PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–12
https://doi.org/10.14719/pst.5423

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REVIEW ARTICLE

Edible film: A future thrust in packaging technology for horticultural crops

Ffadhilah A[1], Chitra R[1]*, Ganga M[1], Prasanthrajan M[2]& Djanaguiraman M[3]

[1]Department of Floriculture and Landscape Architecture, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[2]Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[3]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641003, India

*Email: rchitra@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 18 August 2024
Accepted: 19 October 2024
Available online
Version 1.0 : 11 December 2024

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

CITE THIS ARTICLE
Ffadhilah A, Chitra R, Ganga M, Prasanthrajan M, Djanaguiraman M. Edible film: A future thrust in packaging technology for horticultural crops. Plant Science Today.2024;11(sp4):01-12. https:/doi.org/10.14719/pst.5423

Abstract

The significance of edible film in food packaging is increasingly recognized, especially in preserving perishable items such as fruits and vegetables. Packaging serves crucial functions, including containment, protection and facilitation of product transportation. However, conventional plastic packaging poses significant environmental challenges due to its non-biodegradable nature, contributing to pollution and heightened carbon footprints. In contrast, edible films, derived from natural ingredients like proteins, lipids and polysaccharides, offer a sustainable alternative. These films extend the shelf life of food products and improve food quality by reducing waste and minimizing environmental impact. Adopting edible films in the horticultural sector could significantly enhance post-harvest preservation, ensuring the freshness and quality of produce. As the food industry evolves, the development and application of edible film packaging present a promising avenue for future research, emphasizing sustainability and efficiency in food preservation.

Keywords

edible film; edible packaging; horticulture; post-harvest challenges; shelf life

Introduction

Exterior covering containing the product and packing materials, such as cardboard, plastic, or wood cartons or trays, is called packaging. The packages' functions include enclosing, safeguarding, moving, and delivering the product and inspiring, motivating, & idealizing its components. The primary goals of packaging, like perishable items, include confinement, security, ease of use and efficiency of use, interaction and commercialization (1) . Food packaging systems are integral to the global food industry and pivotal in its operations and success (2). Horticultural crops face significant preservation challenges due to their high perishability, rapid moisture loss, susceptibility to microbial spoilage, sensitivity to physical damage and enzymatic changes that accelerate deterioration during storage and transportation. Fruits and vegetables are crucial to a healthy diet, offering a wealth of vitamins, minerals, antioxidants and dietary fibres. Despite their nutritional value, a significant challenge in preserving these perishable items arises from their elevated moisture content, ranging from 75% to 95%. This high moisture content contributes to these products' swift deterioration and decay, adversely impacting their appearance. The limited shelf life poses a significant obstacle in maintaining the freshness and quality of fruits and vegetables (3). Hence, meticulous handling and packaging play a crucial role in preserving the freshness and quality of fruits and vegetables. Adequate packaging is indispensable for extending the shelf life of these perishable items. As a packaging material, edible films benefit horticultural crops by serving as biodegradable barriers that reduce moisture loss, slow respiration and protect against microbial contamination (4).

Synthetic polymers are the predominant materials for food packaging owing to their cost-effectiveness, malleability and lightweight properties than their glass or metal counterparts. Nonetheless, petroleum-derived plastics present a significant sustainability challenge, contributing to heightened carbon footprints and environmental degradation. Non-biodegradable packaging compounds exacerbate environmental strain, as they engender waste-induced pollution, necessitating urgent attention to foster sustainable alternatives in the packaging domain (5). Compared to conventional packaging techniques, edible packaging offers improved food quality optimization and is a sustainable and biodegradable choice for active food packaging. Its benefits include preserving food quality, extending shelf life, reducing waste and increasing the packaging materials' economic viability. Thus, a suitable solution is required to address the issue of plastic waste, primarily due to food packaging. The cutting-edge packaging materials on the market should be utilized as the industrial world continues to expand. The edible film material was selected as one of the ways to address the current issue of plastic waste. The edible film comprises a thin layer suitable for human consumption, owing to its formulation derived from a variety of natural ingredients like proteins, lipids, polysaccharides, or their combination (6).

In conclusion, exploring the scope of edible film packaging offers a promising avenue for future studies, facilitating a comprehensive understanding of its applications, properties and potential impacts on food preservation and sustainability. For future studies in horticultural crops, investigating the efficacy of edible film packaging holds immense potential to enhance post-harvest preservation, extend shelf life and minimize post-harvest losses in the horticultural industry. This study reviews the preparation, properties, application and future scope of edible film in the packaging sector for horticultural crops.

Edible Films – An Ecofriendly Approach to Packaging

Edible packaging refers to packaging that is safe and suitable for human consumption. It comes in two forms: edible coatings, which are thin layers directly applied to the food surface and edible films, which are thin sheets or films wrapped around the food later. Made from ingredients suitable for human consumption, edible packaging forms a cohesive network and presents minimal waste disposal issues (7). Films containing diverse components, including bioactive compounds, possess the capacity to improve the organoleptic properties of Packaged foods. An edible film can serve as a selective barrier to oxygen, carbon dioxide and moisture, retaining flavour and enhancing structural and mechanical qualities. Different anti-microbial agents could be incorporated into the film formulation to inhibit, reduce, or hinder the growth of microorganisms. Such films can be used to wrap small food slices individually, especially items like pears, beans, almonds and strawberries that aren't packaged individually for practical reasons. Moreover, edible films can be integrated into multi-layer food packaging materials alongside non-edible films (8).

Polymers and preparation methods of edible film

Research on the potential substitution of biologically based, biodegradable materials for synthetic and petroleum-based packaging continues. For many reasons, using bioengineered polymer resources in food packaging is an appealing solution, but there are significant challenges in food technology associated with this as well (9). Based on the sources from which they come, bio-based and biodegradable products can be divided into three groups. They are products made from pure biomass or natural sources, such as lipids, proteins and polysaccharides (10), products generated by microbes, typically categorized under particular polysaccharide types and products made from bio-based monomers (11, 12). Biopolymers used in edible film formation are classified as polysaccharides, proteins and lipids (Fig. 1).

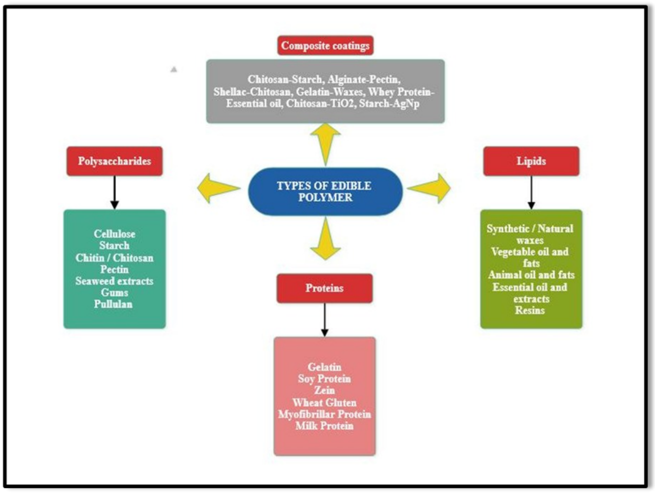

Fig. 1. Types of edible polymers.

Potential Edible Polymers for Film Preparation

Starch

Edible or biodegradable films based on starch primarily originate from tapioca, potatoes, cereal grains, or arrowroot starch, alongside their constituent, Amylopectin and amylose. The production of these films commonly employs two main methods: solution casting followed by drying, known as the wet method and thermoplastic processing, referred to as the dry method (13). Films originating from starch with elevated amylose content demonstrate heightened flexibility, improved oxygen impermeability, increased resistance to oil, enhanced heat-sailing capability and excellent water solubility. Furthermore, films made from potato starch or High -amylose corn starch exhibit enhanced stability throughout maturing compared to other starch formulations (14).

Chitosan

Chitosan, primarily sourced from crustacean shells, is the second most prevalent natural polymer after cellulose and is acknowledged for its non-toxic nature. Chitosan films present numerous benefits, such as the capacity to form films without supplementary additives. They exhibit advantageous oxygen and carbon dioxide permeability alongside notable mechanical strength and barrier characteristics (15). Additionally, chitosan demonstrates potent antimicrobial effects against bacteria, yeasts and moulds (16).

Cellulose derivatives

Cellulose ranks as the most prevalent biopolymer found in nature (17). Among the cellulose ethers that hold substantial commercial importance on a large scale include methyl cellulose (MC), carboxymethyl cellulose (CMC), hydroxypropyl methylcellulose (HPMC), hydroxypropyl cellulose (HPC), hydroxy ethyl cellulose (HEC), ethyl hydroxyethyl cellulose (EHEC) (18).

Proteins

Proteins utilized in film formation may derive from wildlife, comprising Gelatin, casein, concentrate and isolate, Whey protein, egg albumin, collagen and from plant sources like wheat, corn, soybean, rice, cotton seed and peanut (19). Proteins and carbohydrate film densely packed matrix and well–organized hydrogen-bonded network structure makes them excellent oxygen barriers. (20).

Lipids

A diverse range of hydrophobic compounds has been employed in formulating edible film coatings (EFC). These compounds include animal and vegetable oils and fats, such as peanut, palm, coconut, lard, butter, cocoa, fatty acid, mono -, di- and triglycerides. Additionally, waxes like carnauba, candelilla, jojoba, beeswax and paraffin, along with natural resins such as guarana, chicle and olibanum, as well as essential oils and extracts like citrus fruits, camphor and mint essential oils, and emulsifiers and surface-active agents such as lecithin, fatty alcohols and fatty acids have been utilized (21). While lipid-based films demonstrate favourable water vapour resistance characteristics, they may display condensed mechanical resilience and heightened oxygen penetration. Combining these ingredients may result in physical and chemical interactions, potentially leading to films with enhanced properties (22).

Preparation of Edible film

The film-forming material can be used to create edible films. Film materials must be dissolved and distributed in a solvent during the manufacturing process, such as alcohol, water, or a combination of alcohol and water, or a blend of alternate diluents. It is feasible to add plasticizers, antimicrobials, flavourings and colourants. Free-standing films can be created by casting and drying the film-forming solution at a suitable temperature and relative humidity. (23).

Solvent casting

Solvent casting is a widely employed technique in creating edible hydrocolloid films. In this method, solutions or dispersions of edible materials, often containing water or water-ethanol blends, are evenly spread onto an appropriate base and subsequently dried out. While the films are drying, the vaporization of solvents leads to a decrease in the polymers' solubilization, resulting in the alignment of polymer chains and the formation of films. The choice of substrate is crucial to ensure the resulting film can be easily peeled off without injury once the diluents have dissipated. Typically, the films undergo air drying in an air-circulated oven over some period. It is desirable to achieve an optimal moisture content in the dried film. The structural characteristics of the film are influenced by various factors, including drying parameters (thermal level and moisture content), Wet cast thickness and the composition of the Casting solution (24). Fig. 2. represents the steps in preparing edible film using solvent casting.

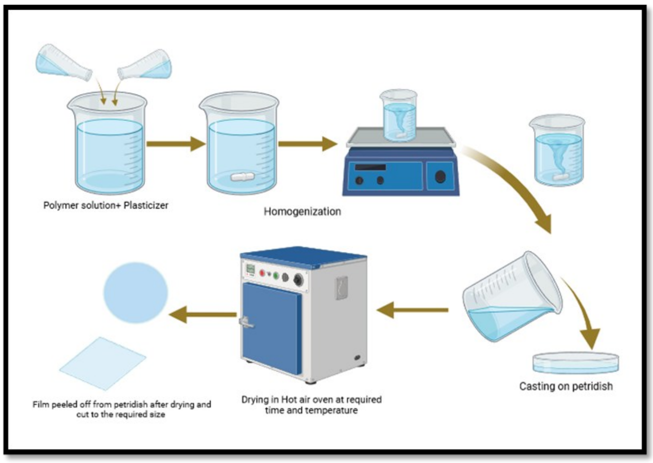

Fig. 2. Preparation of edible film.

Extrusion process

Feeding, kneading, and heating are the three stages of the extrusion process, a commercial way of making edible films. Utilizing this technique, extruded films' physicochemical qualities and structural attributes can both be enhanced (25). The film components are mixed in the feeding zone and air compressed to reduce the moistness of the constituents; this process is also referred to as a "dry process" because it works greatest with minimal water or solvents. The mixture's strain, temperature, and density rise as the ingredients pass through the kneading zone. These materials are then heated above the glass conversion temperature to facilitate conversion into a melt form, which is squeezed out through a suitably shaped nozzle by the rotating force of an extrusion screw. Following this, the resultant materials undergo a chilling process to shape into the film. (26). Mechanical and thermal energy are crucial for producing extruder-based films. The screw speed plays a significant role in determining the specific mechanical energy involved. Additionally, various factors such as heating chamber temperature, feed moisture level, nozzle size, pressure and power input are essential considerations to ensure the effectiveness of the moulding process and the quality of the last products. These factors collectively contribute to the extrusion processs' ability to shape and form the desired film characteristics (27).

Compression molding

Compression moulding, among the earliest techniques, is renowned for its sustainability owing to its low energy consumption and swift formation. In compression moulding, film-forming materials undergo heating within a mould under substantial pressure until they solidify. The duration of processing is a pivotal factor in shaping the properties of the films produced. Typically, compression moulding is integrated using the extrusion technique to make a film-forming materials before their primary thermoforming process (28).

Injection molding

Though injection moulding is mainly employed to create plastic products, it can also produce edible films in large quantities. This process has three steps: filling, packing and cooling. It has three characteristics: pre-injection pressure temperature, Molding temperatures and injection pressure (29). This technique can be combined with the extrusion process to generate a film. There are few studies on the injection moulding technique (28).

Properties of Edible Film

Functional properties

The primary purpose of edible film and coatings is to act as a barrier between food and the environment, preventing moisture, air, flavour, scent and oil. Furthermore, the edible film preserves food integrity by providing an appropriate degree of mechanical protection. It is feasible to improve the protective properties of edible films by including nutrients, tastes, antioxidants and antimicrobials (30). Barrier properties are pivotal in assessing edible films' effectiveness in shielding foods from environmental factors and neighbouring ingredients. Oxygen and Water vapour permeability are commonly evaluated to ascertain the films' capability to inhibit moisture and oxygen transmission.

Furthermore, the mechanical protection edible films provide is typically evaluated by determining various tensile properties. These properties include Youngs' Modulus (YM), which quantifies the films' stiffness about the pulling force applied per unit area during stretching. Tensile strength specifies the maximum force per cross-section area required to fracture a film. Additionally, elongation at break denotes an extent to which the film can expand before rupturing and is stated as a percentage (%) (31). The mechanical properties of some of the selected biopolymeric films are displayed in Table 1.

Water Vapour Permeability

The origin and process parameters of biopolymer films are responsible for their generally higher water vapour permeability values when compared to synthetic films. Most hydrocolloid films are classified as hydrophilic materials and in recent years, scientists have become very interested in improving those materials' water resistance. Furthermore, the width of the film influences other physical properties of the film, including its water resistance (32). Water transport within Edible films derived from products comprising starch presents a multifaceted phenomenon, primarily because of the intricate interaction between sorbed water molecules and the polymeric structure of starch. The Water sorption isotherm observed on high- amylose Starch-based films typically exhibits highly non-linear behaviour within the considered temperature range of 5-45 °C.

Consequently, the permeability of these films to water vapour is significantly influenced by various parameters, including temperature, film thickness and the content of plasticizers. Specifically, it has been observed that the WVP of high amylose corn starch (HACS) films fabricated in laboratory settings tends to increase with rising temperatures within 5 to 40 °C (33). The water vapour permeability for some of the selected biopolymers is described in Table 2.

Table 1. Mechanical properties of selected biopolymer

S. No	Polymers used	Tensile Strength (TS) as (MPa)	Youngs' Modulus (YM) as (MPa)	Elongation at Break (EB) as (%)	Reference
1.	Gum and protein extract from Cajanus Cajan seed	0.002–0.046	0.014–0.044	0.74–4.60	(68)
2.	Banana peel– flour	0.14–0.70	3.0–33.1	9.84–19.6	(69)
3.	Grass pea–flour	0.70	26.2	32.2	(70)
4.	Soy protein extract	1.93	1.19	3.95	(71)
5.	Fruit and vegetable mixture residue– flour	1.20–2.90	0.03–0.16	20–51	(72)
6.	Eggplant flour & corn starch	2.36–4.29	42.7–65.5	19.7–37.3	(73)
7.	Eggplant – flour	5.33	92.24	65.09	(73)
8.	Whey protein extract	5.34	–	10.08	(74)
9.	Chia– flour	0.77–6.26	25.6–681.4	1.05–5.16	(75)
10.	Starch lentil flour powder	2.10–6.30	0.86–4.8	42–149	(76)

Table 2. Water vapour permeability (WVP) of selected biopolymer

Polymer	T(°C)	ΔRH (%)	WVP	References
Chia flour	25	0–75	1.58–3.90	(75)
Whey protein isolate	25	0–100	17.3	(74)
Starch–lentil powder	25	0–70	16.1–18.7	(76)
The mixture of fruit and vegetable residue –powder	25	0–100	16.5–20.0	(77)
Banana flour	25	0–100	21.0	(78)
Chitosan	25	30–100	34.5	(79)
Lenthil flour	25	0–50	24.5–35.2	(80)
Wheat starch	25	58–100	130	(81)
Chickpea flour	20	0–100	3480–8870	(82)
Achira flour	25	0–100	53.0	(83)
Cassava starch	–	0–75	2.51–3.83	(84)

Abbreviations: T-temperature; ΔRH-relative humidity differentials

Role of Additives Enhancing the Properties of Edible Film

Essential oil

Essential oils from natural origins have been incorporated into films as antimicrobial agents (34). In direct food applications, considerable quantities of essential oils are typically required to provide an effective antimicrobial activity, which may affect the products' inappropriate flavours and odours (35). The antimicrobial effectiveness of edible films is determined by whether or not essential oils migrate onto the food surface or remain embedded in the film when incorporated. Essential oil migration is influenced by ionic osmosis processes, electrostatic interaction among the antimicrobial as well as polymer chains, potential structural alterations brought on by the essential oil and the environmental factors to which the edible Essential oils obtained from natural origins have been incorporated into films as antimicrobial agents (34). In direct food applications, considerable quantities of essential oils are typically required to provide an effective antimicrobial activity, which may affect the products' inappropriate flavours and odours (35). The antimicrobial effectiveness of edible films is determined by whether or not essential oils migrate onto the food surface or remain embedded in the film when incorporated. The migration of essential oils is affected by ionic osmosis mechanisms, electrostatic interactions between the antimicrobial agents and polymer chains, potential changes in structure induced by the essential oils and environmental conditions impacting the edible films (36). Essential oil diffusion on edible films is influenced by the polymer, plasticizer, elaboration process, surface food characteristics such as pH and water activity, hydrophilic film properties, temperature and storage time (37, 38). Diverse chemical characteristics of essential oils interact differently with plasticizer, polymer and film structure, which may prevent essential oil migration (36, 39).

Emulsifiers

Emulsifiers exhibit amphiphilic properties, encompassing both Polar and non-polar components, thereby enabling these to act as surface dynamic agents of modulating interfacial energies within immiscible systems, such as lipid water interfaces or air-water surfaces. Their incidence proves indispensable in forming and stabilizing finely dispersed lipid particles within composite emulsion films. Additionally, emulsifiers are pivotal in achieving optimal surface wettability, facilitating thorough surface coverage and strong adhesion to coated surfaces. Among the noteworthy emulsifiers, natural lecithins stand out as significant contributors. At the same time, sodium lauryl sulfate, glycerol monopalmitate, acetylated monoglyceride, glycerol monostearate, polysorbate 60, polysorbate 65, polysorbate 80, sodium stearoyl lactylate, sorbitan monostearate and sorbitan monooleate represent some prevalent options employed in various formulations (40).

Antimicrobials

Various natural and artificial antimicrobial agents have been devised and incorporated into diverse Edible packaging materials as viable alternatives to mitigate bacterial proliferation. Among the antimicrobial substances frequently employed in films, notable examples include nisin, enzymes, chitosan, oils, ethylenediaminetetraacetic acid (EDTA), bacteriocins, plant extracts, preservatives, metal nanoparticles, as well as various plant extracts and their corresponding EOs'. Chitosan demonstrates notable antibacterial efficacy against yeast, mould and Gram-positive and Gram–harmful bacterial strains (10). A film incorporating chitosan and thymol nanoparticles has been utilized in food models such as blueberries, tomatoes and cherries. This composite film was tested against various target microorganisms, including *Listeria innocua*, *Salmonellatyphimurium and Staphylococcus aureus*. The results indicated a notably heightened antimicrobial effect attributed to the chitosan-thymol nanoparticles compared to thymol alone (41).

Antioxidants

Chemical compounds called antioxidants slow down or limit oxidation reactions when added to edible packaging materials. Tocopherols, propyl gallate, tertiary butylhydroquinone, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), tartaric acid, polyphenols, ascorbic acid, citric acid, ascorbyl palmitate and carotenoids are a few examples of antioxidants (42). The antioxidant characteristics of Blackberry powder were incorporated into an arrowroot starch-based edible film. The antioxidative attributes of blackberry and similar plant extracts stem from their polyphenol and anthocyanin content, which remain preserved upon integration into the edible film (43).

Addition of plasticizer in physical properties of an edible film

Compared to plastic films like LDPE, edible films typically exhibit higher gas resistance but lower resistance to water vapour. They are often characterized by high brittleness, leading to limited flexibility. The hydrophilic nature of most edible polymers renders them susceptible to water vapour, resulting in water absorption and changes in dimension. To address this, plasticizers have been incorporated into the film-forming solution to enhance flexibility. These molecules disrupt polymer-polymer interactions and establish polymer–plasticizer interactions, imparting softness and flexibility to the edible film. Sugar, food-grade polyols, lipids and glycols are common plasticizers. Notably, this addition of plasticizer significantly enhances the flexibility of edible films without substantially altering their colour, as plasticizers are typically clear and odourless (44).

Nanotechnology in Edible Film Packaging

Nanotechnology is an evolving discipline that concentrates on the development, control, examination and production of materials at the nano-level, usually within the range of 1 to 100 nanometers. Nanotechnology has many applications in various fields of science and technology. Utilizing nanotechnology in food packaging demonstrates significant potential in enhancing packaging materials' primary properties while introducing novel functionalities like active (e.g., antimicrobial) and intelligent (controlled release) features. Hence, nanotechnology offers a promising solution to several challenges associated with conventional packaging, such as inadequate gas barriers and controlled release of bioactive compounds. Nanoparticles can alter packaging polymers' physical and mechanical attributes, enhancing their strength, durability, flexibility, barrier properties and recyclability (45). Nanoparticles and nanomaterials with unique chemical and physical properties compared to larger particles are employed in nano packaging (46).

In addition to improving the mechanical, physical and barrier qualities of edible films and coatings, nanoparticles can act as active component encapsulation systems. Active agents are delivered using edible foods, including nanoparticles. Generally speaking, this has resulted in the creating of a range of edible materials reinforced with nanoparticles, or "nanocomposites" (47). Alumina, iron oxide, copper, copper oxides, gallium, palladium, silver, gold, iron, zinc oxide, silicon dioxide, titanium dioxide and titanium nitride are among the most commonly utilized nanoparticles (48). Titanium dioxide (TiO_2) nanoparticles combined with chitosan offer exceptional advantages for wastewater treatment by synergistically addressing multiple contaminants. TiO_2 effectively degrades organic pollutants through photocatalysis, while chitosan excels in adsorbing heavy metals. The integration of these materials through chemical grafting enhances their efficiency. Chitosan-based films with Ag/TiO_2 nanoparticles demonstrate antibacterial, anticancer and improved mechanical properties. Silver compounds, widely used for antimicrobial purposes, remain effective against pathogens despite potential side effects like skin discolouration from silver nitrate solutions (49). The literature studies include reports of nanoparticles made from food-grade biopolymers, including proteins, polysaccharides, or naturally occurring bioactive substances like lipids and curcumin. Some nanoparticles utilized in edible packaging are nanocellulose, chitosan, starch nanocrystals, nanostarch and nanoclay (50). Preparing chitosan films embedded with silver nanoparticles (AgNPs) for packaging follows a two-step process. Initially, AgNPs are synthesized using chitosan as a stabilizing and reducing agent, with NaOH as a facilitator and microwave irradiation aiding the reaction. The films are then formed through a casting method. Characterization through UV-Vis spectrophotometry identifies an absorption band at 400-413 nm, while TEM analysis reveals particle sizes below 6 nm.

Incorporating AgNPs enhances the swelling capacity, tensile strength and elasticity of the films, conferring antibacterial properties against ESBL and MRSA strains. FTIR analysis highlights interactions between the NH_2 groups of chitosan and the nanoparticles (51). Incorporating TiO_2 into active films enables ethylene scavenging, a critical function for prolonging the post-harvest shelf life of fruits. Additionally, the minimal transfer of TiO_2 from the composite material to food ensures its suitability and safety for applications in food packaging (52). Literature reports the development of biodegradable chitosan-alginate bio-noocomposite films with TiO_2 nanoparticles, fabricated through solvent casting and $CaCl_2$ crosslinking, for food packaging. These films demonstrated enhanced mechanical strength, UV barrier properties and antimicrobial activity against foodborne pathogens, achieving complete biodegradability within three months. Their improved functional and antibacterial properties make them suitable for extending the shelf life of fresh produce (53).

Applications of Edible Film Packaging in the Horticulture Sector

Edible film packaging and its effect on post-harvest quality of Fruits and Vegetables

Edible films and coatings have been found to extend the shelf life and improve the quality of intact fruits and vegetables relative to their cut form. However, given several circumstances during both the pre-and post-harvest phases, significant quality degradation and post-harvest losses are most likely unavoidable (54). The primary factors contributing to these losses are inherent physiological ageing processes and fungal pathogen infestations. Following harvest, around 30% of fruits and vegetables become unsuitable for consumption due to spoilage (55). The leading causes of deterioration in minimally processed fruits and vegetables are a mix of physiological ageing, metabolic changes and microbiological rotting. Browning, softening and water loss in minimally processed fruits and vegetables also degrade their quality (56). Edible films have recently become an efficient choice for the environment and consumers. Their superior moisture, water vapour, carbon dioxide and oxygen barriers influence the physiological deviations in fruits and vegetables. These films shield fruits and vegetables from microbial infestations, oxidative browning, discolouration and off-flavour (57).

Research in Edible Film Packaging in Fresh Fruits and Vegetables

Fruit and vegetable-based films can be formed from a single macromolecule, blends, or even composites or multi-component materials (consisting of macromolecules, fillers, and functional additives). To meet the desired performance, they can be made as single- or multi-layer materials (3). Fresh fruit and vegetable films and coatings need to have low water vapour permeability (WVP) to lower desiccation rates and low oxygen permeability (O_2P) to delay respiration without developing anaerobic conditions that would encourage the formation of off–flavours and ethanol (37). Fig. 3 illustrates the methods of edible film packaging used in fruits and vegetables.

In their research, they developed and utilized alginate-chitosan bilayer edible film (A-Ch BE) to improve the quality and extend the shelf life of figs (*F. carica* var. Mission) (58). The A-Ch BE film demonstrated favourable mechanical properties, such as elasticity and elongation, and exhibited appropriate

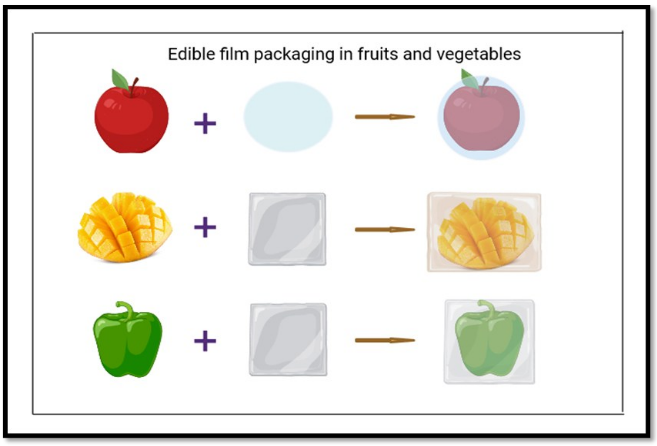

Fig. 3. Schematic representation of edible film packaging done in fruits and vegetables.

water vapour permeability (WVP) and carbon dioxide permeability (PCO_2) values. Throughout the storage duration, regardless of the figs' maturity stage, the A-Ch BE film notably enhanced ethylene emission from the figs. Furthermore, applying the A-Ch BE film aided in preserving the colour and firmness of the figs during storage at 6 °C. Intriguingly, the firmness of the figs not only remained intact but also increased upon film application. Additionally, the superior moisture barrier properties of the developed film contributed to reducing the transpiration rate of the fruits during storage, leading to a significant decrease in fruit weight loss. Consequently, the utilization of the A-Ch BE film emerges as a promising and effective strategy for prolonging the shelf life of fresh figs under conditions of low temperature (6 °C) and high relative humidity (95%).

In a study on pomegranate arils coated with a mixture of chitosan and ascorbic acid and stored at 5±1 ^{0}C, the coating material was found to help protect the material colour, delay bacterial and fungal development until day 21 and produce flavour, aroma, and colour parameters that were at an acceptable level on the 25th day. However, no significant differences were observed in sugar, anthocyanin and organic acid compounds compared to the control (58).

Applying leftover olive oil and chitosan films to apples and strawberries can reduce their microbiological qualities and improve their ability to keep off pathogenic strains and spoiling. This makes it a viable option for a naturally edible coating for apples and strawberries. Applying 10% sodium alginate edible film to Welsh onions (*Allium fistulosu*m L.) was found to have good impacts on the edible films' attributes, including pH, titrable acidity and weight loss (59).

THE edible composite films infused with thyme essential oil (TEO) nanoemulsion at varying concentrations (5%, 10%, 15% and 20%) using tamarind starch (TS) and whey protein concentrate (WPC) at specific ratios for the packaging of tomatoes (61). Their investigation revealed that utilizing nanocomposite edible films containing Thyme essential oil nanoemulsion (20%) notably prolonged the ripening process of tomatoes by reducing their respiration rate. This retardation in ripening was attributed to the presence of thymol and carvacrol in the TEO nanoemulsion, which serve as antioxidants and antimicrobial agents.

In their study, the physical properties of zein–alginate–glycerol edible films and their role in preserving chilli peppers (*Capsicum annum* L.) (62). Their research revealed that utilizing a film formulation comprising 2% zein, 1.5% sodium alginate, and 4% glycerol effectively upheld the quality of the chili peppers throughout a 15-day storage period at 20°C. Application of these edible films resulted in an extension of the shelf life by an additional 3 days for weight loss and 10 days for firmness retention. Some other examples of edible film packaging done in fresh fruits and vegetables are presented in Table 3.

Table 3. Effect of edible films/coatings on the quality of fresh fruits and vegetables

Polysaccharide/Components	Coated Fruit/Vegetable	Coating treatment	Chemical Stability	Physical Stability	References
Alginate/beta-cyclodextrin/ trans cinnamaldehyde/ pectin/calcium lactate	Watermelon (*Citrullus lanatus* (Thunb.) Mansf.)	Layer-by-Layer (LBL) dipping		Shelf-life extent; retention of Firm skin, pH & colour; decrease in loss of weight	(85)
Chitosan	Banana (Musa spp.)	Dipping	Retention of soluble solids	Delay in ripening and retention of peel thickness and colour	(86)
Chitosan/carboxymethyl cellulose/ moringa leaf isolate	Avocado (*Persea americana* Mill.)	Dipping	Increase in manno heptulose and decrease in polyphenol oxidase and lipid peroxidation	Retention of firmness and Moist conditions and decrease in weight loss, respiration rate and electrical conductivity	(87)
Gum arabic	Tomato (*Solanum lycopersicum* L.)	Dipping	Retention of titratable acidity, soluble solid concentration and total antioxidant capacity; retention of ascorbic acid, lycopene, total phenolics and total carotenoid content	Delay in ripening; decrease in weight loss, respiration rate and ethylene production; retention of firmness and colour	(88)
Whey protein (film)	Apple	–	Lowest enzymatic activity, increase in pH, soluble solids, decrease in water activity		(89)
Candelilla wax (film)	Tomato	–	Lower weight loss, less loss of firmness, titratable acidity decreased		(90)

Edible film packaging of minimally processed fruits and vegetables

A study explored the incorporation of bacterial nanocellulose (BC) into thermoplastic potato starch film (TPS) to improve the preservation of fresh-cut mango quality. Various mango segments wrapped with TPS-BC and TPS were compared with unwrapped ones over 5 and 10 days at 10°C. After 5 days, TPS-BC displayed superior tensile strength compared to TPS, attributed to the formation of strong hydrogen bonds between BC and TPS. Mango pieces encased in TPS–BC demonstrated reduced weight and firmness loss during the initial 5-day period, whereas using TPS alone did not affect these parameters. Moreover, the ageing and dehydration of the cut fruits were alleviated by enveloping the mango with TPS–BC films (60). Corn starch films containing thyme essential oil effectively maintained the firmness of mangoes over a 10–day storage period (64).

It was shown that applying an edible coating made of whey protein/pectin film and transglutaminase on fresh-cut apples, potatoes and carrots reduced the growth of microorganisms. Conversely, the carotenoid and phenolic contents of carrots were preserved. Furthermore, there was no change in the chewiness or hardness (61).

Edible film packaging for antimicrobial activity in fresh fruits and vegetables

A study investigated the inhibitory properties of chitosan/ methyl cellulose (MC) films, with and without vanillin, against *Escherichia coli* and *Saccharomyces cerevisiae* on freshly cut cantaloupe and pineapple. They found that both types of films effectively restrained the growth of *E. coli* and *S. cerevisiae* on fresh–cut cantaloupe. The film incorporating vanillin exhibited greater effectiveness than the chitosan/MC films without vanillin. However, it took a longer time for the vanillin–incorporated film to demonstrate its inhibitory effects compared to the films without vanillin (62). The antimicrobial efficacy of film-forming solutions containing sodium caseinate, chitosan, or carboxymethyl cellulose, each infused with 1% of various oleoresins (olive, rosemary, onion, capsicum, garlic, or oregano), against *Listeria monocytogenes* through *in vitro* methods (30). They discovered that these solutions displayed restricted antimicrobial activity against *L. monocytogenes*. The incorporation of basil sweet extract (SBE) as a natural antimicrobial and antioxidant substance into pullulan–based films to prolong the shelf life of apples during refrigeration (67). Their findings indicated that Pullulan coatings containing 24 mg/cm^2 of SBE were successful in extending the shelf life of Jonagored apples.

Bionanocomposite Films in Packaging of Fruits and Vegetables

In a study investigated on the effects of pure SPI coating and SPI/cinnamaldehyde/ZnONP coating on the physicochemical and microbial stability of bananas, demonstrating the widespread acceptance of nanocomposite films for their effectiveness in preserving post-harvest quality. The outcomes of their research revealed a significant reduction in both weight loss and the ripening rate of bananas when employing nanocomposite films. Additionally, the SPI/CIN/ZnO NP nanocomposite coating demonstrated effectiveness in averting detrimental alterations in various sensory aspects of bananas, including firmness, total soluble sugar (TSS) levels and titratable acidity, throughout the storage duration. During a 12-day storage period at 5 °C, the minimally processed papaya parts were coated with edible films made from separate protein using oregano-clay MMT (68). The coated papaya showed reduced microbial growth, mass loss, lightness and pH, as well as a negligible drop in firmness, indicating excellent results in the coating of minimally processed papaya. A cellulose and Ag NP nanocomposite film can lower the microbial content of minimally processed melon and kiwifruit during a10-day storage period at 4 °C (9). The produced films effectively managed the microbe population, resulting in a 99.9% reduction in the overall number of microorganisms, yeasts and molds in the little processed kiwi fruit and melon.

Ag-MMT NPs were added to a calcium-alginate coating to extend the shelf life of fresh-cut carrots. The bacteria counts in carrots with functional coating remained low. The new active packaging may therefore be able to extend the shelf life of fresh-cut carrots for above two months, according to the results (63).

Regulations for Edible Film

Materials used in edible packaging must be classified as Generally Recognized as Safe (GRAS) for their intended application or approved under the United States Food and Drug Administration (USFDA) Code of Federal Regulations or the United States Pharmacopeia/National Formulary (USP/ NF). These materials and additives must adhere to Good Manufacturing Practices (GMP), ensuring they are of food-grade quality and handled as food ingredients. Additionally, their use must comply with the FDA's restrictions (64). Edible films and coatings must comply with region-specific food safety regulations, as variations across countries, like differences between USFDA and Canadian standards, often hinder market growth. Ingredients such as methyl and ethyl esters are permitted under USFDA guidelines but may face restrictions elsewhere. These regulatory inconsistencies act as significant barriers to global market expansion (65). Nanomaterials which are incorporated in edible films are considered hazardous without clear safety evidence, as per IFST guidelines, while EU and Swiss regulations emphasize risk assessment, labeling and size-based definitions. The USFDA advises toxicological profiling for nanomaterial use, though most countries lack specific nanotechnology regulations, necessitating further research (28).

Limitation and Challenges of Edible Film Packaging

Edible packaging offers a sustainable alternative by being consumable alongside food, leaving no waste and degrading more readily than synthetic plastics. Produced from food–grade materials, edible films provide advantages such as excellent sensory qualities, effective barriers and microbiological stability. However, they face challenges, including insufficient mechanical strength, suboptimal water vapor barrier properties and limited scalability for large-scale production. High production costs, potential incompatibility with certain food matrices and inconsistent antimicrobial and antioxidant functionality further hinder their widespread adoption. Additionally, regulatory compliance and consumer acceptance remain critical barriers that must be addressed for commercial success (7) .

Future Thrust

Plastics are the most widely used packaging materials, comprising 42% of the market, followed by paperboard (31%), metals (15%), glass (7%) and other materials (5%). Their dominance is attributed to their cost-effectiveness, lightweight properties and convenience. Plastics play a significant role in food packaging, but post-consumption, most are discarded with minimal recycling. This contributes to environmental pollution, as unrecycled plastics either persist in landfills or are incinerated, releasing harmful gases .

Biopolymers, sourced from renewable plant–based materials and certain animal-derived substances, present an eco–friendly solution to the environmental challenges posed by traditional plastics. Their inherent ability to decompose naturally through microbial activity sets them apart from conventional polymers, which possess intricate molecular structures that hinder biological degradation. Edible films, made from biopolymers like proteins, polysaccharides and lipids, further enhance sustainability by reducing reliance on petroleum-based packaging. By offering biodegradable alternatives, they help minimize waste accumulation in landfills and water bodies, thereby reducing pollution. Additionally, edible films contribute to a lower carbon footprint by utilizing renewable resources, reducing greenhouse gas emissions during production and disposal and promoting a circular economy approach (66).

Research on edible film packaging has primarily focused on fruits and vegetables, with limited studies on flowers, ornamentals, plantation crops and spices. However, edible films hold significant potential in these areas. For example, a study on lemon leaf extract-loaded bio-nanocomposite films demonstrated their effectiveness in preserving jasmine flowers maintaining freshness and natural fragrance over five days (67). This indicates the promising scope of edible films for extending the shelf life and quality of flowers during packaging, transport and storage, making them a valuable innovation in the horticultural sector.

Conclusion

In conclusion, this review explores edible packaging, presenting a promising solution for improving food quality optimization while addressing sustainability concerns in active food packaging. By utilizing thin films made from ingredients suitable for human consumption, edible packaging offers numerous benefits, including preserving food quality, extending shelf life, reducing waste and increasing economic viability. These films can also incorporate bioactive compounds and essential oils in the form of additives to enhance organoleptic properties and serve as selective barriers to oxygen, carbon dioxide and moisture, while application of nanotechnology for packaging further enhances their properties and functionalities. Notably, edible films and layers have demonstrated effectiveness in outspreading the shelf life and quality of the fruits and vegetables. In contrast to traditional plastic packaging, which often ends up in landfills or incinerated, edible packaging can be consumed along with food or beverages, eliminating waste disposal issues altogether. Therefore, edible packaging emerges as a promising and sustainable alternative to conventional plastic packaging, offering a tangible solution to the challenges of preserving food quality and reducing environmental impact.

Authors' contributions

FA collected literature and wrote the manuscript. CR helped edit, summarize and revise the final manuscript. GM reviewed the manuscript and helped in approval. PM helped in revising the manuscript. DM helped edit, summarize and revise the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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