.3% of the fruits and enhancing sensory quality	
Mangoes	Shellac (9%) *Plasticizer: glycerol (2%)*	Tannic acid (0.5%)	RT, 17 days	Weight loss, tissue firmness, respiration rates, physicochemical qualities, browning and lipid peroxidation, aromatic volatiles, and enzyme activities	Extended the shelf life, maintained tissue firmness and weight loss, decelerated respiration rates, enhanced physical properties and chemical qualities, reduced browning and lipid peroxidation, preserved aromatic volatiles, and regulated enzyme activities	(Ma et al., 2021)
Mangoes	Chitosan (2%)/pullulan (2%) (50:50) *Plasticizer: glycerol (1%)*	5% pomegranate peel extract (initial conc. 0.02 g/mL)	23°C, 45% RH, 4°C, 95% RH, 18 days	Weight loss, TSS, TA, pH, sensory quality attributes, firmness, TPC, antioxidant activity	Reduced weight loss and maintained TSS, TA, pH, firmness, TPC, and antioxidant activity	(Kumar et al., 2021c)
Mangoes	Chitosan (0.002 g/mL) and alginate (0.2 w/v) *Surfactant: Tween80 (0.75%)*	Cinnamon essential oil microcapsules	25°C, 50% RH, 14 days	Weight loss, TSS, TA, vitamin C, and respiration rate	Good adhesion to mango surface, improved preservation of TSS, TA, and vitamin C contents, reduced weight loss, and delayed respiration peaks	(Yin et al., 2019)
Nectarines	Chitosan (1%) in glacial acetic acid (1% v/v) and carboxy methylcellulose (1.5%) *Surfactant: Tween20 (1%)*	5% mixed methanolic extract (20% methanolic extract from moringa, marigold, and eucalyptus)	1±1°C, 85-90% RH, 25 days	Weight loss, decay, firmness, ascorbic acid, TPC, antioxidant activity, and sensory evaluation	Coatings reduced decay and weight loss, maintained fruit firmness and preserved functional qualities; layer-by-layer coating very effectively reduced decay and weight loss, maintaining higher levels of key nutrients and overall acceptability for up to 25 days	(Sowmyashree et al., 2021)
Oranges ('Thomson Navel')	Aloe vera gel (30%) *Plasticizer: glycerol (1% v/v)*	Salicylic acid (2 mM)	4±1°C, 80±5% RH, 20, 40, 60, 80 days	Weight loss, firmness, decay index, chilling injury, TSS, TA, vitamin C, TPC, electrolyte leakage, MDA, microbiological analysis, and sensory evaluation	Improved quality of oranges and reduced microbial load and chilling injury, effectively extending the shelf-life of the fruit	(Rasouli et al., 2019)

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Peaches	Sodium alginate (1%)	Rhubarb extract (1 g/mL)	28±1°C, 90% RH, 7 days	Weight loss, firmness, TSS, respiration rate, MDA, polyphenol oxidase activity, sensory evaluation	Reduced weight loss, respiration rate, MDA, and polyphenol oxidase activity	(Li et al., 2019)
Peaches	Chitosan (1% v/v) -grafted with chlorogenic acid	Chlorogenic acid (1:1, 1:0.5, or 1:0.1 molar ratios of chitosan repeat unit to chlorogenic acid)	20°C, 8 days	Weight loss, firmness, decay index, TSS, TA, ascorbic acid content, respiration rate, and reactive oxygen species generation	Maintained quality of peaches and presented a better coating effect than chitosan without chlorogenic acid	(Jiao et al., 2019)
Peanuts (Raw and roasted)	Pectin/pullulan Binary Blend Film (50:50)	*Vitis vinifera* grape seed extract (5 wt% of polymer)	25°C, 85-90% RH, 30 days	Compatibility studies, antimicrobial activity, antioxidant potential, UV blocking properties, gas barrier, and effect on peroxide values	Reduced peroxide values by 75%, delayed rancidity, and extended shelf life	(Priyadarshi et al., 2022)
Pears	Sweet potato starch (0.03 g/mL) *Plasticizer: glycerol (30% w/w, based on the weight of dry starch)*	Cumin essential oil (0.2-0.4%)	25°C, 85-90% RH, 28 days	Weight loss, firmness, rot, changes in color, stomata densities, climacteric rise in respiration	Reduced rot, delayed changes in color and firmness, minimized weight loss, maintained stomata densities and desirable sensory attributes	(Oyom et al., 2022)
Persimmons	Gelatin (2%) *Emulsifier: Tween 80 (25 w/w, based on oil content)* *Plasticizer: 30% Glycerol (30% w/w, based on gelatin content)*	Frog skin oil at concentrations of 5%, 25%, and 50% (w/w, based on gelatin content)	25±2°C, 9 days	Weight loss, Firmness, pH, TSS, color, Respiration and ethylene production, Disease severity inoculated with *Botrytis cinerea*, Sensory evaluation	Higher oil concentrations enhanced the uniformity of the emulsion system and the smoothness of the film surface; coating slowed down fruit damage during storage, reduced weight loss, and lowered TSS, resulted in high firmness and pH; odor and overall acceptance of the coated fruit were negatively impacted by higher concentrations of oil; further improvements are necessary	(Kingwascharapong et al., 2020)
Strawberries	Chitosan (1%)	Ascorbic Acid (1%)	4±1°C, 85±5% RH, 15 days	Weight loss, fruit softening, decay percentage, MDA, hydrogen peroxide, ROS scavenging enzymes	Improved fruit softening and quality, reduced weight loss, decay, MDA, and hydrogen	(Saleem et al., 2021)

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					peroxide compared to chitosan alone	
Strawberries	Chitosan (1% v/v) *Plasticizer: glycerol (30 % w/w)*	Apple peel polyphenols (0.25-1.0%)	20°C, 35-40% RH for 6 days	Weight loss, firmness, decay, TSS, TA, TPC	Reduced weight loss and decay, maintained high TPC, and delayed fruit senescence	(Riaz et al., 2021)
Strawberries	Hydroxyethyl cellulose (1.0-1.5%) and Sodium alginate (0.5-1.5%)	Asparagus waste extract (solid/liquid ratio of 1:40 g/mL)	25°C, 80% RH for 8 days	Weight loss, color change, TPC and flavonoid content, anti-fungal activity	Continuous, smooth, and porous structure, significantly delayed color change, reduced weight loss, and maintained TPC and flavonoid contents	(Liu et al., 2021a)
Strawberries	Carboxymethyl cellulose (1%) *Plasticizer: glycerol (30 % w/w)*	*Lactobacillus plantarum* (10^{11}-10^{13} CFU/mL)	4°C, 16 days	Weight loss, firmness, decay, color, TSS, TA, ascorbic acid and TPC, microbial analysis	Probiotic-loaded coatings positively affect the physicochemical properties of strawberries while not influencing their color, hardness, or other key parameters	(Khodaei ~~&~~ and Hamidi-Esfahani, 2019)
Strawberries	Pectin (3%) from orange peels	Lemon essential oil (2% v/v) and Reuterin (10 mM)	4°C, 31 days	Weight loss, color, moisture content, and fungal spoilage	Coatings did not markedly impact the physicochemical properties but maintained more moisture than the controls and the presence of reuterin significantly reduced the amount of viable *Penicillium* spp. conidia	(Hernández-Carrillo et al., 2021)
Walnut	Chitosan (1.5%) in acetic acid (1% v/v)	25% (v/v) Glycerol ginger extract (10% w/v)	45°C, 10 days	Color, lipid oxidation and peroxide values, and antifungal activity	Functionalized coating reduced oxidation, and growth of *Aspergillus flavus*; sensory tests are neecessary to verify the final acceptability of the treated walnuts	(Shaukat et al., 2023)
Fresh-cut fruits and vegetables						
Artichoke bottoms (fresh-cut)	*Cordia myxa* gum (1%)	Calcium dichloride (1%) or ascorbic acid (1%)	2°C, 95% RH, 9 days	Weight loss, browning, polyphenol oxidase activity (PPO), firmness, vitamin C, TPC, and microbial load	Effectively preserved the quality of artichokes, reducing weight loss, browning, and PPO activities while preserving vitamin C and TPC, and	(El-Mogy et al., 2020)

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					controlled the microbial load (molds and *E. coli*)	
'Fuji' apples (fresh-cut)	Aloe vera gel (40%)	Lemon essential oil (1%) and hydroxypropyl methylcellulose (0.1%)	4±1°C, 90±5% RH, 9 days	Weight loss, color, firmness, ash, fat content, TSS, riboflavin, ascorbic acid	Significantly delayed weight loss, reduction in TSS, color, softening, ripening, browning, and acidity	(Farina et al., 2020)
Apples (fresh-cut)	Alginate (2%) *Plasticizer: glycerol (1.5 % w/w)* *Crosslinker: CaCl$_2$ (2%)*	Oligofructose (8% w/w) and inulin (8% w/w), *Lactobacillus rhamnosus* (9.5%) and *Bifidobacterium animalis* subsp. *lactis* (7.8%) pellets, ascorbic acid (1%)	5±1°C, 8 days in polyolefine film	Probiotic count after storage and gastrointestinal digestion, antioxidant activity, TPC, and sensorial acceptability	After 8 days of storage, probiotics remained viable and the microbiological and nutritional quality of the apple pieces were maintained where both probiotics exerted a bactericidal effect against *L. innocua*	(Alvarez et al., 2021)
Potato strips (fresh-cut)	Garden cress (*Lepidium sativum*) seed extract mucilage *Plasticizer: glycerol (0.5 %)*	Ascorbic acid (500 ppm)	5°C, 95% RH, 12 days, and subsequent frying	Weight loss, texture, browning index, TPC, oil uptake, total microbial count, sensory assessment	Reduced weight loss, browning index, and preserved firmness and TPC during storage of fresh-cut potatoes. Reduction in oil uptake during frying. Favorable sensory ratings, with no noticeable off-flavors or color changes	(Ali et al., 2021)
Dairy products						
Cheeses (fresh)	Alginate (2%), maltodextrin (16%), *Plasticizer: glycerol (2 %)* *Crosslinker: CaCl$_2$ (0.05 mol/dm)*	Bacteriocin-producing lactic acid bacteria encapsulated in beads	4°C and 10°C, 10 days	Weight loss, moisture loss, viability and antibacterial activity of entrapped bacteria, contamination by *Listeria monocytogenes*, migration of *L. monocytogenes* from the surface into cheese, pH, and TA	Maintained cheese quality, reduced contamination, bacteriostatic effect on the growth of *L. monocytogenes* on the surface (coating) of fresh cheese, and the inhibition of spoilage bacteria growth during storage	(Silva et al., 2022)
Iranian ultra-	Chitosan (1.6%)	Natamycin (18.5 ppm)	4±2°C, 6 weeks	Water content, pH, total chloride content, fat, hardness, sensory analysis, and microbial assay	Moderate effects on some physicochemical attributes of the coated cheeses inhibited the	(Nottagh et al., 2020)

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filtrated cheese					growth of spoilage microorganisms and maintained sensory attributes	
Fresh meat and eggs						
Chicken drumsticks	Chitosan (2% w/w)	Lauric arginate (2% w/w)	−18°C, 3 months	Bacterial counts, pH levels, total volatile base nitrogen, thiobarbituric acid values, sensory assessment	Successful decontamination of chicken carcasses and their cut-up parts in poultry processing plants decreases the microbial load, improves oxidative stability, and enhances sensory characteristics	(Abdel-Naeem et al., 2021b)
Beef slices	Shahri Balangu Seed Mucilage (0.02 g/mL) *Surfactant: Tween80*	Cumin essential oil (0.5-2%)	4°C, 9 days	Lipid oxidation, microbial populations, and sensory assessment	Reduction in microbial populations and lipid oxidation, improvement in sensory characteristics, and shelf life extended with higher essential oil concentrations	(Alizadeh Behbahani et al., 2020)
Buffalo meat	Plantago Major Seed Mucilage (PMSM) (0.02 g/mL) *Surfactant: Tween80*	*Citrus lemon* essential oil (0.5-2%)	4°C, 10 days	Lipid oxidation, hardness, microbial growth, sensory properties	Significant suppression of lipid oxidation and microbial growth, maintenance of meat hardness, and sensory properties	(Noshad et al., 2021)
Fresh pork	Sodium alginate (2%)/Carboxymethyl cellulose (2%)	Epigallocatechin gallate (0.8-1.6%)	4±1°C, 7 days	Lipid oxidation, color, total volatile basic nitrogen, total viable microbial count, sensory assessment	Significant reduction in microbial growth and lipid oxidation, maintained color, and improved sensory scores	(Ruan et al., 2019)
Fresh pork	Chitosan (1%) and Gelatine (3%)	Grape seed extract (0.5%) and/or nisin (10^5 IU/mL)	4°C, 20 days	Pork oxidation and microbial spoilage	Effectively reduced pork oxidation and microbial spoilage	(Xiong et al., 2020)
Stored meat	Sodium alginate (2%)	Basil Extract (1-2%)	2°C under light exposure (1200 lx; 12 h/day), 14 days	Lipid oxidation, color, pH, TPC, antioxidant activity, consumer acceptability	An increase in TPC and antioxidant activity, reduction in lipid oxidation, darker meat with more intense colors, and basil inclusion improved consumer acceptability	(Alexandre et al., 2021)
Lamb meat	Sodium alginate (0.02 g/L)	Essential oils from thyme (*Thymus vulgaris* L.) and	2-4°C under light exposure	Lipid oxidation, color, and water-holding capacity	Reduced exudative losses and impacted color characteristics, particularly increasing yellowness	(Guerrero et al., 2020)

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	Crosslinker: calcium chloride solution (2% w/v)	garlic (*Allium sativum* L.) (0.05% w/w)	(1200 lx; 12 h/day), 7 days		and chrome, the addition of thyme essential oil maintained color during display and showed significantly lower lipid oxidation	
Eggs	Chitosan (0-3%) *Plasticizer: glycerol (2% v/v)*	Propolis extract (0-70%)	27°C, 14 days	Weight loss, shell strength, haugh unit, egg white pH, egg yolk pH, foaming capacity, oil separation values, and bactericidal activity	Improved quality of eggs and extended their shelf life due to the significant bactericidal activity against *Salmonella enteritidis*	(Ezazi et al., 2021)
Fish and seafood						
Fresh salmon fillet	Salmon bone gelatine (2%) and chitosan (2%)	Gallic acid (0.2% (v/v)) and/or clove oil (0.5% (v/v))	4°C, 15 days	Lipid and protein oxidation, color, pH, and microbial growth	Inhibited oxidation and microbial growth, improved antioxidant effects	(Xiong et al., 2021)
Black tiger shrimp	Chitosan (2%)/gelatin (2%)	Longkong pericarp extract (0.5-1.5%)	4°C, 20 days	Lipid and protein oxidation, melanosis, polyphenol oxidase activity, pH, and microbial growth	Controlled melanosis and polyphenol oxidase activity, minimized lipid and protein oxidation and inhibited microbial growth	(Nagarajan et al., 2021)
Silver pomfret (*Pampus argenteus*) fish steaks	Corn starch (2%)	fumaric acid (0.5%)	4±0.2°C, 15 days	Total volatile base nitrogen, thiobarbituric acid, peroxide value, pH, and sensory quality with microbiological assessment of total viable count, psychrotrophic count, *Pseudomonas* spp., and H_2S-producing bacteria	Corn starch-based coating delayed lipid oxidation, while fumaric acid effectively increased the preservative action of coating by significantly inhibiting microbial growth as well as lipid quality deterioration, without negatively impacting organoleptic properties	(Remya et al., 2022)

†Edible coating materials are expressed as % w/v, unless specified differently; RT – room temperature; RH – relative humidity

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Table 5. The potential of nanotechnology application in edible coatings development.

Product	Nanoproduct (coating)	Storage conditions	Results	Reference
Avocados	ZnO nanoparticles in chitosan/gum arabic coating, synthesized via hydrothermal method	23°C, 8 days	Extended freshness by 7 days	(Le et al., 2021)
Apple	Nanofiber coating – a blend of silk fibroin, polyvinyl alcohol, honey and curcumin	RT, one month	Enhanced shelf life for a month with maintained texture, quality, and stiffness; uncoated rot after just one week, losing stiffness by the 18th day and deteriorating completely by the 20th day	(Singh and Packirisamy, 2022)
Apple	Coating emulsion based on bacterial cellulose nanocrystals, fish gelatin and cinnamon essential oil	25°C, 21 days	Inhibitory effect against *P. expansum* and *B. cinerea* growth	(Razavi et al., 2022a)
		4°C, 60 days	Decrease in weight loss and respiration rate/ethylene production	(Razavi et al., 2022b)
Apple slices	Resveratrol-loaded zein nanofibers via electrospinning	RT, 6 hours	Controlled moisture loss and color retention	(Maria Leena et al., 2020)
Bananas	Nanofiber coating – a blend of silk fibroin, polyvinyl alcohol, honey and curcumin	RT, 10 days	Shelf-life extended by four days, and banana texture, stiffness, and quality were maintained while the uncoated banana on the 6th day lost its stiffness and emitted a foul smell	(Singh and Packirisamy, 2022)
Bananas	ZnO nanoparticles in chitosan/gum arabic coating, synthesized via hydrothermal method	35°C, 54% RH, 18 days	Shelf life extended by more than 17 days	(La et al., 2021)
Berry fruits	Beeswax-in-water Pickering emulsions stabilized with cellulose nanofibrils and carboxymethyl chitosan	Ambient conditions	Inhibitory effect on spoilage organisms such as *S. aureus* or *E. coli*	(Xie et al., 2020)
Bell peppers	Chitosan nanoparticles encapsulating α-pinene synthesized by the nanoprecipitation method	12±2°C, 21 days followed by 5 days at 20±2°C	Significant reductions in weight loss, maintenance of firmness, color, and other physical attributes, and suppression of *Alternaria alternata*	(Hernández-López et al., 2020)
Bell pepper (red) (fresh-cut)	$CaCl_2$/low molecular weight chitosan/tea tree oil nanoemulsion coating	4°C, 21 days	Controlled microbial colonization, retained total phenolic and flavonoid content, and antioxidant activity, and maintained overall quality for up to 18 days	(Sathiyaseelan et al., 2021)
Guavas	Nanostructured chitosan/alginate/nanoZnO coating prepared via a casting method	21±1°C, 80±2% RH, 15 days	Shelf life is extended by up to 20 days	(Arroyo et al., 2020)

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Pears (Huangguan)	Cross-linked cassava starch-based nanocomposite coating with starch nanocrystals	20°C, 4 weeks	Extended shelf life for up to 28 days	(Dai et al., 2020)
Raspberries	A gelatin-based edible coating containing Propolis ethanolic extract, formulated via two methods: direct integration and encapsulation within zein nanocapsules	5°C, 11 days	More flexible and deformable edible films with enhanced antifungal activity, lower fungal decay during cold storage	(Moreno et al., 2020)
Pineapples (fresh-cut)	Sodium alginate coating with different concentrations of citral nanoemulsion obtained via ultrasonic emulsification	4°C, 90% RH, 12 days	Shelf life is extended while maintaining quality parameters and reducing microbial contamination	(Prakash et al., 2020)
Strawberries	Sustainable nanomaterials (SNM): wood cellulose nanocrystals (WCNC), wood cellulose nanofibers (WCNF), sugarcane cellulose nanofibers (SCNF), chitin nanofibers (CTNF), chitosan nanofibers (CSNF)	8°C, 13 days	All the SNM coatings exhibited good antifungal activity (against *Botrytis cinerea*) and helped maintain fruit freshness. The antifungal activity was influenced by the functional groups and particle size of these nanomaterials. WCNC/CSNF blend exhibited the best performance in antifungal activity and color change delay	(Sun et al., 2021)
Tomatoes	Carnauba wax nanoemulsion obtained using a high-pressure processing	23±1°C, 80% RH, 15 days	Effectively reduced weight loss and enhanced gloss and appearance of tomatoes, without significantly impacting gas permeability, oxygen and carbon dioxide production, color, or sugar content	(Miranda et al., 2022)
Tomatoes	Nanoemulsion edible coating composed of carboxymethyl cellulose and cardamom essential oil	25±2°C, 15 days	Reduced weight loss, firmness, TSS and TA, and oxidative stress during storage; maintained the levels of antioxidant enzymes, prevented oxidative damage-induced senescence of tomatoes; lower microbial load in coated tomatoes	(Das et al., 2022)
Tomatoes	Alginate-based coating enriched with oregano essential oil nanoemulsion (high-pressure homogenization), prepared via cross-linking with $CaCl_2$	RT, 14 days	Reduced microbial growth, extended shelf life of tomatoes, and improved performance with nanoemulsion	(Pirozzi et al., 2020)
Cheddar cheese (fresh-cut)	Whey protein isolates nanofibers using a fibrillation process combined with carvacrol	4°C, 10 days	Improved antioxidant and antimicrobial activity, better physical properties, reduced weight loss, and improved texture of cheese	(Wang et al., 2019)

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	and glycerol, high-shear homogenization for emulsion preparation			
Turkey fillets	Alginate with *Trachyspermum ammi* essential oil nanoemulsion edible coating prepared using ultrasonic emulsification	4±1℃, 12 days	Inhibited growth of *Listeria monocytogenes,* extending shelf life	(Kazemeini et al., 2021)
Pork loin (fresh)	Pectin coating loaded with oregano essential oil and resveratrol nanoemulsion prepared using a high-speed homogenizer	4°C, 15 days	Extended shelf life by minimizing pH and color changes, slowing lipid and protein oxidation, preserving meat tenderness, and inhibiting microbial growth	(Xiong, Li, et al., 2020)
Shrimp	Alginate coating with grapefruit seed extract nanoparticles prepared using ultrasonic emulsification	4°C, 8 days	Shelf life extended by over 5 days	(Baek et al., 2021)
Hairtail fish	Eugenol-chitosan nanoemulsion coating prepared using ultrasound-mediated emulsification	4°C, 18 days	Prevented oxygen and microorganism intrusion, slowed lipid and protein oxidation, and maintained fish quality	(Liu et al., 2021b)

†RT – Room temperature; RH – Relative humidity

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Figure captions

Figure 1. Schematic diagram illustrating the process of preparing edible coatings.

Figure 2. Example of nanotechnology application in the development of edible coatings

Figure 1.

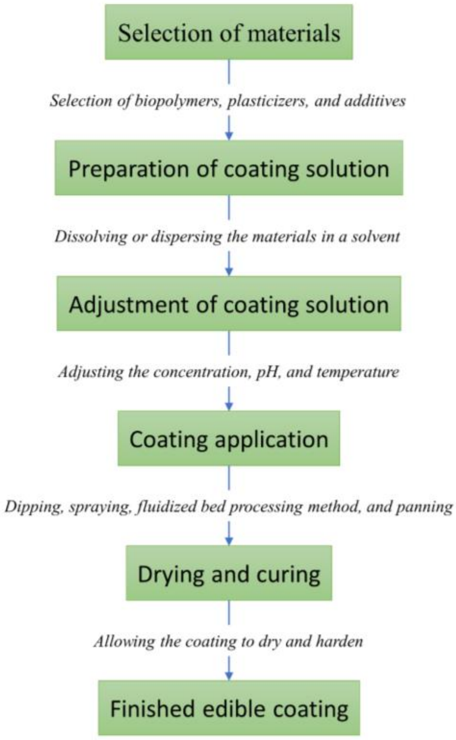
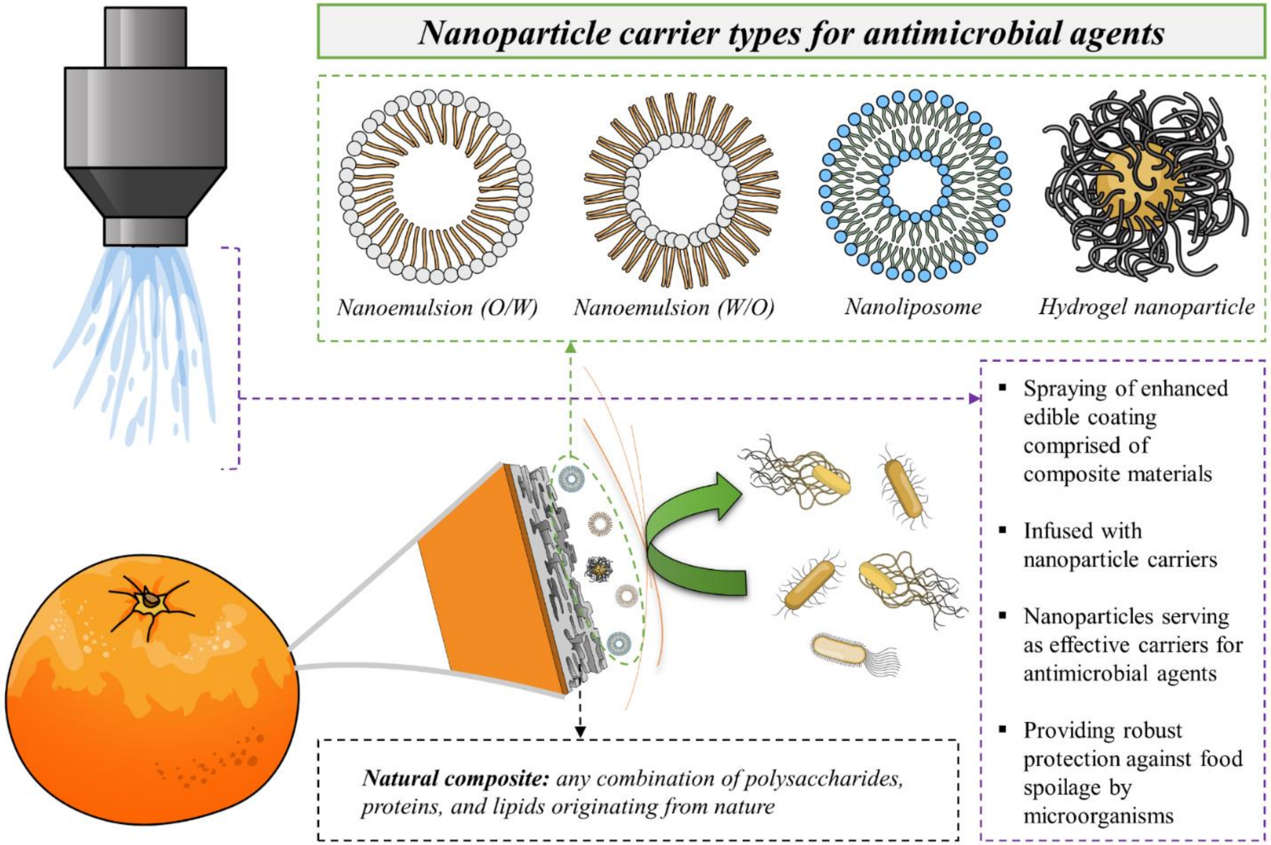

Selection of materials
Selection of biopolymers, plasticizers, and additives
Preparation of coating solution
Dissolving or dispersing the materials in a solvent
Adjustment of coating solution
Adjusting the concentration, pH, and temperature
Coating application
Dipping, spraying, fluidized bed processing method, and panning
Drying and curing
Allowing the coating to dry and harden
Finished edible coating

Figure 2.


Nanoparticle carrier types for antimicrobial agents
Nanoemulsion (O/W)
Nanoemulsion (W/O)
Nanoliposome
Hydrogel nanoparticle
Spraying of enhanced edible coating comprised of composite materials
Infused with nanoparticle carriers
Nanoparticles serving as effective carriers for antimicrobial agents
Providing robust protection against food spoilage by microorganisms
Natural composite: *any combination of polysaccharides, proteins, and lipids originating from nature*