



# Active packaging for vegetables: latest innovations and future research directions

Nur Rahmawati

Faculty of Agricultural Technology, Hasanuddin University, Makassar 90245, Indonesia

## Abstract

Active packaging is an important innovation in maintaining quality, safety, and extending the shelf life of fresh vegetables, which have more vulnerable postharvest physiological characteristics compared to fruit, such as high respiration rates, rapid water loss, and sensitivity to wilting. This study aims to examine the development of research on active packaging for vegetables through a bibliometric approach and systematic review. The results show that publications on active packaging for vegetables have increased significantly over the past 25 years, with a sharp surge during the 2019–2024 period and a peak in the number of documents in 2024. India is the most productive country based on the number of documents, while Brazil has the highest number of citations. Keyword co-occurrence analysis indicates that active packaging is the central theme connected to major clusters such as 1-methylcyclopropene, biodegradable, antibacterial, antimicrobial activity, and chitosan. Recent trends also point to topics like bioactive compounds, polyphenols, ethylene scavenger, polylactic acid, biodegradable film, controlled release, food safety, nanotechnology, and coating. Additionally, the International Journal of Biological Macromolecules is identified as the main publication hub, with many contributions from India, China, and Brazil. Overall, this study emphasizes that the field of active packaging for vegetables is rapidly developing and shows a shift towards the development of biopolymer-based materials and natural compounds that are more environmentally friendly and more specific to the physiological needs of fresh vegetables.

## Article History

Received December 10, 2025

Accepted February 12, 2026

Published May 21, 2026

## Keywords

Active Packaging,  
Bibliometric Analysis,  
Vegetable Preservation  
and Biopolymers

## 1. Introduction

In recent years, the global production and consumption of fruits and vegetables has increased rapidly, driven by the growth of the world population and improvements in eating habits and health awareness (1). Villanova-Estors et al. (2025), also stated that in today's fast-paced society, the preference for healthy, fresh, and ready-to-eat foods is on the rise (2). This trend has highlighted the ability of the food industry to ensure the safety and extend the shelf life of fresh and perishable products, such as minimally processed fruits and vegetables (3).

Fresh fruits and vegetables naturally experience a decline in quality after harvest, and the rate of this decline is influenced by various factors including respiration rate, ethylene production, compositional changes, water loss, physiological disorders, and pathological damage (4). Therefore, appropriate packaging technology is needed to enhance their safety and shelf life. Furthermore, a well-designed food packaging system can prevent fresh products from spoilage (5–7).

Food packaging plays a primary role in protecting food products from external environmental influences. The main objective of food packaging is to store food in the best and most economical way, to meet the requirements of industry and consumers, to ensure food safety, and to minimize environmental impact (8). Advances in food packaging research have led to the development of active packaging. Active packaging is a system in which the packaging has been modified to maintain or enhance the sensory aspects, safety, and quality of food (9). Additionally, active packaging has the potential to replace the addition of active compounds to foods, reduce the migration of particles from packaging materials into food, and eliminate industrial processes that could introduce pathogenic microorganisms into products (10). This packaging system also offers the advantage of reducing foodborne outbreaks and food recalls (11).

In recent years, as consumer interest in convenient food handling and longer shelf life has increased (9,12), numerous review publications have emerged describing new technologies in food packaging, especially those related to active packaging for horticultural products. Cui et al. (2024), reviewed the enhanced functions of electrospun films with natural materials for active packaging applications for fruits and vegetables (13). Mao et al. (2025), reviewed the functions of starch-based packaging (films or coatings) containing polyphenols, focusing on the ability of active packaging to maintain quality and extend the shelf life of fruits and vegetables (14). Wang et al. (2025), reviewed the current status and future prospects of coatings and functional films derived from silk protein as a novel biomaterial for the preservation of fruits and vegetables (15). In addition, a review by Nian et al. (2024), details the development of biodegradable active packaging for perishable crops, specifically addressing polymer composition, material interactions, and application methods (16). However, research on active packaging so far has been mostly directed toward fruits, so vegetables still receive less attention. Given that the postharvest characteristics of fresh vegetables differ greatly from those of fruits, such as high respiration rates, rapid water loss, very short shelf lives, and sensitivity to visual changes like wilting, this review becomes highly relevant. Therefore, there is a need to develop active packaging optimized for vegetables. A specific review of active packaging for vegetables is of high urgency to meet industry and consumer needs, rather than serving only as a complement in general horticultural studies. To the best of our knowledge, there has not yet been, there has not yet been a bibliometric review specifically focused on active packaging for fresh vegetables.

This review aims to comprehensively examine the development of active packaging innovations that have been applied to horticultural products, with a special emphasis on fresh vegetables. The research focus is directed at exploring the postharvest differences between fruits and vegetables, considering that vegetables have a higher respiration rate, a shorter shelf life, and are more susceptible to wilting and moisture loss, which are not as intensely observed in fruits. By analyzing previous studies, this review seeks to identify existing limitations, namely the tendency in the literature to merge fruits and vegetables into a single category, thus the specific active packaging needs of vegetables have not been optimally accommodated. This review also employs bibliometric analysis, focusing on which authors, journals, countries, and themes have achieved the highest visibility and impact in the field of active packaging for vegetables. Therefore, this review is intended to formulate future research directions that are more focused on the development of active packaging based on biopolymers and natural, environmentally friendly compounds, tailored to the

unique physiological characteristics of fresh vegetables, so as to enhance the quality, safety, and shelf life of products in the food distribution chain.

## 2. Materials and Methods

Data search mechanism for this review can be seen in Figure 1. The data for this article review is sourced from a reputable research database, specifically Scopus (scopus.com). To minimize bias and maintain consistency amid changes to the database, data collection was conducted on July 16, 2025. The search methodology utilized quotation marks and Boolean operators (“AND” and “OR”). The search keywords used were TITLE-ABS-KEY “Active Packaging” OR “Vegetables”. Selected documents met the following criteria: published between 2000 and 2025, written in English, categorized as articles, reviews, book chapters, conference papers, or books, and in the final stage of publication. Documents not meeting these criteria were disqualified. An initial dataset of 387 documents was downloaded in CSV format and organized in Microsoft Excel for easier data management, with duplicate data removed. Subsequently, the data was imported into OpenRefine version 3.9.3 (<https://openrefine.org>) to manually merge words with the same meaning (17). For example, Polylactic acid and poly(lactic acid) were combined. Shelf life and Shelf-life were also manually merged into Shelf life. Furthermore, Electrospinning, Electro spun nanofibers, and electro spun membrane were consolidated into Electrospinning to facilitate visualization. Singular and plural forms of the same noun, such as Polysaccharide and Polysaccharides, were also manually combined. Additionally, VOSviewer version 1.6.20 was used to create graphical bibliometric mapping and visualize publication trends, authorship networks, citation patterns, and keyword clusters in research articles. Meanwhile, RStudio version 4.5.0 was used to analyze and visualize bibliometric data regarding the relationships between journals publishing the most articles, countries with high publication contributions, and the most frequently used keywords in studies on active packaging for vegetables. Finally, Tableau 2025.2 was used as an advanced visualization tool to present bibliometric trends and insights interactively.

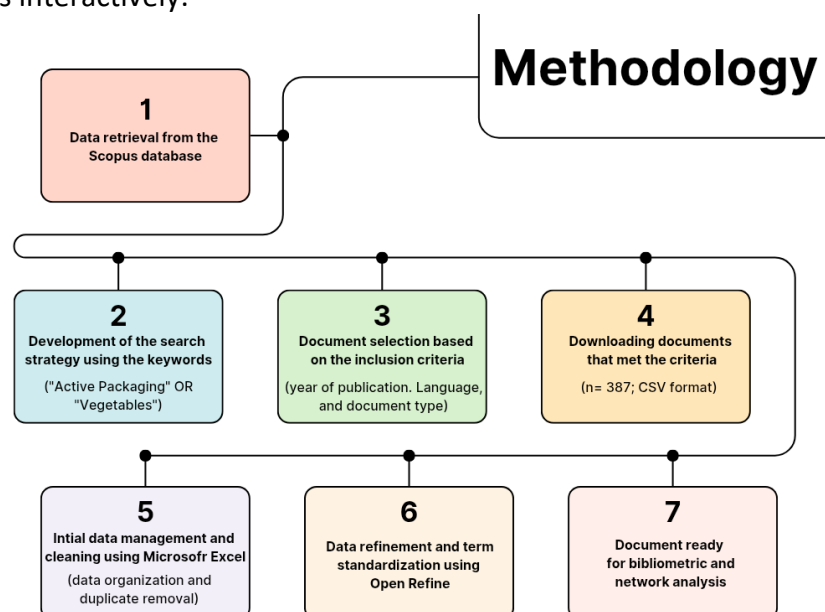


Figure 1. Data search mechanism for bibliometric analysis.

### **3. Results and Discussion**

#### *3.1. Publication trends*

Based on the results of the bibliometric analysis in Figure 2, research on active packaging innovation applied to vegetables has experienced a significant upward trend from 2000 to 2025. The development of this research can be seen from the number of available documents, including articles, books, book chapters, conference papers, and reviews. The increasing number of publications on active packaging for vegetables is a response to market demands for quality, safety, and shelf life of fresh food products, as well as a solution to address significant post-harvest losses before the products reach consumers. This aligns with the findings of Miteluț et al. (2021), who state that fresh products are generally highly perishable by nature, thus experiencing rapid quality decline during storage and transportation (18). Several researchers have shown that active packaging is an efficient technological innovation for preserving vegetables. According to Da Silveira and Rabanal (2022), active packaging is a solution to extend shelf life, improve the quality and safety of food products, and has attracted the interest of researchers due to its ability to prevent spoilage and maintain the freshness, firmness, and color vibrancy of food, thereby making it more appealing to consumers (19). Active packaging can also address environmental issues associated with traditional packaging (19,20). In addition, active packaging offers a solution for leafy green vegetables that have been contaminated with microbes linked to several outbreaks of human gastrointestinal infections, by helping to improve food microbial safety and therefore reduce the incidence of foodborne illnesses (21).

Based on the results of the bibliometric analysis in Figure 2, it shows that research on active packaging innovation applied to vegetables has experienced a significant upward trend from 2000 to 2025. The development of this research can be seen from the number of available documents, including articles, books, book chapters, conference papers, and reviews. The increasing number of publications on active packaging for vegetables is a response to market demands for quality, safety, and shelf life of fresh food products, as well as a solution to address significant post-harvest losses before the products reach consumers. This aligns with the findings of Miteluț et al. (2021), who state that fresh products are generally highly perishable by nature, thus experiencing rapid quality decline during storage and transportation (18). Several researchers have shown that active packaging is an efficient technological innovation for preserving vegetables. According to Da Silveira and Rabanal (2022), active packaging is a solution to extend shelf life, improve the quality and safety of food products, and has attracted the interest of researchers due to its ability to prevent spoilage and maintain the freshness, firmness, and color vibrancy of food, thereby making it more appealing to consumers (19). Active packaging can also address environmental issues associated with traditional packaging (19,20). In addition, active packaging offers a solution for leafy green vegetables that have been contaminated with microbes linked to several outbreaks of human gastrointestinal infections, by helping to improve food microbial safety and therefore reduce the incidence of foodborne illnesses (21).

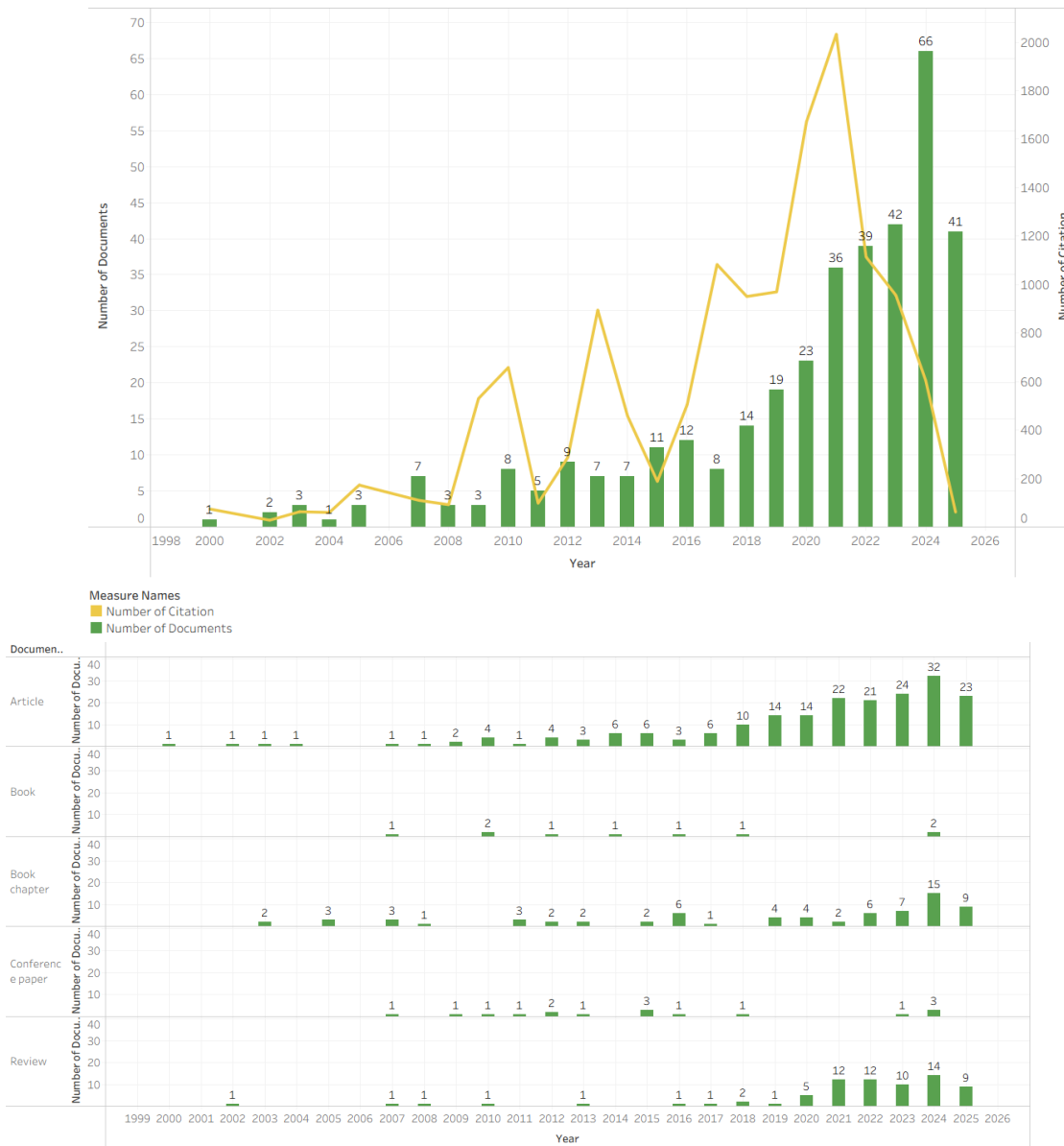


Figure 2. Trends in journal publications on active packaging for vegetables from 2000 - 2025.

Publication trend data from 2000-2025 resulted in a total of 387 documents, consisting of 214 articles (55.30%), 75 reviews (19.38%), 72 book chapters (18.60%), 17 conference papers (4.39%), and 9 books (2.32%), with an average annual increase in publication volume of around 20%. The sharpest increase occurred from 2019 to 2024, with a peak in publications in 2024 (66 documents) and a peak in citations in 2021 (2,033 citations). Then, in 2025, the number of documents declined to 41 and citations dropped to 62. This was due to the publication year still being in progress, so the data on the number of documents and citations had not yet been fully collected. Based on Figure 2, it can be seen that the highest number of publications came from articles, where the number of articles continued to rise each year, especially from 2016 until its peak in 2024 with 32 documents. Meanwhile, the book document type had the lowest number of publications, with only one or two books published in certain years, and often no publications at all in some years. This significant difference is because articles can be published more quickly than books, allowing research findings to be disseminated more rapidly. In addition, articles to be published must

go through a peer review or editorial review process to ensure their quality and selectivity. This distinguishes them from books and other forms of publication.

### 3.2. Co-occurrence analysis of author keywords

Co-occurrence analysis of author keywords is a bibliometric method used to understand relationship patterns between keywords in scientific publications and identify emerging topics (22). In this analysis, keywords act as nodes; if two keywords frequently appear together in a document, they are connected by a network where thicker connections signify stronger relationships. This process aims to identify frequently used keyword groups, helping researchers cluster relevant topics and predict future research trends (23).

The visualization in Figure 3a and 3b shows bibliometric results from VOSviewer using a minimum occurrence threshold of 5, which identified 44 keywords out of 918 with a total link strength of 555. Each keyword is represented by a circle; larger circles indicate a higher number of publications containing that corresponding term (17), while specific colors represent close relationships within the same cluster. Network visualization (Figure 3a) illustrates the relationships between these keywords to reveal the thematic structure of research on “active packaging for vegetables.” This keyword network consists of 44 items across six color-coded clusters: red (1), green (2), dark blue (3), yellow (4), purple (5), and light blue (6).

Based on Figure 3a, the keyword “active packaging” occupies a central position, connecting six distinct clusters. The primary group, Cluster 1 (red), includes 12 items and 158 occurrences focusing on active packaging. Other clusters include Cluster 2 (green, 10 items) on 1-methylcyclopropene, Cluster 3 (dark blue, 7 items) on biodegradability, Cluster 4 (yellow, 7 items) on antibacterial properties, Cluster 5 (purple, 6 items) on antimicrobial activity, and Cluster 6 (2 items) on chitosan. These clusters are critical for developing innovative vegetable packaging that extends shelf life and ensures safety while remaining environmentally friendly. Such technologies minimize postharvest losses, support efficient distribution, and promote a sustainable environment.

The overlay visualization in Figure 3b maps keyword relationships over a time dimension to reveal research trends. Purple circles represent keywords prominent from 2016–2018, green indicates emerging topics from 2019–2021, and yellow denotes keywords popular from 2021–2023. This visualization identifies topics with the potential to become future research focal points, including “bioactive compounds”, “polyphenols”, “ethylene scavenger”, “polylactic acid”, “biodegradable film”, “controlled release”, “mechanical properties”, “food preservation”, “food safety”, “antibacterial”, “antioxidant activity”, “nanotechnology”, and “coating”.



losses, Indian researchers have rapidly adopted active and smart packaging for various horticultural commodities, including vegetables (24,26). This significant focus makes India the most productive country currently conducting research on active packaging for vegetables.

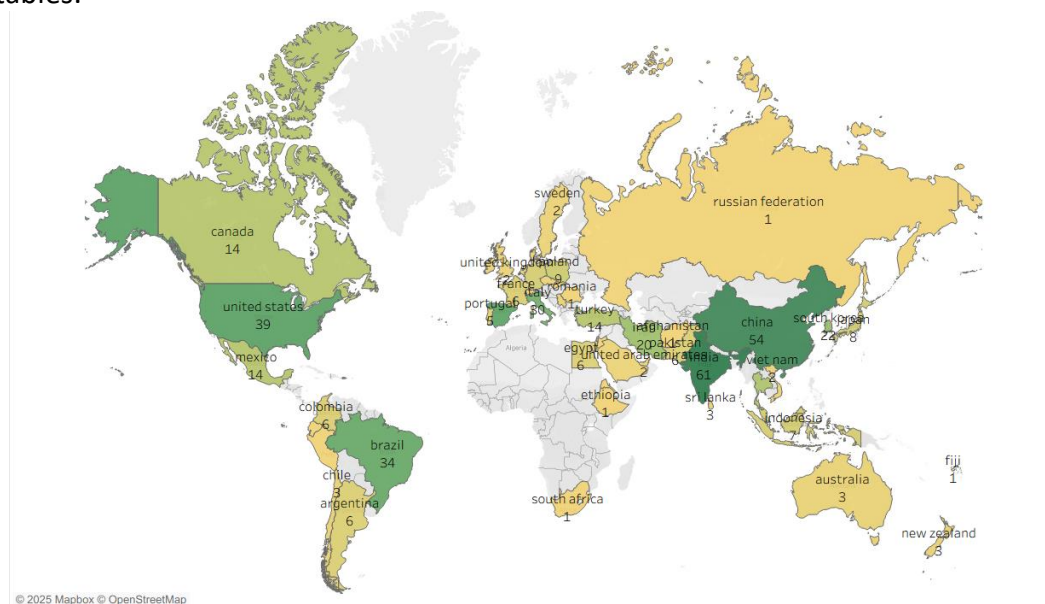


Figure 4. Number of documents on active packaging for vegetables published among countries.

In addition, there are 15 countries ranked based on the highest number of citations in research on active packaging for vegetables (Table 1). Brazil holds the top position with the highest number of citations (2160), followed by India in second place (2011), and Spain in third (1788). A high number of citations indicates that research from these countries is frequently referenced by other researchers. This means that scientific publications from these countries are considered innovative, relevant, and have made a significant contribution to the development of research in the field of active packaging for vegetables.

Table 1. Top 15 countries with the highest number of citations in research on active packaging for vegetables

Rank	Country	Documents	Citations	Total link strength
1	Brazil	34	2160	11
2	India	61	2011	19
2	Spain	37	1788	24
3	United States	39	1735	26
4	Italy	30	1674	17
5	China	54	1228	19
6	South Korea	22	905	14
7	Iran	20	890	11
8	Poland	9	603	5
9	Mexico	14	574	5
10	Turkey	14	566	8
11	Canada	14	334	6
12	Portugal	5	304	2
13	Malaysia	8	300	6
14	France	6	296	1
15	Germany	7	206	10

### 3.4. Relationship between journal country, and keywords

The results of the bibliometric analysis presented in Figure 5 show the interrelationship between journals publishing the most articles, countries with high publication contributions, and the most frequently used keywords in studies on active packaging for vegetables. According to Figure 5, the International Journal of Biological Macromolecules is the main publication hub, with most of its articles published by authors from India, China, and Brazil, focusing on keywords such as active packaging, antioxidant, shelf life, and antimicrobial. A study published in the International Journal of Biological Macromolecules by researchers from India successfully developed an edible coating based on guar gum and almond gum with the addition of 0.05% oregano essential oil, which was able to extend the shelf life of okra by up to 4 days at room temperature storage conditions (around 23 °C) by delaying weight loss, maintaining firmness, slowing down respiration rates, and inhibiting the growth of microbes such as *E. coli*, *S. aureus*, and *A. niger* (27). Researchers at Wuhan Polytechnic University, China, also developed an edible composite film made from sodium alginate, gum arabic, and glycerol, enriched with natamycin as an antimicrobial agent. The results showed that sweet potatoes coated with this film retained good processing quality for up to 120 days of storage (28). In addition, Brazilian researchers have successfully increased the antioxidant activity of biodegradable films based on starch and gelatin containing *Tetradenia riparia* extract within 10 days of storage (29,30).

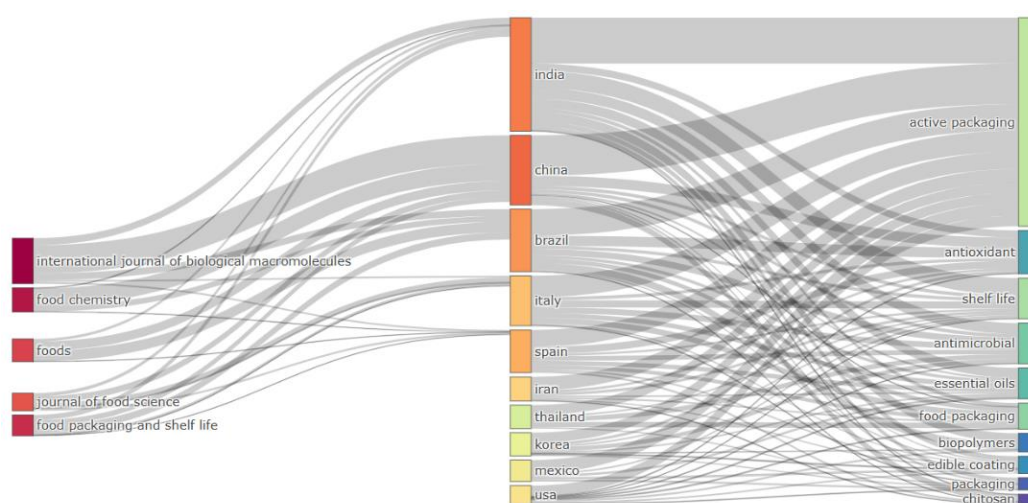


Figure 5. The Relationship between journals, countries, and keywords in articles on active packaging for vegetables.

### 3.5. Edible packaging

Plastics-based and synthetic materials are not biodegradable and cause many problems for the environment as well as human health. According to research and market reports (2020–2025), annual consumption of plastics-based materials has increased by approximately 230 million tons to date (31). To minimize these environmental issues and address health and safety concerns, edible packaging offers a suitable and renewable solution. Edible packaging (edible coatings and films) are excellent environmentally friendly options for extending the shelf life of food products over a longer period by slowing oxidation, moisture transfer, enzymatic metabolic activity, and microbial spoilage (32–34). Several types of biopolymers such as polysaccharides (cellulose, starch, pectin,

hemicellulose, gum, agar, alginate, chitosan, pullulan, and others), proteins (gluten, soy protein, zein, casein, collagen, whey protein, and fish protein), lipids (beeswax, shellac wax, carnauba wax, free fatty acids, and oils), and their composites can be used to develop edible coatings and films to extend the shelf life of fruits, vegetables, meat, meat products, and other items (31,35,36). In addition, plasticizers (glycerol, propylene glycol, and polyethylene glycol), as low-molecular-weight and non-volatile compounds, are used to improve the viscosity, resistance, flexibility, solubility, barrier, thermal, and mechanical properties of edible films and coatings by reducing hardness, deformation, density, viscosity, and the electrostatic charge of polymers (31). At the same time, plasticizers alter the three-dimensional molecular structure of biopolymers, reducing the energy required for molecular motion and the formation of hydrogen bonds between polymer chains (35).

### 3.5.1. Edible film

Edible film is a thin sheet that has been pre-formed, typically molded and dried before being applied to the surface of food, which can serve as a stand-alone wrapper or as a coating material (37). Both edible films and coatings can enhance food preservation, but edible films can provide more versatile packaging applications, offering better barrier properties and greater mechanical strength, which allows them to be used as independent and multilayer packaging systems (12). Novel materials used in the preparation of edible films include fruit and vegetable residues such as peels, pomace and seeds, sugarcane bagasse, polysaccharides, animal proteins, plant proteins, lipids, and waxes, including cellulose derivatives, pectin, alginate, starch, carrageenan, pullulan, and chitosan (38). Edible films are developed using two main methods: the first is the wet method and the other is the dry method (37). The wet method, also known as the solvent casting technique, involves dissolving organic materials in a solution or condensed liquid phase. This solution is then applied to a substrate using techniques such as spin coating, slot-die coating, or inkjet printing, and is subsequently dried to form a solid film layer (34,39,40). Meanwhile, the dry method (extrusion) involves converting raw organic materials from a solid powder form into a gas phase, which then condenses onto the substrate in a high vacuum environment (34,39). Both wet and dry methods are essential for the production of edible films, each with its own advantages and applications. The wet method is more adaptable for the addition of various additives and is easier to use on a laboratory scale, while the dry method is more efficient for large-scale production (34,39,40).

Edible films were initially produced as solid sheets and then used as protective coatings for food products. Since they can be consumed together with the food, waste disposal issues are practically eliminated. If not consumed, edible films degrade much faster than plastic packaging, resulting in substantial subsequent cost reductions (41). Enhancing nutritional value, preventing microbial attacks during long-term storage, and protecting the environment from the harmful effects of plastic-based packaging materials are some important applications of edible films in the food sector (42). Edible materials offer many advantages, such as extending the shelf life of food products, reducing waste, and maintaining food quality (37). However, edible films generally have fewer barrier and mechanical properties; to address these limitations, some additives such as glycerol and sorbitol are included as plasticizers to enhance flexibility (43). On a commercial scale, edible films are used for packaging various foods such as fruits and vegetables, dairy, and meat products (37).

The addition of natural active compounds to biodegradable polymers to produce edible films can prevent food spoilage by releasing active agents into the storage environment (44). Several bioactive compounds used in the production of edible films include glycosides, polysaccharides, phenolic acids, carotenoids, and flavonoids (45). This type of film can be used as active packaging because it contains antioxidant activity aimed at minimizing changes in sensory properties and nutrient degradation in order to extend the shelf life of food products (46). The development of active edible films provides an alternative packaging material that is sustainable with a lower carbon footprint compared to petroleum-based packaging (47).

### 3.5.2. Edible coating

The edible coating is a very thin layer of edible material applied to the surface of fresh products to create a physical barrier. This innovative approach to edible coating technology replaces synthetic packaging, which has traditionally been less preferred. Edible coatings are biodegradable and mostly organic, making them a more sustainable solution to environmental issues caused by plastic waste (48). Polymers are responsible for edible coatings, serving as the main factor that binds them as solids and enables film formation (49). The most common biopolymers are, for example, chitosan, alginate, and pectin, which are widely used due to their biocompatibility and functional flexibility (50).

Edible coating results in the formation of a thin layer, usually less than 0.3 mm thick, on the surface of vegetables and fruits. This coating has distinct characteristics, namely it can be consumed and is imperceptible to the tongue (51). By controlling the transfer of oxygen, carbon dioxide, aroma, and flavor compounds in food, edible coatings can enhance food quality and extend the shelf life of fresh products (52). In addition, the use of edible coating enforces strict safety regulations as they are directly applied to the surface of vegetables and fruits (51). Edible coatings are non-toxic and relatively inexpensive, making them a preferred choice for preserving fresh products (53).

Edible coatings are applied as a thin layer by dipping, pouring, spraying, brushing, or extruding onto the product surface to serve as a barrier to gas exchange and inhibit the ripening process (18). One of the main issues with these coating solutions is their instability against flocculation and coalescence (54). To overcome this, the droplet size is reduced to the nanometer scale, resulting in a nano-emulsion. A nano-emulsion is a suspension with oil droplet sizes ranging from 10 to 500 nm, created by mixing two immiscible phases (usually oil and water) and stabilizing them with surfactants (55).

### 3.6. Edible film preparation method

Edible film is typically developed for use as food wrapping, assisting external packaging in its protective function, while also acting as a passive protective layer without sensory or nutritional appeal. In this context, edible film should be colorless and tasteless, and should not interfere with the sensory properties of the food (56). Edible film can also be used as pouches or sachets, especially for energy drinks and meal replacement shakes, which, when added to hot or cold liquids, dissolve and release their contents, providing customer convenience, portion control, and reduction of solid waste (34). Edible film can be manufactured from edible substances through various methods shown in Table 2.

Table 2. Processing techniques and functional properties of biopolymer-based active packaging materials

Biopolymer Matrix and Components	Processing Technique	Key Functional Benefits	Technical Limitations	Ref.
Chitosan (Pure or Nano-ZnO)	Dipping or Spraying (Coating + MAP)	Strong antimicrobial effect; color/texture retention; uniform coverage	Long drying times; potential weight loss; thickness control challenges	(57, 58)
Nano-Chitosan	Coating (Microporous Packaging)	Reduced respiration/water loss; inhibits browning and microbial growth	Limited effectiveness as a standalone method	(59)
Chitosan (+ Thyme Essential Oil)	Casting (Edible Film)	Reproducible; easy component integration; biodegradable	Long processing time (42h); requires neutralization post-drying	(60)
Starch-based (Moth bean / Cassava + PBAT)	Dipping or Blown Extrusion	Time-efficient; excellent thickness control; industrial scalability	Potential thermal degradation; long drying times (24h); solution waste	(61, 62)
PLA and Gelatin	Electrospinning (Double Layer)	High surface area; efficient encapsulation; sustained ingredient release	Difficult to scale for mass production	(63)
Cellulose (CMC) (+ Lemon oil)	Solvent Casting (Edible Film)	Even distribution; flexible formulation; high reproducibility	Volatilization of oils; requires 24h conditioning; long drying (16h)	(64)
$\beta$ -cyclodextrin	Spraying (Active Cardboard)	Industrial-scale ready; adaptable to various surfaces	Reduced mechanical resistance of the box; requires dilution	(65)
Alginate & PVA/Gelatin (+ Chrysanthemum / Neem)	Solvent Casting (Edible Film)	Eco-friendly; simple fabrication; homogeneous structure	Difficult to scale; long stirring/drying (up to 48h); volatile loss	(66, 67)
Whey Protein (WPC)	Dipping (Edible Coating)	Very simple and rapid application (3 min)	Risk of non-uniform layer thickness	(68)
Xanthan Gum	Spraying (Edible Coating)	Reduces browning/oxidation (up to 84%); high automation potential	Surface cracking; reduced barrier/antimicrobial efficacy at high speeds	(69)

### 3.6.1. Casting

Casting is widely used for preparing polysaccharide-based edible films due to its simplicity, flexibility, and cost-effectiveness (70). The process involves drying a film-forming solution on a smooth surface before release, primarily at laboratory scales before industrial application (34,37). Solvent casting involves three steps: first, biopolymers are dissolved in edible, non-toxic solvents like water or ethanol, ensuring all ingredients are completely dispersed (41). Second, the solution is poured into molds, such as glass or stainless steel, to form a uniform layer. Finally, drying at room or controlled temperatures evaporates the solvent, creating a solid, edible film (34,71). Casting is the primary technique for producing vegetable-targeted edible films at laboratory and pilot scales. It has been used to develop carboxymethyl cellulose films with encapsulated lemon oil for wrapping cherry tomatoes and spinach (64). Similarly, Yang et al. (2024) used this method for a gelatin-sodium alginate composite film enriched with neem essential oil to maintain cherry tomato quality (67). Furthermore, chitosan films reinforced with thyme essential oil have shown potential for

preserving the freshness of mustard greens (60). Casting is preferred because the high temperatures of alternative techniques can degrade biopolymers and diminish film properties (56). Cast films are typically transparent with strong mechanical properties, such as stretchability and break-resistance (72). The method also facilitates the addition of bioactive compounds, plasticizers, and cross-linkers to enhance barrier and functional properties (73). Despite its cost-effectiveness at the laboratory scale, industrial scaling presents challenges in maintaining uniformity (71). Limitations such as small film size (<25 cm), long drying times (2–3 days), and uneven thickness make current laboratory methods unsuitable for industry; therefore, continuous manufacturing processes with higher production rates are necessary (74).

### 3.6.2. Extrusion

Extrusion, or dry processing, forms films through a thermomechanical process without solvents, inducing a solid-to-liquid phase transition (75). The process involves three zones: adding, mixing, and heating, typically incorporating 10% to 60% plasticizers like polyethylene glycol or sorbitol (76). This method relies on both mechanical and thermal components (76). Adjusting screw speed influences shear stress, uniformity, and residence time; notably, higher speeds can reduce torque and improve precise adjustments to film properties (77). Dry processing is commonly used for thermoplastic packaging containing starch and proteins, such as corn, wheat, or soy, where heat enhances protein denaturation and starch gelatinization (78). However, high temperatures in the heating zone restrict biopolymer selection to heat-resistant varieties to prevent material degradation. Additionally, while extrusion offers advantages in uniformity and scalability, the high cost of equipment and production can make it less suitable for certain commercial-scale applications (71). For vegetables like broccoli, extrusion effectively creates biodegradable active films by incorporating ethylene-absorbing or antibacterial essential oils (62). A significant advancement is vertical hot melt extrusion, which ensures the even distribution of bioactive compounds within the polymer matrix. This results in active packaging with antimicrobial and antioxidant qualities that prolong shelf life while minimizing waste and improving the overall sustainability of food packaging practices (79).

### 3.7. Edible coating preparation method

Edible coating is a thin layer applied directly to the surface of food products. This edible coating preserves and maximizes food quality, and it is widely used as a post-harvest practice, especially for perishable products such as fruits and vegetables (80). These coatings represent a substitute for natural protective wax coatings and can be completely made from renewable materials such as natural polymers (81). Edible coating can be applied in liquid form directly onto food, and it is considered an integral unit with the food product itself (82). Moreover, these coatings can be produced as single or multi-layer coatings depending on the desired characteristics (83). Edible coating is carefully applied to the surface of food products and reduces food degradation by forming a barrier that prevents or regulates the transfer of gases and moisture from the atmosphere, thereby reducing cellular respiration and microbial growth (84). Edible coatings can also reduce color changes, microbial proliferation, flavor changes, and eventually browning in freshly cut fruits and vegetables (85). As with other food coating production processes, the formulation of edible coatings must take into account various parameters, such as barrier properties (oxygen and

carbon dioxide permeability), optical properties (should be transparent and colorless), and sensory characteristics (should be tasteless, flavorless, and odorless), as well as being acceptable for use as carriers for texture enhancers and nutraceuticals (52,86). Edible coating is applied directly to the surface of food through several methods such as dipping, spraying, brushing, layer by layer, and electrospinning, followed by drying to form a continuous food-grade protective layer (87).

### 3.7.1. Dipping

The dip coating method is currently the primary technique for laboratory applications and is the most common method for food coating due to its operational simplicity and low cost. This technique is particularly effective for thoroughly coating foods with uneven surfaces or complex shapes, such as fresh produce (88,89). Generally, an edible coating mixture is applied to fruits and vegetables for 5–30 seconds. The process involves three essential steps: first, the preparation of the solution where biopolymers are dissolved in a solvent (71). Next, the item is immersed into the coating solution at a constant speed, ensuring uniform coverage and full interaction with the coating matrix (90). Finally, as the solvent evaporates during drying, a protective coating layer is formed (71). Research highlights the method's efficiency across different crops. Kumar et al. (2021) revealed that coating eggplant surfaces is a simple and efficient process, requiring only 5 minutes of immersion (91). Excess solution is easily removed using a strainer, resulting in a uniform layer. Similarly, Abedi et al. (2021) found that fresh spinach could be evenly coated with a shorter dipping time of just 3 minutes (68). Furthermore, Dulta et al. (2025) demonstrated that coating eggplant with chitosan containing ZnO nanoparticles for 20 minutes creates a semi-permeable barrier. This barrier inhibits the exchange of gases (oxygen and carbon dioxide) and water vapor, resulting in a smooth surface with fewer wrinkles and a homogeneous distribution of nanoparticles (58).

Despite its popularity, the dipping process faces several challenges, including layer dilution, waste accumulation, microbial growth, and potential damage to the food's outer layer, such as peeling off natural wax (89). To address these limitations, several modified methods have emerged: double-dipping provides thicker, more durable coatings through two immersions with partial drying, while dynamic dipping reduces material buildup to ensure uniform distribution (92,93). Industrial scalability and thickness control are enhanced via automated conveyor systems (94). Furthermore, vacuum-assisted dipping utilizes pressure to help coatings penetrate porous or uneven surfaces, temperature-controlled dipping employs heated or chilled solutions to improve adhesion and freshness (96), and electrostatic-assisted dipping minimizes waste by using electrical attraction to ensure consistent surface coverage (49,95,96).

The drying stage remains a major bottleneck, as it can take up to 24 hours to complete. To overcome this, production cycles must be optimized by controlling coating thickness, adjusting solution and product temperatures, and selecting compatible materials (97). Integrating alternative drying technologies also offers significant improvements. For example, ultrasound-assisted drying can reduce drying time by 20–30% through the "sponge effect" and the formation of microchannels (98,99). Hybrid methods, such as combining microwave and hot air, have proven effective in increasing drying rates; for instance, coated kiwi fruit saw significantly reduced drying times at 450 W and 90°C (100,101). Additionally, infrared drying accelerates evaporation through direct surface heating without

compromising quality (102), while microwave vacuum drying provides rapid, uniform results by combining volumetric heating with low-pressure principles (102,103).

### 3.7.2. Spraying

Spraying is a widely utilized method for applying edible coatings, valued for its simplicity and operational ease (104). This technique involves applying a sprayable substance directly onto food surfaces using a nozzle, with the sprayer positioned at a specific distance to ensure even coverage (71). The advantages of the spraying technique include cost-effectiveness and efficiency due to minimal solvent use, the ability to apply multiple layers, avoidance of coating solution contamination, temperature control, and the capacity to operate on large surfaces. Furthermore, spraying allows for precise control of coating thickness, producing layers as thin as 20  $\mu\text{m}$  (105). This method has been widely studied and proven effective for various vegetable commodities, often offering advantages over the dipping method in maintaining physical quality. Leceta et al. (2015) reported that the spraying method on carrots suppressed weight loss more significantly than dipping, while chitosan coatings applied via spraying maintained product firmness for up to nine days, surpassing both control and dipped samples (57). Nevertheless, this method has limitations, such as generally weaker antimicrobial activity and the potential for the final product to develop a slightly sour taste or mild off-flavors. In active packaging development, Buendía–Moreno et al. (2020) utilized this method to apply EOs- $\beta$ CD inclusion complexes onto active cardboard (65). Scanning Electron Microscopy (SEM) tests confirmed that spraying resulted in a homogeneous layer with evenly distributed particles, providing adequate water resistance and high industrial applicability, though it requires solution dilution and may slightly reduce the mechanical resistance of the packaging. Regarding processed cut vegetables, Lara et al. (2020) tested xanthan gum-based coatings (0.1–0.5%) on sliced lotus roots using a pilot spraying system (69). This system reduced total color change by up to 84.38%, suppressed enzymatic browning, and inhibited the growth of *Bacillus subtilis* while supporting continuous production automation. However, challenges regarding coating integrity arose, as cracks were found at certain concentrations and antimicrobial effectiveness decreased with short spraying times (10 seconds) or very thin layers (17–66.67  $\mu\text{m}$ ). Generally, horticultural products like tomatoes, cucumbers, carrots, and peppers are highly suitable for the spraying method, provided solutions have low viscosity to prevent nozzle clogging (106). Modern developments have surpassed conventional limitations through air-assisted and electrostatic spraying, which improve coverage on irregular surfaces and minimize material wastage (49,107). Additionally, the industry has adopted nano-spraying and thermal spraying to produce uniform particles smaller than 100 nm, enabling the formation of denser, more functional layers on horticultural surfaces (106).

### 3.7.3. Layer by layer

The layer-by-layer (L-b-L) method in the production of active edible coating packaging is a technique in which different biopolymer layers are alternately deposited or layered one by one. This technique utilizes electrostatic interactions between the layers to form a composite layer that enhances the physicochemical properties and activity of the resulting edible coating. By using this method, the coating's ability to contain and release active substances such as antimicrobial or antioxidant agents can be improved, thereby extending

shelf life and enhancing the quality of the packaged food (108). More simply, layer-by-layer represents the process of alternately depositing thin layers of different polymers, which can significantly improve coating performance compared to conventional single layers in terms of controlling gas transfer, water diffusion, as well as the controlled release of active substances in foods (109,110).

The layer-by-layer (L-b-L) method offers several advantages compared to other coating techniques. One of these is its highly precise control over the growth of film layers at the nanometer scale, resulting in high-quality, uniform multilayers with significantly customizable composition. This technique enables the formation of flexible and transparent film structures with good mechanical strength (111). However, the layer-by-layer method also faces several challenges. The process often requires a longer time to construct the desired multilayer, since coating is carried out alternately and repeatedly. The L-b-L method needs to be further developed to become faster and more efficient, for example through automation such as a spin-spray system, which increases deposition speed without compromising quality. On an industrial scale, another challenge is the ability to adapt this technique to rapid and cost-efficient mass production processes compared to conventional coating techniques such as spray-coating (111,112).

#### 3.7.4. Electrospinning

Electrospinning in the production of active edible packaging is a technique used to produce polymer nanofibers with extremely small sizes and porous morphologies, resulting in a very large specific surface area. This technique utilizes electrostatic forces to continuously draw polymer solutions into thin fibers, forming fibrous mats that serve as active packaging materials. Nanofibers produced by electrospinning can be functionalized or supplemented with bioactive compounds, such as antimicrobial agents or antioxidants, to extend shelf life and enhance food safety. The advantages of this method include the ability to produce porous structures with high nano/micro fiber sizes, thereby increasing the efficiency of active ingredient encapsulation and controlled release in food packaging. Furthermore, electrospinning is a non-thermal processing technique, making it highly suitable for bioactive materials that are sensitive to heat (113,113,114). This application also allows for the creation of films or composite layers with excellent mechanical and barrier properties, holding great potential for the development of biodegradable, biopolymer-based packaging (115,116).

However, the electrospinning method faces several main drawbacks, including technical challenges in processing certain types of natural polymers directly due to their physicochemical properties. For example, alginate is difficult to electrospin directly because of its rigid molecular chains and limited chain bonding (117). Another challenge involves controlling the release of active substances, which must be optimized so that the packaging provides long-lasting active functions; instability or rapid release can reduce packaging effectiveness (118). Additionally, electrospinning involves relatively high production costs compared to conventional manufacturing methods, affecting commercialization (119). To address these shortcomings, strategies such as optimizing the electrospinning process through multi-fluid techniques or polymer blending have been developed to handle difficult polymers (117). Utilizing cyclodextrin inclusion complexes as carriers can also enhance the stability and controlled release of active ingredients (118). Ultimately, new electrospinning methods and the combination of natural and synthetic polymers can improve mechanical

properties and active functions while maintaining biocompatibility and biodegradability (113).

### 3.8. Active agent in packaging

#### 3.8.1. Essential oil

Essential oils contain active compounds such as phenolics, monoterpenes, terpene alcohols, and aldehydes, which possess high antibacterial and antioxidant activities, making them ideal agents for improving the mechanical properties and chemical stability of packaging and packaged foods. In their applications, biofilms containing essential oils are capable of inhibiting bacteria such as *Staphylococcus aureus* and *Escherichia coli*, as well as enhancing the oxidative stability of food by reducing lipid and protein degradation (120,121). The types of essential oils commonly used in the production of active packaging include various oils extracted from aromatic plants that possess antimicrobial and antioxidant properties. Some of the essential oils frequently used in active packaging applications include essential oils from rosemary, thyme, peppermint, clove, cinnamon, oregano, lemon, eucalyptus, geranium, lavender, and citronella (122,123).

The process of making biofilms containing essential oils generally involves mixing essential oils with biocompatible polymer materials such as chitosan, cellulose, or other biodegradable polymers using certain methods such as solvent casting. One commonly used method is dissolving the polymer in a suitable solvent, followed by adding the essential oil at various desired concentrations. The mixture is then molded or poured onto a flat surface and allowed to dry under controlled temperature and humidity, thus forming a homogeneous thin film. This mixing process must consider the stability of essential oils, as they tend to be volatile and sensitive to light and heat, so techniques such as microencapsulation are often applied to protect the essential oils and control their release, in order for the biofilm to have optimal antimicrobial and antioxidant activity (120,124).

#### 3.8.2. Plant extracts

Plant extracts as active agents in the production of active packaging refer to the use of bioactive compounds obtained from various parts of plants such as leaves, flowers, stems, or root bark that possess antimicrobial, antioxidant, and other functional properties. These extracts are integrated into packaging materials, especially biocompatible and biodegradable polymers, to enhance the packaging's ability to protect food from microbiological spoilage and oxidation, thereby extending shelf life and maintaining product quality. The bioactive compounds in these plant extracts, often comprising phenolics, flavonoids, and terpenes, can interact chemically or physically with the polymer matrix, strengthening the film structure and providing a natural preservative effect (31,124,125). In addition to providing protection by inhibiting microbial growth and scavenging free radicals responsible for oxidation, plant extracts can also improve the mechanical and barrier properties against oxygen or water vapor in packaging. Thus, active packaging based on plant extracts offers a safer and more environmentally friendly alternative to synthetic preservatives, while supporting the production of sustainable and healthy food (126,127).

The process of integrating plant extracts into biocompatible polymers is carried out by mixing the extract and polymer solutions, followed by material formation techniques, as well as appropriate crosslinking or encapsulation processes, with validation of chemical and physical characterization to ensure successful integration and preservation of bioactive

properties (128–130). Several other innovative methods can also be used, such as electrospinning to form nanofibers containing plant extracts, microencapsulation to protect the extract from degradation, or specific chemical reactions to covalently bind bioactive compounds to the polymer matrix, thereby enhancing the stability and controlled release of active compounds (131–134).

### 3.8.3. Active agents from microbes

Active agents from microbes, such as bacteriophages, antimicrobial peptides, and bacteriocins from lactic acid bacteria, are incorporated into packaging to extend shelf life and enhance safety. Bacteriophages selectively target pathogens like *Salmonella*, *Listeria*, and *E. coli* without affecting beneficial organisms (135). Additionally, microbial metabolites like organic acids and enzymes serve as antimicrobials to inhibit harmful growth (136). These agents help maintain food quality, address antimicrobial resistance, and satisfy consumer demand for natural preservation methods (135). Incorporation methods include direct mixing, coating, and encapsulation. Direct mixing blends antimicrobial agents into the polymer base before film formation, while coating applies the active solution onto the packaging surface. Encapsulation protects agents like probiotics or metabolites within matrices such as hydrogels or microcapsules to enhance stability and ensure controlled release during storage (137,138). For probiotics, matrix materials like polysaccharides, proteins, and hydrocolloids are preferred for their biocompatibility and ability to maintain microbial viability. These agents inhibit pathogens by producing bacteriocins, competing for adhesion sites, or lowering pH (138). Similarly, bacteriophages are applied via fortification or impregnation into films to direct antimicrobial activity specifically against pathogens without harming beneficial microbiota (135,139).

### 3.8.4. Nanoparticles or nanomaterials

Nanoparticles or nanomaterials used as active agents in the production of active packaging are materials with extremely small particle sizes, generally ranging from 1–100 nanometers, which possess unique physical and chemical properties that can enhance food packaging functions. These nanomaterials can be organic or inorganic particles utilized to provide antimicrobial activity, oxygen absorption capability, UV light resistance, and to improve the mechanical and barrier properties of packaging materials. Due to their extremely small size, nanoparticles have a large surface area, making them more effective in interacting with microorganisms or other substances that can spoil food (140,141).

Examples of nanoparticles commonly used as active agents in active packaging include metal and metal oxide nanoparticles such as zinc oxide (ZnO), copper sulfide (CuS), and zinc sulfide (ZnS) nanoparticles, which possess strong antimicrobial activity and are capable of improving the mechanical and barrier properties of packaging. In addition, biopolymer-based nanocomposites containing these nanoparticles are also used to produce packaging that is both biodegradable and functionally active (141,142). By applying these nanoparticles, active packaging can extend the shelf life of food products, prevent deterioration caused by microbes and oxidation, and enhance the safety and quality of food during storage (143). However, it is also important to consider safety aspects, including the potential migration of nanoparticles into food and their toxic effects on humans and the environment (140).

### *3.9. Active packaging applications for vegetables*

The development of active packaging with antimicrobial agents, antioxidants, carbon dioxide emitters, oxygen scavengers, and ethylene scavengers offers effective solutions to problems of damage and spoilage in fresh vegetables in an environmentally friendly and consumer-safe manner, while also reducing food waste and enhancing food safety (8). Table 3 presents several applications of active packaging for fresh vegetables based on their function.

Active packaging based on antimicrobial agents, antioxidants, carbon dioxide emitters, oxygen scavengers, and ethylene scavengers has been widely applied to various types of vegetables such as carrots, eggplants, cabbage, cucumbers, spinach, lettuce, cherry tomatoes, broccoli, and okra, as well as various types of fresh-cut vegetables. The use of natural antimicrobial agents integrated into the packaging system allows for the controlled and sustained low-level release of active substances, enabling them to combat microbes without causing adverse effects on the taste or quality of the vegetables (21). Antioxidant agents in active packaging help prevent product oxidation, which can damage the nutrients and color of vegetables. Integrating antioxidants into packaging materials provides protection against oxidative damage during storage, thus maintaining the freshness and nutritional value of the vegetables (8). Carbon dioxide emitters function to adjust the CO<sub>2</sub> level inside the packaging, which is crucial for controlling the respiration of fresh vegetables and inhibiting the rate of spoilage. Increased CO<sub>2</sub> inside the packaging can limit the growth of aerobic microbes and slow down the ripening process, thus extending the shelf life of vegetables (144). Oxygen scavengers are used to eliminate excess oxygen inside the packaging, which can accelerate oxidation and the growth of aerobic microbes. Reducing oxygen helps preserve freshness and slows down enzymatic and microbiological degradation in vegetables (8,113). Finally, ethylene scavengers are especially important for vegetable products that are sensitive to the ethylene hormone, which accelerates ripening and spoilage. Ethylene scavengers in active packaging can bind or oxidize ethylene, thereby slowing down ripening processes, reducing damage, and extending the shelf life of vegetables (145).

Active packaging technology is also combined with modified atmosphere packaging (MAP) and edible coating layers. The combination of edible coating with MAP enables double protection: edible coating reduces water loss and microbial growth, while MAP controls the atmosphere around the product. In addition, edible coating can be combined with microporous packaging that allows selective gas exchange between the inside of the package and the external environment (146). Similarly, active packaging paper is usually supplemented with active agents such as antimicrobial compounds, antioxidants, or ethylene absorbers that can slow down the ripening and spoilage processes of vegetables (16).

Table 3. Active packaging applications for vegetables.

Commodity	Composition	Packaging Type	Storage Conditions	Target Microbes	Bioactive Performance and Effects	Ref.
Baby Carrots	Nano-Chitosan (5%) + Chitosan (1.5%) + Glycerol (0.45%)	Edible Coating + MAP	4 °C (MAP)	<i>B. cereus</i> , <i>coliform</i> , <i>Pseudomonas spp.</i> , <i>S. aureus</i> , yeasts, and molds	Inhibits broad-spectrum growth; maintains color and texture attributes over 15-day cold storage.	(57)
Fresh-cut Eggplant	MMS + Basil leaf extract (15%) + Sorbitol (25%)	Edible Coating + Microporous Packaging	3 °C	Aerobic bacteria, molds, and yeasts	Extends shelf life to 15 days; lowest microbial counts (5.46 log CFU/g bacteria; 4.66 log molds/yeast); reduces respiration rate (4.94 mL CO <sub>2</sub> kg <sup>-1</sup> h <sup>-1</sup> ) and delays phenolic/anthocyanin loss.	(59)
Eggplant	Chitosan + ZnO nanoparticles (0.25 g/L)	Edible Coating	25±1 °C	-	Extends shelf life to 16 days; improves film moisture and mechanical properties; prevents water loss and delays color changes.	(61)
Eggplant	Poly (lactic acid) (PLA) / Gelatin + Eugenol (0.3 g/100g)	Edible Coating	4 °C	Total bacteria and fungi	Extends shelf life to 20 days; inhibits growth (3.96 log bacteria; 3.17 log fungi); maintains total phenolic (TPC) and anthocyanin (TAC) capacity; 49.03% antioxidant activity.	(58)
Cucumber	Carboxymethyl cellulose (CMC) + Lemon Essential Oil (0.1%) + Tween 80 (0.2%) + Sorbitol (25%)	Double Layer Membrane	4 °C	Aerobic bacteria, molds, and yeasts	Extends shelf life from 15 to 21 days; maintains higher firmness and antioxidant enzyme activity; reduces weight loss, skin discoloration, and MDA levels.	(63)
Cherry Tomato & Baby Spinach	Gelatin / Sodium Alginate + Neem Essential Oil (2.0%)	Edible Film	22±2 °C	<i>E. coli</i> O157:H7; mesophilic aerobic bacteria	Maintains appearance and texture for 4 days; inhibits target microbes by 0.65–1.0 log units; provides UV-blocking and 25.95% DPPH radical scavenging.	(64)
Cherry Tomato	β-cyclodextrin + Carvacrol / Oregano / Cinnamon (70:10:20)	Edible Film	25±1 °C	<i>Botrytis cinerea</i>	Destroys hyphal structure and reduces spore germination; reduces weight loss by 57.33% and disease incidence by 72.4%; exhibits slow-release properties.	(67)
Fresh Bell Pepper	Cassava Starch / Poly	Active Cardboard	8 °C	<i>Enterobacteria</i> ; molds	Extends shelf life to 18 days; <i>Enterobacteria</i>	(65)

Commodity	Composition	Packaging Type	Storage Conditions	Target Microbes	Bioactive Performance and Effects	Ref.
	(Butylene adipate-co-terephthalate) (PBAT) + Zeolite (1.5%)	Box			reduced by 1–2 log units; spoilage <5%; carvacrol residue remains safe (<1 mg/kg).	
Broccoli Florets	Sodium alginate (SA) / Polyvinyl alcohol (PVA) + Chrysanthemum leaf extract (7.5%)	Edible Film	12 °C	-	Acts as an ethylene scavenger; reduces metabolism and weight loss; maintains color and Vitamin C content for 7 days.	(62)
Green Chillies	Whey Protein Concentrate (WPC) + Rosemary essential oil (0.6%)	Edible Film	Room Temp	<i>S. aureus</i> , <i>B. subtilis</i> , <i>E. coli</i> , <i>P. aeruginosa</i> , <i>C. albicans</i>	Extends shelf life to 10 days; limits weight loss; provides ~46% antioxidant capacity and UV barrier protection.	(66)
Fresh Spinach	Chitosan + Thyme Essential Oil (EO) + ZnO + Nano clay + Polyethylene glycol (PEG)	Edible Coating	4 °C	Total mesophilic microbes; Coliform	Extends shelf life by 10 days; reduces mesophilic/coliform counts to 0.57/0.23 log CFU/g; prevents pH decline and preserves chlorophyll.	(68)
Collard Greens	Xanthan gum (0.1–0.5%) + Citric acid + Glycerol	Edible Film	Refrigerator	Total aerobic bacteria; yeast and mold	Preserves sensory quality for 24 days; reduces water vapor transmission and weight loss; retains dissolved solids and acidity.	(60)
Fresh-cut Lotus Root	Chitosan/ Nanocrystalline Cellulose (NCC) + Nisin (0.6 g/L)	Edible Coating	5 °C	<i>Bacillus subtilis</i>	Reduces total color change by up to 84.38% and inhibits enzymatic browning; automated production potential.	(69)
Baby Cabbage	PLA / Cellulose + Eugenol / Carvacrol / Trans-anethole	Composite Film	Room Temperature	<i>Pectobacterium carotovorum</i>	Inhibits <i>P. carotovorum</i> ; reduces oxygen permeability by 54.4% and water vapor by 12.9%; lowest levels of decay and weight loss.	(147)
Iceberg Lettuce	Generator ClO <sub>2</sub> (1492) / CO <sub>2</sub> (M0011) / O <sub>2</sub> Scavenger (X1907)	PP/CE Micro-perforated film	4 °C	Coliform bacteria	5-day shelf life; sachets improve freshness and aroma; effective antimicrobial activity (especially <i>Carvacrol</i> in PP).	(148)
Iceberg Lettuce	CMC / Flaxseed mucilage + Burdock extract (0.75 g/g)	Edible Film	4,10,22 °C	<i>E. coli</i> O157:H7; aerobic bacteria	Effective control of <i>E. coli</i> across temperatures; higher CO <sub>2</sub> inhibition at 10–22°C than 4°C.	(21)

Commodity	Composition	Packaging Type	Storage Conditions	Target Microbes	Bioactive Performance and Effects	Ref.
Fresh-cut Potatoes	Nanocomposite Alginate + Thymol (Nanoemulsion / NLC)	Active Coating	5 °C	Total bacteria; molds and yeasts	Reduces total microbes by 49.27%; maintains Vitamin C and phenols; reduces oil absorption and acrylamide formation (0.63×).	(149)
Carrot	Guar / Almond Gum + Oregano EO (0.15%)	Edible Coating	5±1 °C	<i>E. coli</i> , <i>S. aureus</i> , Lactic acid bacteria	Reduces respiration rate and total viable organisms; increases total phenolic/flavonoid content and DPPH scavenging activity.	(150)
Okra	Konjac glucomannan	Edible Coating	23 °C	<i>E. coli</i> , <i>S. aureus</i> , <i>A. niger</i>	4-day shelf life extension; slows weight loss (12.74%); maintains higher antioxidant and antimicrobial activity.	(27)
Okra	Gum Arabic + Australian native plant extracts	Edible Coating	4±1 °C	-	Reduces cell membrane damage; decreases browning by regulating ROS synthesis and antioxidant activity.	
Fresh-cut Capsicum	PLA / PBAT / Chitosan	Edible Coating	Cold storage	<i>P. viridiflava</i> , <i>B. subtilis</i> , <i>R. diobovata</i>	Maintains low bacterial count (~3 log CFU/g) up to 10 days of storage.	(151)
Broccoli	LDPE + Pyrogallol acid + Sodium carbonate	Bioactive Film	23 °C	-	Controlled release of ClO <sub>2</sub> gas; preserves color and inhibits oxidase activity; maintains quality for 8 days.	(152)
Peeled Garlic	Active Paper + 1-MCP / KMnO <sub>4</sub> -MCM-41 / Cinnamon EO	Modified LDPE Film	5 °C & 25 °C	-	Oxygen scavenging system; maintains excellent quality up to 30 days at 5°C (20 days at 25°C).	(153)
<i>Agaricus bisporus</i>	SA / Gum Arabic / Glycerol + Natamycin	Active Paper	25±2 °C	-	Ethylene absorption and removal; delays softening, browning, and weight loss during room temperature storage.	(154)
Sweet Potatoes	Chitosan + Acetic acid (1%) + Glycerol (15%)	Edible Film	-	-	Study of physicochemical and antibacterial properties for preservation.	(28)

### 3.10. Future perspective

Active packaging is no longer designed for a single function, but is now aimed at being able to combine several mechanisms at once, such as antimicrobial and antioxidant activity, ethylene control, gas exchange regulation, and moisture control. This approach is important because vegetable spoilage generally occurs as a result of the interaction of various factors, ranging from high respiration rates, water loss, enzymatic browning, to the growth of

spoilage microorganisms. In addition, research trends also show a strong shift towards the use of biodegradable and bio-based materials. In the future, the integration of active and intelligent packaging presents a promising prospect, as packaging will not only extend shelf life but also be able to monitor product quality changes in real time. Active packaging for vegetables has the potential to evolve into a more adaptive, precise packaging system that meets food safety requirements and environmental sustainability demands. The main challenge is the gap between laboratory-scale research findings and industrial application, as the performance of active packaging under controlled conditions does not necessarily match real-world distribution scenarios. Another challenge is controlling the release of active compounds to ensure their effectiveness throughout the shelf life. The use of biopolymers still has limitations in mechanical properties and durability compared to conventional plastics. The effectiveness of active packaging is also influenced by the characteristics of each type of vegetable, making research results difficult to generalize. Future research needs to focus on aspects of food safety, consumer acceptance, standardization of testing methods, cost efficiency, and evaluation of the sustainability of packaging materials.

#### 4. Conclusions

The bibliometric analysis of 387 Scopus documents from 2000–2025 reveals a strong growth trend in research on active packaging for vegetables, with a significant surge between 2019 and 2024. This growth emphasizes its vital role in maintaining the quality, safety, and shelf life of fresh produce. Geographically, India is the most productive contributor, while Brazil leads in citations, indicating high scientific influence. Keyword analysis identifies active packaging as a core theme linked to topics like 1-methylcyclopropene, chitosan, and antimicrobial activity, while emerging trends include nanotechnology, polyphenols, and ethylene scavengers. The *International Journal of Biological Macromolecules* acts as the primary publication hub, bridging major contributions from India, China, and Brazil. Despite this progress, future research must address the specific physiological characteristics of vegetables by focusing on biopolymer-based, eco-friendly, and controlled-release technologies tailored for the modern food distribution chain.

#### Acknowledgments

Not applicable.

#### Author Contributions

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, and visualization N.R.

#### Funding

This research received no any external funding.

#### Institutional Review Board Statement

Not applicable.

## Data Availability Statement

Available data are presented in the manuscript.

## Conflicts of Interest

Author declared no conflict of interest.

## References

1. Du L, Huang X, Li Z, Qin Z, Zhang N, Zhai X, et al. Application of Smart Packaging in Fruit and Vegetable Preservation: A Review [Internet]. Vol. 14, Foods. 2025. p. 447. Available from: <https://doi.org/10.3390/foods14030447>
2. Villanova-Estors R, López-Carballo G, López-de-Dicastillo C, Correa-Guimaraes A, Gavara R, Hernández-Muñoz P. Extending the shelf life of fresh-cut vegetables with sustainable packaging: A case study on rocket leaves. Food Packag Shelf Life [Internet]. 2025;50:101558. Available from: <https://doi.org/10.1016/j.fpsl.2025.101558>
3. Mostafidi M, Sanjabi MR, Shirkhan F, Zahedi MT. A review of recent trends in the development of the microbial safety of fruits and vegetables. Trends Food Sci Technol [Internet]. 2020;103:321–32. Available from: <https://doi.org/10.1016/j.tifs.2020.07.009>
4. Agustin-Salazar S, Torrieri E, Immirzi B, Di Lorenzo ML. Cellulose-based sustainable packaging of leafy vegetables: an experimental study on the shelf life of baby spinach. Org Agric [Internet]. 2023 Dec 15;14. Available from: <https://doi.org/10.1007/s13165-023-00450-5>
5. Batziakas KG, Singh S, Ayub K, Kang Q, Brecht JK, Rivard CL, et al. Reducing postharvest losses of spinach stored at nonoptimum temperatures with the implementation of passive modified atmosphere packaging. HortScience. 2020;55(3):326–35.
6. D'Aquino S, Mistriotis A, Briassoulis D, Di Lorenzo ML, Malinconico M, Palma A. Influence of modified atmosphere packaging on postharvest quality of cherry tomatoes held at 20°C. Postharvest Biol Technol [Internet]. 2016;115:103–12. Available from: <https://doi.org/10.1016/j.postharvbio.2015.12.014>
7. Khan MR, Di Giuseppe FA, Torrieri E, Sadiq MB. Recent advances in biopolymeric antioxidant films and coatings for preservation of nutritional quality of minimally processed fruits and vegetables. Food Packag Shelf Life [Internet]. 2021;30:100752. Available from: <https://doi.org/10.1016/j.fpsl.2021.100752>
8. Sharma K, Yadav R, Rajput R. Smart Packaging Materials: A Review of Existing and Emerging Packaging Technologies and their Applications. J Sci Res Reports [Internet]. 2025 Apr 24;31(5 SE-Review Article):53–68. Available from: <https://doi.org/10.9734/jsrr/2025/v31i53004>
9. Ahmed MW, Haque MA, Mohibullah M, Khan MSI, Islam MA, Mondal MHT, et al. A review on active packaging for quality and safety of foods: Current trends, applications, prospects and challenges. Food Packag Shelf Life [Internet]. 2022;33:100913. Available from: <https://doi.org/10.1016/j.fpsl.2022.100913>
10. Schaefer D, Cheung WM. Smart Packaging: Opportunities and Challenges. Procedia CIRP [Internet]. 2018;72:1022–7. Available from: <https://doi.org/10.1016/j.procir.2018.07.011>

- <https://doi.org/10.1016/j.procir.2018.03.240>
11. Vilela C, Kurek M, Hayouka Z, Röcker B, Yildirim S, Antunes MDC, et al. A concise guide to active agents for active food packaging. *Trends Food Sci Technol* [Internet]. 2018;80:212–22. Available from: <https://doi.org/10.1016/j.tifs.2018.08.006>
  12. Rehman A, Jafari SM, Aadil RM, Assadpour E, Randhawa MA, Mahmood S. Development of active food packaging via incorporation of biopolymeric nanocarriers containing essential oils. *Trends Food Sci Technol* [Internet]. 2020;101:106–21. Available from: <https://doi.org/10.1016/j.tifs.2020.05.001>
  13. Cui X, You Y, Ding Y, Sun C, Liu B, Wang X, et al. Improving the function of electrospun film by natural substance for active packaging application of fruits and vegetables. *LWT* [Internet]. 2024;191:115683. Available from: <https://www.sciencedirect.com/science/article/pii/S0023643823012628>
  14. Mao S, Zhang J, Wu Q, Xu Y, Zhang T, Lu C. Roles of polyphenols incorporated in starch-based films and coatings for fruits and vegetables preservation: A review. *Trends Food Sci Technol* [Internet]. 2025;163:105170. Available from: <https://doi.org/10.1016/j.tifs.2025.105170>
  15. Wang Y, Wu W, Liu R, Chen H, Gao H. Silk protein functionalized coatings and films as a novel biomaterial for fruit and vegetable preservation: current state and future prospects. *Curr Opin Food Sci* [Internet]. 2025;64:101329. Available from: <https://doi.org/10.1016/j.cofs.2025.101329>
  16. Nian L, Wang M, Sun X, Zeng Y, Xie Y, Cheng S, et al. Biodegradable active packaging: Components, preparation, and applications in the preservation of postharvest perishable fruits and vegetables. *Crit Rev Food Sci Nutr* [Internet]. 2024;64(8):2304–39. Available from: <https://doi.org/10.1080/10408398.2022.2122924>
  17. Dirpan A, Ainani AF, Djalal M. A Review on Biopolymer-Based Biodegradable Film for Food Packaging: Trends over the Last Decade and Future Research [Internet]. Vol. 15, *Polymers*. 2023. p. 2781. Available from: <https://doi.org/10.3390/polym15132781>
  18. Miteluț AC, Popa EE, Drăghici MC, Popescu PA, Popa VI, Bujor OC, et al. Latest Developments in Edible Coatings on Minimally Processed Fruits and Vegetables: A Review [Internet]. Vol. 10, *Foods*. 2021. p. 2821. Available from: <https://doi.org/10.3390/foods10112821>
  19. da Silveira MF, Rabanal RC. Active Food Packaging: A Brief Review of Biodegradable Films, Edible Coatings, and Sachets. *Infarma - Ciências Farm* [Internet]. 2022 Jul 1;34(2 SE-Artigo de Revisão):128–38. Available from: <https://doi.org/10.14450/2318-9312.v34.e2.a2022.pp128-138>
  20. Sani MA, Azizi-Lalabadi M, Tavassoli M, Mohammadi K, McClements DJ. Recent Advances in the Development of Smart and Active Biodegradable Packaging Materials [Internet]. Vol. 11, *Nanomaterials*. 2021. p. 1331. Available from: <https://doi.org/10.3390/nano11051331>
  21. Lu H, Zhu J, Li J, Chen J. Effectiveness of active packaging on control of *Escherichia coli* O157: H7 and total aerobic bacteria on iceberg lettuce. *J Food Sci* [Internet]. 2015;80(6):M1325–9. Available from: <https://doi.org/10.1111/1750-3841.12878>
  22. Catone MC, Diana P, Giordano G. Keywords Co-occurrence Analysis to Map New Topics and Recent Trends in Social Research Methods BT - *Advanced Information Networking and Applications*. In: Barolli L, Amato F, Moscato F, Enokido T, Takizawa M, editors. Cham: Springer International Publishing; 2020. p. 1078–88. Available

- from: [https://doi.org/10.1007/978-3-030-44041-1\\_93](https://doi.org/10.1007/978-3-030-44041-1_93)
23. Yuan C, Li G, Kamarthi S, Jin X, Moghaddam M. Trends in intelligent manufacturing research: a keyword co-occurrence network based review. *J Intell Manuf* [Internet]. 2022;33(2):425–39. Available from: <https://doi.org/10.1007/s10845-021-01885-x>
  24. Sharma S, Nakano K, Kumar S, Katiyar V. Edible packaging to prolong postharvest shelf-life of fruits and vegetables: A review. *Food Chem Adv* [Internet]. 2024;4:100711. Available from: <https://doi.org/10.1016/j.focha.2024.100711>
  25. Wason R, Arora P, Tomar A, Arora D. A novel, low-cost, smart IoT based framework for fruit and vegetable quality detection during transit in India. *Int J Inf Technol* [Internet]. 2023;15(3):1509–19. Available from: <https://doi.org/10.1007/s41870-023-01177-y>
  26. Bhardwaj A, Alam T, Talwar N. Recent advances in active packaging of agri-food products: a review. *J Postharvest Technol*. 2019;7(1):33–62.
  27. Shinde MM, Malik M, Kaur K, Gahlawat VK, Kumar N, Chiraang P, et al. Formulation and characterization of guar gum and almond gum based composite coating and their application for shelf-life extension of okra (*Hibiscus esculentus*). *Int J Biol Macromol* [Internet]. 2024;262:129630. Available from: <https://doi.org/10.1016/j.ijbiomac.2024.129630>
  28. Yuan Y, Wang H, Fu Y, Chang C, Wu J. Sodium alginate/gum arabic/glycerol multicomponent edible films loaded with natamycin: Study on physicochemical, antibacterial, and sweet potatoes preservation properties. *Int J Biol Macromol* [Internet]. 2022;213:1068–77. Available from: <https://doi.org/10.1016/j.ijbiomac.2022.06.040>
  29. Friedrich JCC, Silva OA, Faria MGI, Colauto NB, Gazzin ZC, Colauto GAL, et al. Improved antioxidant activity of a starch and gelatin-based biodegradable coating containing *Tetradenia riparia* extract. *Int J Biol Macromol*. 2020;165:1038–46.
  30. Matheus JRV, de Farias PM, Satoriva JM, de Andrade CJ, Fai AEC. Cassava starch films for food packaging: Trends over the last decade and future research. *Int J Biol Macromol* [Internet]. 2023;225:658–72. Available from: <https://doi.org/10.1016/j.ijbiomac.2022.11.129>
  31. Kumar N, Pratibha, Prasad J, Yadav A, Upadhyay A, Neeraj, et al. Recent Trends in Edible Packaging for Food Applications — Perspective for the Future. *Food Eng Rev* [Internet]. 2023;15(4):718–47. Available from: <https://doi.org/10.1007/s12393-023-09358-y>
  32. Kadzińska J, Janowicz M, Kalisz S, Bryś J, Lenart A. An overview of fruit and vegetable edible packaging materials. *Packag Technol Sci* [Internet]. 2019;32(10):483–95. Available from: <https://doi.org/10.1002/pts.2440>
  33. Kumar N, Pratibha, Trajkovska Petkoska A, Khojah E, Sami R, Al-Mushhin AAM. Chitosan Edible Films Enhanced with Pomegranate Peel Extract: Study on Physical, Biological, Thermal, and Barrier Properties [Internet]. Vol. 14, *Materials*. 2021. p. 3305. Available from: <https://doi.org/10.3390/ma14123305>
  34. Suhag R, Kumar N, Petkoska AT, Upadhyay A. Film formation and deposition methods of edible coating on food products: A review. *Food Res Int* [Internet]. 2020;136:109582. Available from: <https://doi.org/10.1016/j.foodres.2020.109582>
  35. Díaz-Montes E, Castro-Muñoz R. Edible Films and Coatings as Food-Quality Preservers: An Overview [Internet]. Vol. 10, *Foods*. 2021. p. 249. Available from:

- <https://doi.org/10.3390/foods10020249>
36. Mironescu M, Lazea-Stoyanova A, Barbinta-Patrascu ME, Virchea LI, Rexhepi D, Mathe E, et al. Green Design of Novel Starch-Based Packaging Materials Sustaining Human and Environmental Health [Internet]. Vol. 13, Polymers. 2021. p. 1190. Available from: <https://doi.org/10.3390/polym13081190>
  37. Pawase PA, Rout S, Tripathy S, Pathare AM, Srivastav PP, Bashir O, et al. Recent advances in cellulose, chitosan, and protein-based edible films for sustainable food packaging: A comprehensive review. *Int J Biol Macromol* [Internet]. 2025;321:146172. Available from: <https://doi.org/10.1016/j.ijbiomac.2025.146172>
  38. Galus S, Arik Kibar EA, Gniewosz M, Kraśniewska K. Novel Materials in the Preparation of Edible Films and Coatings—A Review [Internet]. Vol. 10, Coatings. 2020. p. 674. Available from: <https://doi.org/10.3390/coatings10070674>
  39. Spindler JP, Hamer JW, Kondakova ME. OLED Manufacturing Equipment and Methods BT - Handbook of Advanced Lighting Technology. In: Karlicek R, Sun CC, Zisis G, Ma R, editors. Cham: Springer International Publishing; 2017. p. 417–41. Available from: [https://doi.org/10.1007/978-3-319-00176-0\\_26](https://doi.org/10.1007/978-3-319-00176-0_26)
  40. Thao NTH, Hung DV, Tu NTM, Nga LH. Edible Plastics/Films or Biopolymers from Food Materials. In: Materials Science Forum [Internet]. Trans Tech Publ; 2024. p. 97–105. Available from: <https://doi.org/10.4028/p-kWTw4a>
  41. Kong P, Rosnan SM, Enomae T. Carboxymethyl cellulose–chitosan edible films for food packaging: A review of recent advances. *Carbohydr Polym* [Internet]. 2024;346:122612. Available from: <https://doi.org/10.1016/j.carbpol.2024.122612>
  42. Sadeghizadeh-Yazdi J, Habibi M, Kamali AA, Banaei M. Application of edible and biodegradable starch-based films in food packaging: A systematic review and meta-analysis. *Curr Res Nutr food Sci J* [Internet]. 2019;7(3):624–37. Available from: <https://doi.org/10.12944/CRNFSJ.7.3.03>
  43. Kumar L, Ramakanth D, Akhila K, Gaikwad KK. Edible films and coatings for food packaging applications: a review. *Environ Chem Lett* [Internet]. 2022;20(1):875–900. Available from: <https://doi.org/10.1007/s10311-021-01339-z>
  44. Li K, Li Y, Jin H, Feng B, Jiang G. Konjac glucomannan/polyvinyl alcohol/citric acid–based active food-packaging films containing *Polygonatum sibiricum* polysaccharide. *Food Chem Adv* [Internet]. 2024;4:100660. Available from: <https://doi.org/10.1016/j.focha.2024.100660>
  45. Kaur J, Singh J, Rasane P, Gupta P, Kaur S, Sharma N, et al. Natural additives as active components in edible films and coatings. *Food Biosci* [Internet]. 2023;53:102689. Available from: <https://doi.org/10.1016/j.fbio.2023.102689>
  46. Venezia V, Prieto C, Verrillo M, Grumi M, Silvestri B, Vitiello G, et al. Electrospun films incorporating humic substances of application interest in sustainable active food packaging. *Int J Biol Macromol* [Internet]. 2024;263:130210. Available from: <https://doi.org/10.1016/j.ijbiomac.2024.130210>
  47. Rusli A, Syamsuar, Santi A, Malle S, Arfini F, Arsyad MA, et al. Application of antimicrobial edible film incorporated with *Caulerpa racemosa* crude extract as active packaging of seaweed dodol. *Appl Food Res* [Internet]. 2024;4(2):100625. Available from: <https://doi.org/10.1016/j.afres.2024.100625>
  48. Pham TT, Nguyen LL, Dam MS, Baranyai L. Application of Edible Coating in Extension of Fruit Shelf Life: Review [Internet]. Vol. 5, *AgriEngineering*. 2023. p. 520–36.

- Available from: <https://doi.org/10.3390/agriengineering5010034>
49. Aljabary AMAO, Awlqadr FH, Altemimi AB, Abdulrahman ABM, Saeed MN, Hesarinejad MA. Advances in oil-based edible coatings for postharvest preservation of fruits and vegetables: A comprehensive review of biopolymer types, functional plant oils, nanoemulsion systems, and application techniques. *J Agric Food Res* [Internet]. 2025;24:102425. Available from: <https://doi.org/10.1016/j.jafr.2025.102425>
  50. Muñoz-Tebar N, Pérez-Álvarez JA, Fernández-López J, Viuda-Martos M. Chitosan Edible Films and Coatings with Added Bioactive Compounds: Antibacterial and Antioxidant Properties and Their Application to Food Products: A Review [Internet]. Vol. 15, *Polymers*. 2023. p. 396. Available from: <https://doi.org/10.3390/polym15020396>
  51. Sapna, Sharma C, Pathak P, Yadav SP, Gautam S. Potential of emerging “all-natural” edible coatings to prevent post-harvest losses of vegetables and fruits for sustainable agriculture. *Prog Org Coatings* [Internet]. 2024;193:108537. Available from: <https://doi.org/10.1016/j.porgcoat.2024.108537>
  52. Armghan Khalid M, Niaz B, Saeed F, Afzaal M, Islam F, Hussain M, et al. Edible coatings for enhancing safety and quality attributes of fresh produce: A comprehensive review. *Int J Food Prop* [Internet]. 2022 Dec 31;25(1):1817–47. Available from: <https://doi.org/10.1080/10942912.2022.2107005>
  53. de Oliveira Filho JG, Albiero BR, Cipriano L, de Oliveira Nobre Bezerra CC, Oldoni FCA, Egea MB, et al. Arrowroot starch-based films incorporated with a carnauba wax nanoemulsion, cellulose nanocrystals, and essential oils: a new functional material for food packaging applications. *Cellulose* [Internet]. 2021;28(10):6499–511. Available from: <https://doi.org/10.1007/s10570-021-03945-0>
  54. Panwar A, Kumar V, Dhiman A, Thakur P, Sharma V, Sharma A, et al. Nanoemulsion based edible coatings for quality retention of fruits and vegetables-decoding the basics and advancements in last decade. *Environ Res* [Internet]. 2024;240:117450. Available from: <https://doi.org/10.1016/j.envres.2023.117450>
  55. Ho TM, Abik F, Mikkonen KS. An overview of nanoemulsion characterization via atomic force microscopy. *Crit Rev Food Sci Nutr* [Internet]. 2022 Jun 29;62(18):4908–28. Available from: <https://doi.org/10.1080/10408398.2021.1879727>
  56. Viana RM, Sá NMSM, Barros MO, Borges M de F, Azeredo HMC. Nanofibrillated bacterial cellulose and pectin edible films added with fruit purees. *Carbohydr Polym* [Internet]. 2018;196:27–32. Available from: <https://doi.org/10.1016/j.carbpol.2018.05.017>
  57. Leceta I, Molinaro S, Guerrero P, Kerry JP, de la Caba K. Quality attributes of map packaged ready-to-eat baby carrots by using chitosan-based coatings. *Postharvest Biol Technol* [Internet]. 2015;100:142–50. Available from: <https://doi.org/10.1016/j.postharvbio.2014.09.022>
  58. Dulta K, Ağçeli GK, Singh S, Pandey VK, Thakur A, Chauhan PK, et al. Unveiling the effects of ZnO nanoparticle incorporated chitosan coating on postharvest quality of eggplant (*Solanum melongena* L.). *Food Control* [Internet]. 2025;168:110912. Available from: <https://doi.org/10.1016/j.foodcont.2024.110912>
  59. Wu D, Zhang M, Bhandari B, Guo Z. Combined effects of microporous packaging and nano-chitosan coating on quality and shelf-life of fresh-cut eggplant. *Food Biosci*

- [Internet]. 2021;43:101302. Available from: <https://doi.org/10.1016/j.fbio.2021.101302>
60. Zehra A, Wani SM, Jan N, Bhat TA, Rather SA, Malik AR, et al. Development of chitosan-based biodegradable films enriched with thyme essential oil and additives for potential applications in packaging of fresh collard greens. *Sci Rep* [Internet]. 2022;12(1):16923. Available from: <https://doi.org/10.1038/s41598-022-20751-1>
61. Kumar R, Ghoshal G, Goyal M. Effect of basil leaves extract on modified moth bean starch active film for eggplant surface coating. *LWT* [Internet]. 2021;145:111380. Available from: <https://doi.org/10.1016/j.lwt.2021.111380>
62. Marzano-Barreda LA, Yamashita F, Bilck AP. Effect of biodegradable active packaging with zeolites on fresh broccoli florets. *J Food Sci Technol* [Internet]. 2021;58(1):197–204. Available from: <https://doi.org/10.1007/s13197-020-04529-9>
63. Li M, Yu H, Xie Y, Guo Y, Cheng Y, Qian H, et al. Effects of double layer membrane loading eugenol on postharvest quality of cucumber. *LWT* [Internet]. 2021;145:111310. Available from: <https://doi.org/10.1016/j.lwt.2021.111310>
64. Khalil RKS, Sharaby MR, Abdelrahim DS, ElLeithy AE. A novel multifunctional carboxymethyl cellulose packaging film with encapsulated lemon oil for quality enhancement of cherry tomato and baby spinach leaves. *Food Packag Shelf Life* [Internet]. 2024;42:101267. Available from: <https://doi.org/10.1016/j.fpsl.2024.101267>
65. Buendía-Moreno L, Soto-Jover S, Ros-Chumillas M, Antolinos-López V, Navarro-Segura L, Sánchez-Martínez MJ, et al. An innovative active cardboard box for bulk packaging of fresh bell pepper. *Postharvest Biol Technol* [Internet]. 2020;164:111171. Available from: <https://doi.org/10.1016/j.postharvbio.2020.111171>
66. Madihalli S, Masti SP, Eelager MP, Chougale RB, Dalbanjan NP, Praveen Kumar SK. Sodium alginate/poly (vinyl alcohol) active films incorporated with Chrysanthemum leaves extract as an eco-friendly approach to extend the shelf life of green chilies. *Int J Biol Macromol* [Internet]. 2025;302:140926. Available from: <https://doi.org/10.1016/j.ijbiomac.2025.140926>
67. Yang Z, Chen B, Tahir HE, Li Z, Huang X, Li M, et al. Gelatin/sodium alginate-based biodegradable films functionalized by persimmon pectin/ovalbumin-stabilized neem essential oil Pickering emulsion: Application for cherry tomato preservation. *Prog Org Coatings* [Internet]. 2024;192:108448. Available from: <https://doi.org/10.1016/j.porgcoat.2024.108448>
68. Abedi A, Lakzadeh L, Amouheydari M. Effect of an edible coating composed of whey protein concentrate and rosemary essential oil on the shelf life of fresh spinach. *J Food Process Preserv* [Internet]. 2021;45(4):e15284. Available from: <https://doi.org/10.1111/jfpp.15284>
69. Lara G, Yakoubi S, Villacorta CM, Uemura K, Kobayashi I, Takahashi C, et al. Spray technology applications of xanthan gum-based edible coatings for fresh-cut lotus root (*Nelumbo nucifera*). *Food Res Int* [Internet]. 2020;137:109723. Available from: <https://doi.org/10.1016/j.foodres.2020.109723>
70. Wu L, Cui B, Dong D, Wu Z, Li J, Lu L, et al. Effect of mixture microstructure/compatibility on the properties of type-A gelatin-dextran edible films. *Carbohydr Polym* [Internet]. 2024;329:121733. Available from:

- <https://doi.org/10.1016/j.carbpol.2023.121733>
71. Fan Y, Ren J, Xiao X, Cao Y, Zou Y, Qi B, et al. Recent advances in polysaccharide-based edible films/coatings for food preservation: fabrication, characterization, and applications in packaging. *Carbohydr Polym* [Internet]. 2025;364:123779. Available from: <https://doi.org/10.1016/j.carbpol.2025.123779>
  72. Berti S, Jagus RJ, Flores SK, González-Martínez C. Antimicrobial Edible Starch Films Obtained By Casting and Thermo-compression Techniques. *Food Bioprocess Technol* [Internet]. 2024;17(4):904–16. Available from: <https://doi.org/10.1007/s11947-023-03172-4>
  73. Salama HE, Abdel Aziz MS, Alsehli M. Carboxymethyl cellulose/sodium alginate/chitosan biguanidine hydrochloride ternary system for edible coatings. *Int J Biol Macromol* [Internet]. 2019;139:614–20. Available from: <https://doi.org/10.1016/j.ijbiomac.2019.08.008S0141813019343661>
  74. Jeya Jeevahan J, Chandrasekaran M, Venkatesan SP, Sriram V, Britto Joseph G, Mageshwaran G, et al. Scaling up difficulties and commercial aspects of edible films for food packaging: A review. *Trends Food Sci Technol*. 2020;100:210–22.
  75. Huntrakul K, Yoksan R, Sane A, Harnkarnsujarit N. Effects of pea protein on properties of cassava starch edible films produced by blown-film extrusion for oil packaging. *Food Packag Shelf Life* [Internet]. 2020;24:100480. Available from: <https://doi.org/10.1016/j.fpsl.2020.100480>
  76. Calderón-Castro A, Vega-García MO, de Jesús Zazueta-Morales J, Fitch-Vargas PR, Carrillo-López A, Gutiérrez-Dorado R, et al. Effect of extrusion process on the functional properties of high amylose corn starch edible films and its application in mango (*Mangifera indica* L.) cv. Tommy Atkins. *J Food Sci Technol* [Internet]. 2018;55(3):905–14. Available from: <https://doi.org/10.1007/s13197-017-2997-6>
  77. Karnwal A, Rauf A, Jassim AY, Selvaraj M, Al-Tawaha ARMS, Kashyap P, et al. Advanced starch-based films for food packaging: Innovations in sustainability and functional properties. *Food Chem X* [Internet]. 2025;29:102662. Available from: <https://doi.org/10.1016/j.fochx.2025.102662>
  78. Nilsuwan K, Guerrero P, Caba K de la, Benjakul S, Prodpran T. Properties of fish gelatin films containing epigallocatechin gallate fabricated by thermo-compression molding. *Food Hydrocoll* [Internet]. 2019;97:105236. Available from: <https://doi.org/10.1016/j.foodhyd.2019.105236>
  79. de Margerie V, Gallas M. Vertical Hot Melt Extrusion: A Cutting Edge Technology for Personalized and Sustainable Food Systems. *Phys Sci Biophys J* [Internet]. 8(2 SE-Articles):1–9. Available from: <https://doi.org/10.23880/psbj-16000276>
  80. Perez-Vazquez A, Barciela P, Carpena M, Prieto MA. Edible Coatings as a Natural Packaging System to Improve Fruit and Vegetable Shelf Life and Quality [Internet]. Vol. 12, *Foods*. 2023. p. 3570. Available from: <https://doi.org/10.3390/foods12193570>
  81. Cvanić T, Šovljanski O, Popović S, Erceg T, Vulić J, Čanadanović-Brunet J, et al. Progress in Fruit and Vegetable Preservation: Plant-Based Nanoemulsion Coatings and Their Evolving Trends. Vol. 13, *Coatings*. 2023. p. 1835.
  82. Trajkovska Petkoska A, Daniloski D, D’Cunha NM, Naumovski N, Broach AT. Edible packaging: Sustainable solutions and novel trends in food packaging. *Food Res Int* [Internet]. 2021;140:109981. Available from:

- <https://doi.org/10.1016/j.foodres.2020.109981>
83. Otoni CG, Avena-Bustillos RJ, Azeredo HMC, Lorevice M V, Moura MR, Mattoso LHC, et al. Recent advances on edible films based on fruits and vegetables—a review. *Compr Rev Food Sci Food Saf* [Internet]. 2017;16(5):1151–69. Available from: <https://doi.org/10.1111/1541-4337.12281>
  84. Nunes C, Silva M, Farinha D, Sales H, Pontes R, Nunes J. Edible Coatings and Future Trends in Active Food Packaging-Fruits' and Traditional Sausages' Shelf Life Increasing. *Foods* (Basel, Switzerland) [Internet]. 2023 Sep;12(17). Available from: <https://doi.org/10.3390/foods12173308>
  85. Venkatesan U, Muniyan R. Review on the extension of shelf life for fruits and vegetables using natural preservatives. *Food Sci Biotechnol* [Internet]. 2024;33(11):2477–96. Available from: <https://doi.org/10.1007/s10068-024-01602-3>
  86. Rohasmizah H, Azizah M. Pectin-based edible coatings and nanoemulsion for the preservation of fruits and vegetables: A review. *Appl Food Res* [Internet]. 2022;2(2):100221. Available from: <https://doi.org/10.1016/j.afres.2022.100221>
  87. Kumar N, Pratibha, Neeraj, Ojha A, Upadhyay A, Singh R, et al. Effect of active chitosan-pullulan composite edible coating enrich with pomegranate peel extract on the storage quality of green bell pepper. *LWT* [Internet]. 2021;138:110435. Available from: <https://doi.org/10.1016/j.lwt.2020.110435>
  88. Zhang S, Kuang Y, Xu P, Chen X, Bi Y, Peng D, et al. Applications of Prolamin-Based Edible Coatings in Food Preservation: A Review [Internet]. Vol. 28, *Molecules*. 2023. p. 7800. Available from: <https://doi.org/10.3390/molecules28237800>
  89. Patil V, Shams R, Dash KK. Techno-functional characteristics, and potential applications of edible coatings: A comprehensive review. *J Agric Food Res* [Internet]. 2023;14:100886. Available from: <https://doi.org/10.1016/j.jafr.2023.100886>
  90. dos Passos Braga S, Magnani M, Madruga MS, de Souza Galvão M, de Medeiros LL, Batista AUD, et al. Characterization of edible coatings formulated with chitosan and Mentha essential oils and their use to preserve papaya (*Carica papaya* L.). *Innov Food Sci Emerg Technol* [Internet]. 2020;65:102472. Available from: <https://doi.org/10.1016/j.ifset.2020.102472>
  91. Ghoshal G. Chapter 10 - Recent Trends in Active, Smart, and Intelligent Packaging for Food Products. In: Grumezescu AM, Holban AMBTFP and P, editors. *Handbook of Food Bioengineering* [Internet]. Academic Press; 2018. p. 343–74. Available from: <https://www.sciencedirect.com/science/article/pii/B9780128115169000105>
  92. Liyanapathirana A, Dassanayake RS, Gamage A, Karri RR, Manamperi A, Evon P, et al. Recent Developments in Edible Films and Coatings for Fruits and Vegetables [Internet]. Vol. 13, *Coatings*. 2023. p. 1177. Available from: <https://doi.org/10.3390/coatings13071177>
  93. Nikolaev S V, Benin A V, Popov AM. Methodology of the selection of effective dipping and control over the filling depth of open-textured construction materials. *J Phys Conf Ser* [Internet]. 2021;2131(2):22055. Available from: <https://doi.org/10.1088/1742-6596/2131/2/022055>
  94. Rahman NR, Syaâ€™roni I, Hartanto A, Prasetyono AD, Subiantoro I. Design and Build a Microcontroller Based Dip Coater Tool with An Automatic Calibration System. *Indones Phys Rev* [Internet]. 2024 Nov 11;8(1 SE-Articles):48–61. Available from: <https://doi.org/10.29303/ipr.v8i1.364>

95. Atanasova K, Savov V. Effect of process conditions on waterborne wood coating performance applied by dipping. *Bull Transilv Univ Brasov Ser II For Wood Ind Agric Food Eng* [Internet]. 2023;1–22. Available from: <https://doi.org/10.31926/but.fwiafe.2023.16.65.3.1>
96. Wu H, Forghani B, Sajib M, Undeland I. A Recyclable Dipping Strategy to Stabilize Herring (*Clupea harengus*) Co-products During Ice Storage. *Food Bioprocess Technol* [Internet]. 2021;14(12):2207–18. Available from: <https://doi.org/10.1007/s11947-021-02717-9>
97. Malakar S. Active edible coating combined with novel pre-treatment technique for drying of foods: Mechanistic insights, enhancing drying performance and product quality. *Food Biosci* [Internet]. 2024;60:104527. Available from: <https://doi.org/10.1016/j.fbio.2024.104527>
98. Bhargava N, Mor RS, Kumar K, Sharanagat VS. Advances in application of ultrasound in food processing: A review. *Ultrason Sonochem* [Internet]. 2021;70:105293. Available from: <https://doi.org/10.1016/j.ultsonch.2020.105293>
99. Sulaiman A, Silva FVM. Chapter Thirteen - Principles of sonication and its equipment in the food industry. In: Jafari SM, Therdthai NBTN thermal FPO, editors. *A volume in Unit Operations and Processing Equipment in the Food Industry* [Internet]. Woodhead Publishing; 2023. p. 435–64. Available from: <https://doi.org/10.1016/B978-0-12-818717-3.00001-9>
100. Adnoui M, Jiang L, Zhang XJ, Zhang LZ, Pathare PB, Roskilly AP. Computational modelling for decarbonised drying of agricultural products: Sustainable processes, energy efficiency, and quality improvement. *J Food Eng* [Internet]. 2023;338:111247. Available from: <https://doi.org/10.1016/j.jfoodeng.2022.111247>
101. Rajabi F, Karimi S, Abbasi H, Layeghinia N. Influence of edible coatings pretreatment on the performance of microwave and combined microwave-hot air drying of kiwifruit. *Food Bioprod Process* [Internet]. 2025;153:286–97. Available from: <https://doi.org/10.1016/j.fbp.2025.07.003>
102. Wu Y, Liu Y, Jia Y, Feng CH, Zhang H, Ren F, et al. Effects of thermal processing on natural antioxidants in fruits and vegetables. *Food Res Int* [Internet]. 2024;192:114797. Available from: <https://doi.org/10.1016/j.foodres.2024.114797>
103. Makovic D, Shukla V, Leitao SB, Yu J, Padilla-Zakour OI, Chen C. Microwave vacuum drying for crispy beet snacks: Process development, drying kinetics, and product qualities. *Innov Food Sci Emerg Technol* [Internet]. 2026;108:104402. Available from: <https://doi.org/10.1016/j.ifset.2025.104402>
104. Guarnieri A, Triunfo M, Ianniciello D, Tedesco F, Salvia R, Scieuzo C, et al. Insect-derived chitosan, a biopolymer for the increased shelf life of white and red grapes. *Int J Biol Macromol* [Internet]. 2024;275:133149. Available from: <https://doi.org/10.1016/j.ijbiomac.2024.133149>
105. Senturk Parreidt T, Müller K, Schmid M. Alginate-Based Edible Films and Coatings for Food Packaging Applications [Internet]. Vol. 7, *Foods*. 2018. p. 170. Available from: <https://doi.org/10.3390/foods7100170>
106. Olunusi SO, Ramli NH, Fatmawati A, Ismail AF, Okwuwa CC. Revolutionizing tropical fruits preservation: Emerging edible coating technologies. *Int J Biol Macromol* [Internet]. 2024;264:130682. Available from: <https://doi.org/10.1016/j.ijbiomac.2024.130682>

107. Rani R, Sahu G, Gopu G, Chauhan A, Nayak MK, Mazumder K, et al. Study of chargeability of coating materials and optimization of design and performance parameters of the developed electrostatic spray coating system. *J Food Eng* [Internet]. 2025;391:112460. Available from: <https://doi.org/10.1016/j.jfoodeng.2024.112460>
108. Valencia GA, Luciano CG, Monteiro Fritz AR. Smart and Active Edible Coatings Based on Biopolymers BT - Polymers for Agri-Food Applications. In: Gutiérrez TJ, editor. Cham: Springer International Publishing; 2019. p. 391–416. Available from: [https://doi.org/10.1007/978-3-030-19416-1\\_20](https://doi.org/10.1007/978-3-030-19416-1_20)
109. Adhikari M, Koirala S, Anal AK. Edible multilayer coating using electrostatic layer-by-layer deposition of chitosan and pectin enhances shelf life of fresh strawberries. *Int J Food Sci Technol* [Internet]. 2023 Feb 1;58(2):871–9. Available from: <https://doi.org/10.1111/ijfs.15704>
110. Ribeiro AM, Estevinho BN, Rocha F. Preparation and Incorporation of Functional Ingredients in Edible Films and Coatings. *Food Bioprocess Technol* [Internet]. 2021;14(2):209–31. Available from: <https://doi.org/10.1007/s11947-020-02528-4>
111. Gittleson FS, Kohn DJ, Li X, Taylor AD. Improving the Assembly Speed, Quality, and Tunability of Thin Conductive Multilayers. *ACS Nano* [Internet]. 2012 May 22;6(5):3703–11. Available from: <https://doi.org/10.1021/nn204384f>
112. Butt MA. Thin-Film Coating Methods: A Successful Marriage of High-Quality and Cost-Effectiveness- A Brief Exploration [Internet]. Preprints. Preprints; 2022. Available from: <http://dx.doi.org/10.20944/preprints202207.0177.v1>
113. Zhang C, Li Y, Wang P, Zhang H. Electrospinning of nanofibers: Potentials and perspectives for active food packaging. *Compr Rev Food Sci Food Saf* [Internet]. 2020 Mar 1;19(2):479–502. Available from: <https://doi.org/10.1111/1541-4337.12536>
114. Zhao L, Duan G, Zhang G, Yang H, He S, Jiang S. Electrospun Functional Materials toward Food Packaging Applications: A Review [Internet]. Vol. 10, *Nanomaterials*. 2020. p. 150. Available from: <https://doi.org/10.3390/nano10010150>
115. Figueroa-Lopez KJ, Castro-Mayorga JL, Andrade-Mahecha MM, Cabedo L, Lagaron JM. Antibacterial and Barrier Properties of Gelatin Coated by Electrospun Polycaprolactone Ultrathin Fibers Containing Black Pepper Oleoresin of Interest in Active Food Biopackaging Applications [Internet]. Vol. 8, *Nanomaterials*. 2018. p. 199. Available from: <https://doi.org/10.3390/nano8040199>
116. Râpa M, Vasile C. Processing and properties of chitosan and/or chitin biocomposites for food packaging. In: *Food Packaging* [Internet]. CRC Press; 2020. p. 291–326. Available from: <https://doi.org/10.1201/9780429322129-11>
117. Wróbel P, Zwolińska J, Szopa D, Witek-Krowiak A. Towards Enhanced Electrospinning of Alginate—Can Recent Strategies Overcome Limitations? A Review [Internet]. Vol. 17, *Polymers*. 2025. p. 2255. Available from: <https://doi.org/10.3390/polym17162255>
118. Patiño Vidal C, López de Dicastillo C, Rodríguez-Mercado F, Guarda A, Galotto MJ, Muñoz-Shugulí C. Electrospinning and cyclodextrin inclusion complexes: An emerging technological combination for developing novel active food packaging materials. *Crit Rev Food Sci Nutr* [Internet]. 2022 Jul 8;62(20):5495–510. Available from: <https://doi.org/10.1080/10408398.2021.1886038>
119. Shen C, Yang Z, Wu D, Chen K. The preparation, resources, applications, and future trends of nanofibers in active food packaging: a review. *Crit Rev Food Sci Nutr*

- [Internet]. 2024 Oct 13;64(26):9656–71. Available from: <https://doi.org/10.1080/10408398.2023.2214819>
120. Kandirmaz EA, Zelzele OB. The production of ecofriendly biofilm with natural oil for food packaging. In: 10th International Symposium on Graphic Engineering and Design [Internet]. 2020. p. 221–7. Available from: <https://doi.org/10.24867/GRID-2020-p23>
  121. Sungur Ş, Atan MM. Effect of Active Packaging Films Containing Natural Antioxidant Essential Oils on the Oxidative Stability of the African Catfish (*Clarias gariepinus*). *Nat Eng Sci* [Internet]. 2020;5(3):155–66. Available from: <https://doi.org/10.28978/nesciences.832984>
  122. Dharmalingam K, Roy A, Anandalakshmi R. Essential Oils in Active Films and Coatings. *Biopolym Food Packag Innov Technol Appl* [Internet]. 2022;422–44. Available from: <https://doi.org/10.1002/9781119702313.ch13>
  123. Sardar NR, Akbari SH, Modi RB, Tiwari M, Tagalpallewar GP. Application of Essential Oils in Food Packaging: A Concise Review. *Eur J Nutr Food Saf* [Internet]. 2024 Mar 19;16(3 SE-Review Article):60–7. Available from: <https://doi.org/10.9734/ejnfs/2024/v16i31399>
  124. Arman Kandirmaz E. Fabrication of rosemary essential oil microcapsules and using in active packaging. 2021;36(2):323–30. Available from: <https://doi.org/10.1515/npprj-2021-0014>
  125. Xie Q, Liu G, Zhang Y, Yu J, Wang Y, Ma X. Active edible films with plant extracts: a updated review of their types, preparations, reinforcing properties, and applications in muscle foods packaging and preservation. *Crit Rev Food Sci Nutr* [Internet]. 2023 Dec 21;63(32):11425–47. Available from: <https://doi.org/10.1080/10408398.2022.2092058>
  126. Barzan G, Sacco A, Giovannozzi AM, Portesi C, Schiavone C, Salafranca J, et al. Development of innovative antioxidant food packaging systems based on natural extracts from food industry waste and *Moringa oleifera* leaves. *Food Chem* [Internet]. 2024;432:137088. Available from: <https://doi.org/10.1016/j.foodchem.2023.137088>
  127. Sarkhel S, Kaur S, Das R, Sharma A, Kheto A, Saha D, et al. Antimicrobial active packaging with biopolymers and natural extracts: sustainable solutions and technological challenges. *Sustain Food Technol* [Internet]. 2026;4(2):1225–61. Available from: <http://dx.doi.org/10.1039/D5FB00689A>
  128. Radisavljevic A, Stojanovic DB, Petrovic M, Radojevic V, Uskokovic P, Rajilic-Stojanovic M. Electrospun polycaprolactone nanofibers functionalized with *Achillea millefolium* extract yield biomaterial with antibacterial, antioxidant and improved mechanical properties. *J Biomed Mater Res Part A* [Internet]. 2023 Jul 1;111(7):962–74. Available from: <https://doi.org/10.1002/jbm.a.37481>
  129. Sandhya J, Veeralakshmi S, Kalaiselvam S. Tripolyphosphate crosslinked *Triticum aestivum* (wheatgrass) functionalized antimicrobial chitosan: Ameliorating effect on physicochemical, mechanical, invitro cytocompatibility and cell migration properties. *J Biomol Struct Dyn* [Internet]. 2021 Mar 8;39(5):1635–44. Available from: <https://doi.org/10.1080/07391102.2020.1736160>
  130. Suryavanshi V, Suresh PK, Das C, Maharana T. Physicochemical properties and in-vitro release study of CFLE-chitosan microsphere beads. *J Polym Res* [Internet]. 2019;26(12):288. Available from: <https://doi.org/10.1007/s10965-019-1954-7>
  131. Abd Elgair M, Mirghani MES, Mariod A. Chitosan and Chitosan-Essential Oil

- Composites as Edible Coatings for Meat and Meat Products: A Review. *Recent Adv Food, Nutr Agric* [Internet]. 2025;16(2):109–20. Available from: <http://dx.doi.org/10.2174/012772574X301555240503070126>
132. Teixeira BS. Physicochemical properties of potato starch films containing natural extracts of turmeric and hibiscus. 2023; Available from: <https://doi.org/10.30574/msarr.2023.8.2.0087>
  133. Bialik-Was K, Tyliczszak B, Walczyk D, Malina D, Sobczak-Kupiec A. Cytotoxicity analysis of hydrogels based on chitosan incorporated with variable amounts of silver nanoparticles. *Front Bioeng Biotechnol* [Internet]. 2016;4. Available from: <https://doi.org/10.3389/conf.FBIOE.2016.01.00456>
  134. Tang Y, Liu L, Han J, Zhang Z, Yang S, Li S, et al. Fabrication and Characterization of Multiple Herbal Extracts-loaded Nanofibrous Patches for Topical Treatment of Acne Vulgaris. *Fibers Polym* [Internet]. 2021;22(2):323–33. Available from: <https://doi.org/10.1007/s12221-021-0156-1>
  135. Wagh R V, Priyadarshi R, Rhim JW. Novel Bacteriophage-Based Food Packaging: An Innovative Food Safety Approach [Internet]. Vol. 13, *Coatings*. 2023. p. 609. Available from: <https://doi.org/10.3390/coatings13030609>
  136. Duda-Chodak A, Tarko T, Petka-Poniatowska K. Antimicrobial Compounds in Food Packaging [Internet]. Vol. 24, *International Journal of Molecular Sciences*. 2023. p. 2457. Available from: <https://doi.org/10.3390/ijms24032457>
  137. Anwar RW, Sugiarto, Warsiki E. The comparison of antimicrobial packaging properties with different applications incorporation method of active material. *IOP Conf Ser Earth Environ Sci* [Internet]. 2018;141(1):12002. Available from: <https://doi.org/10.1088/1755-1315/141/1/012002>
  138. Oliveira JM, Jesus M, Santos JN, Mata F, Dehghani S, Santos J, et al. Application of Probiotic Bacteria in Active Packaging for the Food Industry: Review [Internet]. Vol. 8, *Sci*. 2026. p. 58. Available from: <https://doi.org/10.3390/sci8030058>
  139. Verma K, Kumar Y. Role of Bacteriophages in Active Food Packaging. In: *Advances in Sustainable Food Packaging Technology* [Internet]. Apple Academic Press; 2024. p. 115–32. Available from: <https://doi.org/10.1201/9781003395249-7>
  140. Agriopoulou S, Stamatelopoulou E, Skiada V, Tsarouhas P, Varzakas T. Emerging Nanomaterial Applications for Food Packaging and Preservation: Safety Issues and Risk Assessment [Internet]. Vol. 70, *Proceedings*. 2021. p. 7. Available from: [https://doi.org/10.3390/foods\\_2020-07747](https://doi.org/10.3390/foods_2020-07747)
  141. Ashfaq A, Khursheed N, Fatima S, Anjum Z, Younis K. Application of nanotechnology in food packaging: Pros and Cons. *J Agric Food Res* [Internet]. 2022;7:100270. Available from: <https://doi.org/10.1016/j.jafr.2022.100270>
  142. Roy S, Ezati P, Priyadarshi R, Biswas D, Rhim JW. Recent advances in metal sulfide nanoparticle-added bionanocomposite films for food packaging applications. *Crit Rev Food Sci Nutr* [Internet]. 2024 May 29;64(14):4660–73. Available from: <https://doi.org/10.1080/10408398.2022.2144794>
  143. Bansal V, Chawla R. Nanoactive Packaging for Quality Enhancement. In: *Active Packaging for Various Food Applications* [Internet]. CRC Press; 2021. p. 37–50. Available from: <https://doi.org/10.1201/9781003127789-5>
  144. Madhan S, Espírito Santo C, . LPA, . PDS, . PDG. Active and Intelligent Packaging with Phase Change Materials to Promote the Shelf Life Extension of Food Products. *KnE*

- Eng [Internet]. 2020 Jun 2;5(6 SE-Articles):232–241. Available from: <https://doi.org/10.18502/keg.v5i6.7037>
145. Mariah MA, Vonnie JM, Erna KH, Nur'Aqilah NM, Huda N, Abdul Wahab R, et al. The Emergence and Impact of Ethylene Scavengers Techniques in Delaying the Ripening of Fruits and Vegetables [Internet]. Vol. 12, Membranes. 2022. p. 117. Available from: <https://doi.org/10.3390/membranes12020117>
146. Wilson MD, Stanley RA, Eyles A, Ross T. Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables. Crit Rev Food Sci Nutr [Internet]. 2019 Feb 4;59(3):411–22. Available from: <https://doi.org/10.1080/10408398.2017.1375892>
147. Li B, Sun Z, Tian Z, Meng X, Wang N, Liu Z, et al. Preparation and performance characterization of antimicrobial films based on chitosan-nisin-nanocrystalline cellulose and its preservation effect applied to baby cabbage. Int J Biol Macromol [Internet]. 2025;300:140247. Available from: <https://doi.org/10.1016/j.ijbiomac.2025.140247>
148. Wiczyńska J, Cavoski I. Antimicrobial, antioxidant and sensory features of eugenol, carvacrol and trans-anethole in active packaging for organic ready-to-eat iceberg lettuce. Food Chem [Internet]. 2018;259:251–60. Available from: <https://doi.org/10.1016/j.foodchem.2018.03.137>
149. Esmaeili F, Mehrabi M, Babapour H, Hassani B, Abedinia A. Active coating based on carboxymethyl cellulose and flaxseed mucilage, containing burdock extract, for fresh-cut and fried potatoes. LWT [Internet]. 2024;192:115726. Available from: <https://doi.org/10.1016/j.lwt.2024.115726>
150. Talesh AA, Amiri S, Radi M, Hosseinifarahi M. Effect of nanocomposite alginate-based edible coatings containing thymol-nanoemulsion and/or thymol-loaded nanostructured lipid carriers on the microbial and physicochemical properties of carrot. Int J Biol Macromol [Internet]. 2025;308:129196. Available from: <https://doi.org/10.1016/j.ijbiomac.2023.129196>
151. Seididamyeh M, Mantilla SMO, Netzel ME, Mereddy R, Sultanbawa Y. Gum Arabic edible coating embedded aqueous plant extracts: Interactive effects of partaking components and its effectiveness on cold storage of fresh-cut capsicum. Food Control [Internet]. 2024;159:110267. Available from: <https://doi.org/10.1016/j.foodcont.2023.110267>
152. Zhang Y, Li Y, Ning H, Lu L, Tang Y. Preparation of bioactive film for regulating chlorine dioxide release based on the hygroscopic properties of chitosan and its application in broccoli preservation. Int J Biol Macromol [Internet]. 2025;290:138972. Available from: <https://doi.org/10.1016/j.ijbiomac.2024.138972>
153. Singh S, Gaikwad KK, Lee YS. Development and application of a pyrogallol acid-based oxygen scavenging packaging system for shelf life extension of peeled garlic. Sci Hortic (Amsterdam) [Internet]. 2019;256:108548. Available from: <https://doi.org/10.1016/j.scienta.2019.108548>
154. Ni X, Yu J, Shao P, Yu J, Chen H, Gao H. Preservation of Agaricus bisporus freshness with using innovative ethylene manipulating active packaging paper. Food Chem [Internet]. 2021;345:128757. Available from: <https://doi.org/10.1016/j.foodchem.2020.128757>