



REVIEW ARTICLE

Edible coating technologies for fruits and vegetables: Current advances, emerging innovations and future perspectives

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Abstract

In recent years, edible coatings and films have emerged as sustainable postharvest technologies to preserve the quality and freshness of fruits and vegetables and extend their shelf life, thereby reducing the use of conventional plastic packaging. These coatings are thin layers made from consumable materials that form a semi-permeable barrier on the surface of the food to prevent evaporation, transpiration, entrainment of volatiles, microbial contamination and oxidation. Recent developments include the use of certain functional bioactive products, such as plant extracts, antimicrobial agents and antioxidants, that aim to increase the efficiency of the preservative system and improve the safety of the food product. The characteristics of mechanical strength, barrier and controlled release functions are further enhanced through innovative approaches like nanostructured, multi-layered and composite coatings, which improve food safety and quality. Recent innovations have enabled the production of smart coating materials made of polysaccharides, proteins, lipids and composite biopolymer systems embedded with natural antimicrobial and antioxidant agents, essential oils (EOs) and nanomaterials. Active edible coatings assist in preserving colour, structure, nutritional content, sensory attributes and physicochemical quality during the storage period. Additionally, innovative technologies have been developed, such as nano-coatings, smart and bioactive films, which hold promise for enhancing postharvest management with enhanced functionality, sustainability and market potential and decreasing food losses. Overall, there is great potential for edible coatings as a future sustainable strategy towards food preservation and improving food security at global scales.

Keywords: antimicrobial; antioxidants; edible coatings; nanotechnology; smart and bioactive coatings

Introduction

Edible coatings and films are postharvest methods that have been examined for the commercialisation of fruits and vegetables. Notably, these coatings or films can be consumed directly along with the food product without the removal of the coating/film (1). Edible films and coatings serve as a protective outer layer to extend the shelf life of foods during postharvest, transport and storage, thereby preventing water loss, spoilage and deterioration and retaining the quality (colour, freshness, taste and nutrients) of food (2). Functional characteristics are enhanced by the incorporation of antioxidants, antibacterial substances and minerals as well as vitamins. In addition, edible coatings and films have a non-toxic effect on the food quality of fruits and vegetables.

Currently, the world population stands at 7.3 billion and is growing at the rate of 0.7 % annually and is projected to be 9 billion by 2050, which requires action to tackle critical problems including

food insecurity, global hunger and the prevention of malnutrition (3). Consequently, food demand is projected to double and food production needs to scale accordingly: 100–110 % larger than today by 2050 (4). This growth needs to be sustainable, which means taking into account the environmental, social and economic aspects of food production and distribution.

Fruits and vegetables play a key role in the food system and public health and a vital component of the nutrition of the population. Key challenges include climate change adaptation, production sustainability, postharvest quality and storage efficiency. The UN Food and Agriculture Organisation (UN FAO) data for 2018 on the production of fruits worldwide was approximately 870 million metric tons (MMT) and losses across the fruit and vegetable stages of the food chain were estimated at 25–50 % (5). This substantial loss highlights the urgent need for effective strategies to be put in place for food security and sustainability.

From the consumer and environmental point of view, edible coatings/films have been an efficient solution in recent years. As they have good oxygen (O_2), carbon dioxide (CO_2), moisture and water vapour barrier characteristics, they affect the physiological changes in fruits and vegetables. The other benefits of these coatings/films for fruits and vegetables include the prevention of oxidative browning, discolouration, off-flavour and microbiological infestation. The fruit industry throughout the world is facing more and more demands to ensure not only quality assurance and safety for the consumers, but also environmental considerations for postharvest supply chains. Physiologically active and highly perishable fresh fruits are susceptible to handling and transportation loss during the process. Another big problem is the scalability of such an application for the use of edible coatings. Although many edible coatings are effective in the laboratory, scaling up to industrial operations is challenging because of difficulties in uniform coating, drying and adhesion under fluctuating humidity and temperature. Furthermore, there is still insufficient clarity regarding the regulatory environment and the uniform approval processes for edible coating formulations, especially for coatings incorporating bioactive components, which further prevent commercialisation in global markets. Also, low consumer acceptance is a barrier, particularly when coatings change surface appearance, mechanical and barrier properties. As a result, the focus is placed on areas of expertise that are key to coating performance and cross paths with fruit and vegetable physiological processes, storage conditions and integration in the supply chain.

Conventional edible coatings have been mainly made of natural biopolymers like polysaccharides, proteins and lipids, as a means of preventing moisture loss and managing gas exchange while in storage. However, recent developments have greatly broadened the scope of the functions of edible coatings by adding bioactive compounds, essential oils (EOs), plant extracts, probiotics, nanomaterials and controlled-release systems. Additionally, nano-enabled multilayer, active, bioactive and smart edible coatings embedded in food products have enhanced antimicrobial activity, antioxidant capacity, mechanical strength, barrier properties and real-time monitoring of food quality. These innovations provide more effective and sustainable solutions for postharvest preservation than conventional coating technologies.

Previous review articles have focused on specific coating materials, preservation mechanisms or on a specific application; only several articles have presented information related to edible coating technologies. This review gives a comprehensive and updated account of the conventional and new edible coating technologies that are available, especially the latest developments in active, bioactive, nano-enabled, smart and biodegradable coating technologies. Moreover, they are critically analysed in terms of their functional mechanism, application, challenges in commercialisation, regulatory aspects, consumer acceptance, research gaps and future prospects. The review summarises recent advances and provides a comprehensive view of edible coatings used on fruits and vegetables for sustainable postharvest preservation.

Edible coatings

The earliest records indicate that the application of coatings on fruits and vegetables began in China during the 12th century, when citrus fruits such as lemons and oranges were being covered with wax to reduce substantial postharvest losses and preserve fruit quality (6). However, commercial scale application did not occur until 1922, when waxes were introduced to enhance the postharvest

preservation of fruits and vegetables by applying waxes on a commercial scale (7).

The edible coating technology is an effective method for maintaining quality and shelf life of fresh fruits and vegetables during storage (8). These coatings applied in edible form to the surface of the fruit by deposition are referred to as edible coatings. As these films become part of the food and are consumed as such (for fruits where the peel is consumed), the materials used in their composition must be Generally Recognised as Safe (GRAS), i.e., they must be safe and non-hazardous for food applications (9).

Edible films or coatings are protective thin layers (less than 0.3 mm) composed of chemical or biological materials. These coatings cover food products directly, forming a protective shield that inhibits or controls the transpiration of moisture and gases into the atmosphere, reduces microbial activity and slows down the respiration rate of food tissues. Edible coatings are developed based on a range of biopolymers including polysaccharides, proteins and lipid compounds or through a combination of materials that have been developed, resulting in an improvement in properties (10). The application of edible films and coatings to food increases both the quality and safety of food by reinforcing the natural protective barrier and by reducing the transfer of water, gases and soluble substances (11). Edible coatings are environmental friendly, since the materials used are generally biocompatible, biodegradable, non-toxic and are approved by the GRAS and Qualified Presumption of Safety (QPS) lists. Moreover, the properties of the edible films and coatings must possess excellent mechanical and barrier properties as well as physical, microbiological and chemical stability. They should also be inexpensive and not adversely affect the sensory and functional properties of the coated food product (12). Edible coatings provide a semi-permeable barrier to the transport of O_2 , CO_2 , ethylene and water vapour between the fruit surface and the external environment. The permeability of the gases is dependent on the chemical structure, molecular arrangement and hydrophilic or hydrophobic nature of the coating polymer. The edible coatings control gas diffusion, which slows the respiration rate, regulates ethylene formation and action, slows down moisture loss and decreases microbial growth, which helps to increase the shelf life of fruits and vegetables.

Different matrices of edible coating application

The coating solution is applied using dipping, spraying and brushing methods as shown in Fig. 1 and the application of layer-by-layer and electrospraying methods are shown in Fig. 2.

Dipping

The most widely used method is edible coating using a dipping technique, where the food sample is immersed for a specific duration in the coating matrix solution, covering the surface evenly with the coating matrix. This technique can also be adapted to develop multilayer coatings via a step-by-step layer-by-layer deposition process in which the coating solution is applied using the dipping technique, known as the multilayer coating process (13).

Spraying

The second method is the spraying method, where a uniform thin film is sprayed onto the food surface, forming the coating matrix. This technology allows the material to be sprayed on the food surface to dry, reducing the drying time (14).

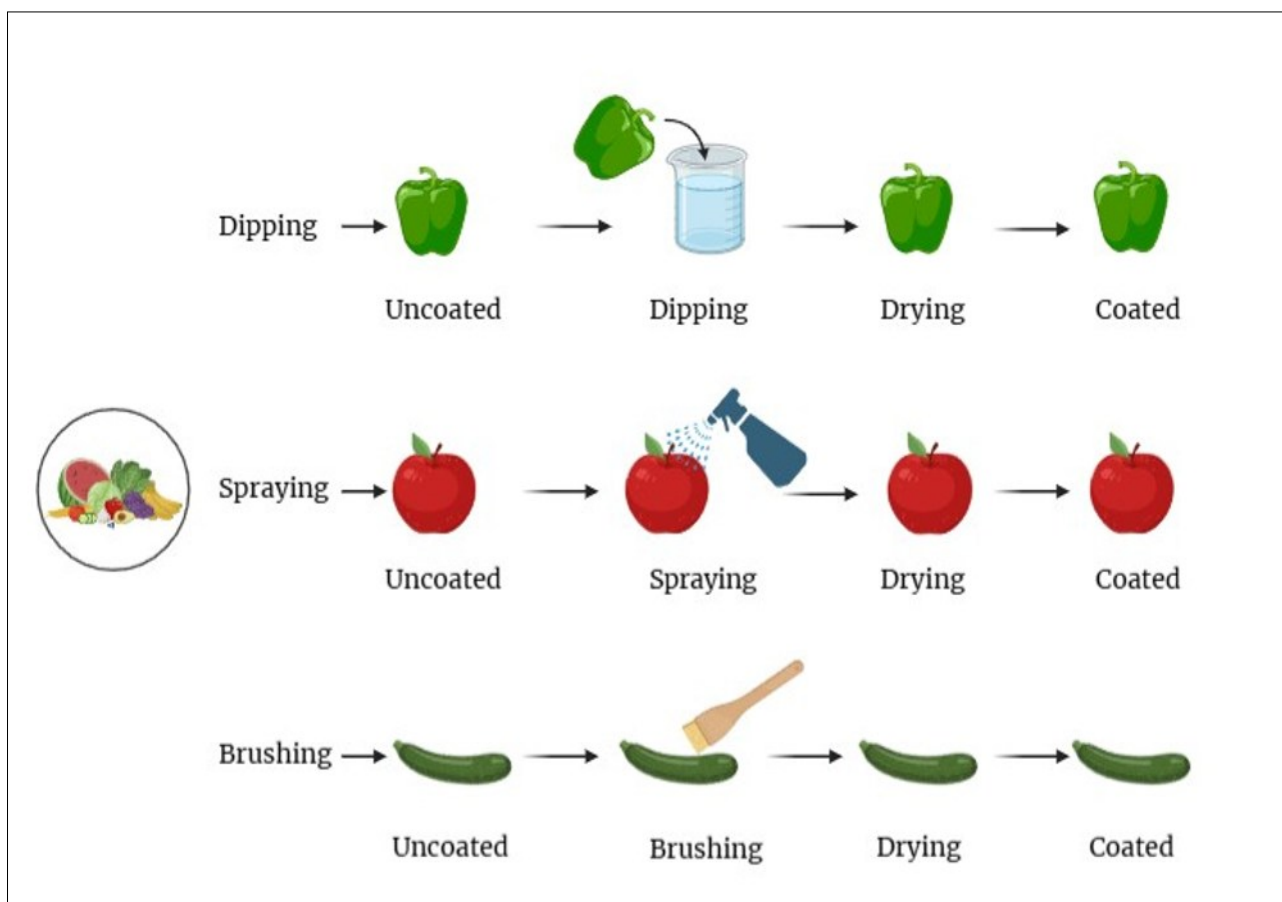


Fig. 1. Conventional edible coating application methods.

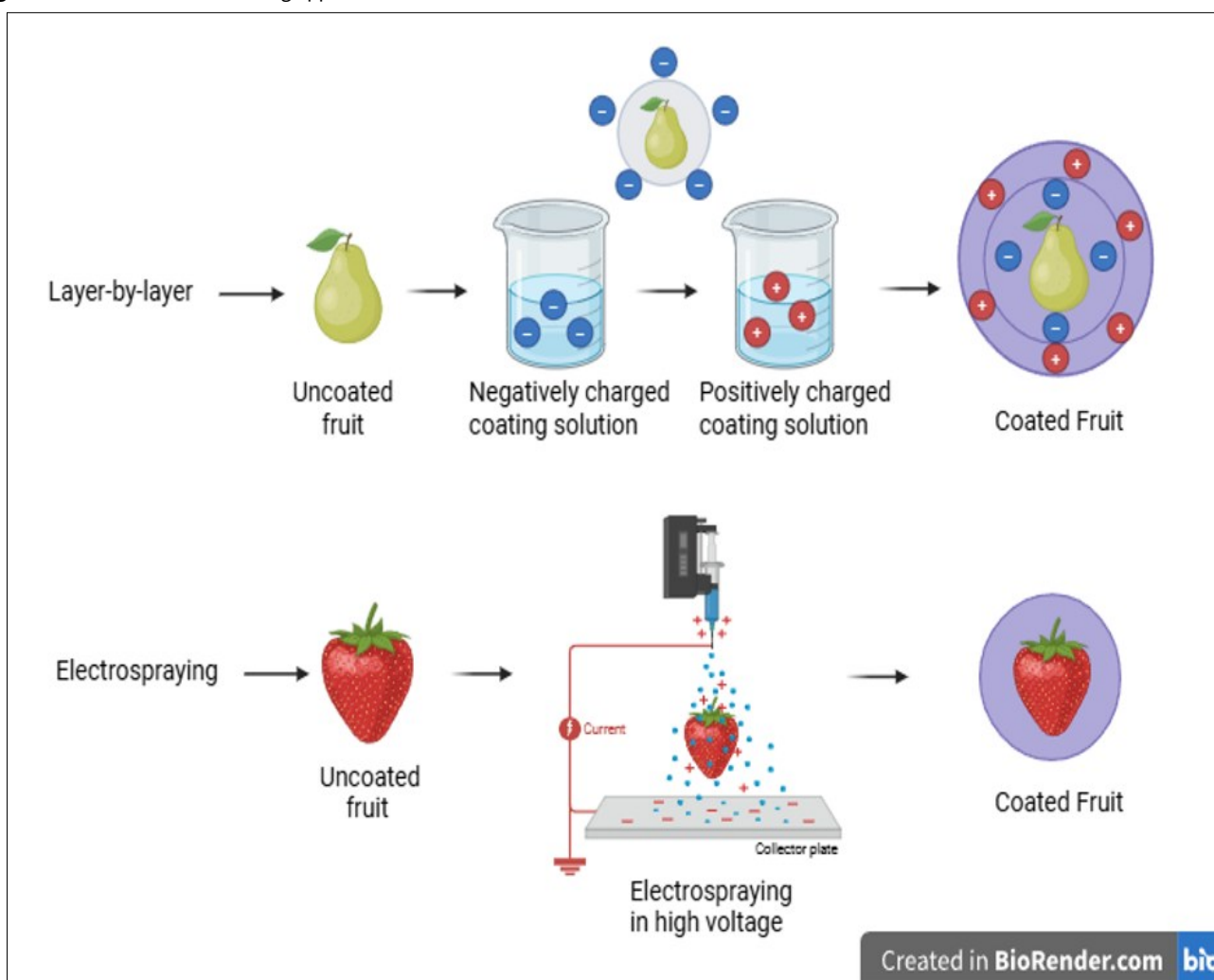


Fig. 2. Advanced edible coating application methods.

Brushing

The brushing technique utilises a sterile applicator or brush to uniformly distribute high-viscosity coating formulations across the fruit surface (15). Coating materials for the fabrication should be consumable along with the fabricated product; their constituents should be GRAS by the US Food and Drug Administration (USFDA) or other food regulatory agencies (16).

Key functional attributes of edible coatings and films

The effectiveness of edible coatings and films, particularly in relation to prolonging the shelf life of fruits and vegetables, relies on their functional properties (mechanical, barrier and bioactive properties). These properties directly influence postharvest fruit quality, offering innovative solutions for sustainable food preservation.

Barrier properties

Edible coatings and films help to control the internal atmosphere of fruits by providing certain selective barrier functions against O₂, CO₂, water vapour and ethylene. This helps lower the rates of respiration, slow down ripening and senescence, decrease the rate of moisture loss and ultimately increase the shelf life. For example, coatings composed of a mixture of gelatin (Gel) and carboxymethyl cellulose (CMC) were determined to be effective in decreasing water vapour permeability in some foods like berries to prevent dehydration (17). Chitosan coatings have been reported to have a semi-permeable property and their application in maintaining the internal gas composition of bananas and avocados has been reported as a promising technique for increasing storage life by blocking the production of ethylene (18).

Mechanical properties

The effectiveness of edible coating and films in maintaining fruit stability during storage and handling is strongly influenced by their mechanical properties, such as strength, flexibility and extensibility. The properties of these are the function of the composition and structure of the polymer matrix and can be customised to suit the application requirements. For instance, composite films containing both polysaccharides and proteins have been shown to have higher tensile strength and flexibility, which is ideal for fruits such as berries (19). These films can be made even more flexible and extensible by adding plasticizers such as glycerol, which will allow them to adhere to the surface of the fruit.

Bioactive properties

The functional efficiency of edible coatings and films can be enhanced through the incorporation of natural antioxidants, nutrients and antimicrobial compounds. These bioactive components exert germicidal effects, mitigate oxidative stress and provide nutrients, which positively affect the safety aspects, nutritive value and organoleptic characteristics of the fruit. The application of *Aloe vera* edible film fortified with grapefruit seed extract on grapes has been reported to be able to control fungi while maintaining fruit quality under cold storage conditions (20). For instance, green tea extract enhanced the mechanical properties, reduced the water vapour transmission and increased the polyphenolic compounds and antioxidant capacity in chitosan films (21).

Extension of fruit shelf life

Numerous studies report successful innovations where the shelf life of various fruits has been significantly prolonged by means of edible films and coatings. Among these, the most studied preservation methods found in the Scopus database focus on the application of

edible coatings or films to strawberries (22). Further, scientific research on fresh-cut fruits has been more widespread than research on whole fruits and a variety of tropical/temperate fruits have been coated with edible films/coatings. Alginate films loaded with zinc oxide nanoparticles (ZnO-NPs) delayed fruit ripening, decreased postharvest decay and consequently extended the storage life of tomatoes up to 16 days (23). This is the same for beeswax-based edible coatings, which prolong plum fruit preservation based on texture and colour, making the fruit more marketable and decreasing food waste (24). In general, the efficacy of edible coatings and films in the preservation of fruits is strongly dependent on their functionality, including barrier properties, mechanical resistance and bioactivity. The use of these edible materials combined with their bioactive properties holds potential for innovations that improve food quality, enhance food sustainability and minimise losses during the postharvest phase. The successful cases shared in the literature illustrate the value of these innovations in solving global food security and food preservation issues.

Functional mechanism

The mode of action behind the coating of fruits and vegetables resembles that of modified atmosphere packaging, which acts as a protective barrier to minimise the transport of gases between the inside of the fruit and the surrounding atmosphere, increasing the concentration of CO₂ and reducing O₂. This environment can favourably reduce the respiration rate, the consumption of stored energy and the development of microorganisms and thereby prolong the shelf life of the fruit effectively (25). The thickness of the coating formed on the fruit surface has a negative relationship with the coating permeability (26). Another critical detail is involved with a low-permeability coating based on resins like shellac, which can almost entirely block gas exchange, leading to the accumulation of CO₂ in the fruit and the production of compounds resulting from the fermentation process that can cause off-flavours, such as acetaldehyde and ethanol, thus affecting fruit quality (27).

In addition to improving quality and maintaining fruit and vegetable post-production, coating substances could be active with food colorants, flavourings, antioxidants, antimicrobials and beneficial microorganisms, etc. Over the last few years, natural bioactive agents have been added to edible coating formulations like EOs, plant extracts, vitamins, antagonistic microorganisms and firming agents in sliced fruit. Nanoemulsions consist of emulsifiers/surfactants that stabilise oil droplets (20–200 nm) dispersed in an aqueous phase with the aim of blocking the aggregation of the oil droplets. These bioactive compounds and texture modifiers are incorporated into the nanoemulsion formulation, which is applied to the fruit surface through dip coating. The water is evaporated during the drying process, resulting in an even distribution of the nano-sized droplets in a continuous biopolymer matrix which sticks to the fruit surface. This forms a semi-permeable protecting layer that slows down moisture evaporation, O₂ and CO₂ exchange and provides the controlled release of antimicrobials and antioxidants. Therefore, the coating slows down ripening, reduces the growth rate of microorganisms, maintains the quality characteristics and extends the shelf life of fruits and vegetables.

Nanoemulsions, nanocomposites and nanoparticles contribute to the improvement of the functional properties of edible coatings, but it is important to consider the safety and regulatory

issues before any commercial application. The size, concentration, coating material and storage conditions of a particle can determine whether it will leach from its coating into the food. Hence, safety assessment tests are essential to investigate their prolonged impacts on human health and the environment. Also, regulatory approval and consumer acceptance are important hurdles for the commercialisation of nano-enabled edible coatings. To boost public confidence and commercial use of nanotechnology, standardised procedures for testing safety, clear rules for regulatory oversight and transparent information about the benefits and safety of nanomaterials must be developed. Fig. 3 illustrates the mechanism of nanoemulsion formation and coating deposition on fruit surfaces.

Classification of edible coatings

Edible coatings are formulated using different materials that can have desirable characteristics. Three broad groups of materials that can be taken to categorise the basic materials to be included in edible coating materials are polysaccharides (chitosan, starch, alginate, gums, cellulose, pectin, etc.), lipid compounds (fatty acids, waxes and oils) and proteins (whey protein, egg albumin, gelatin, zein, wheat gluten, soy protein, casein, etc). Table 1 illustrates the performance of edible coatings/films for fruits and vegetables. The other coating is referred to as a composite coating and the coating is formed by the combination of more than one material. Another strategy explored in the context of edible coatings is the addition of functional additives with the aim of increasing properties: antioxidants, antimicrobial agents, minerals and vitamins were added to the polymer matrix (31).

Edible coatings and films are classified by means of their composition. The coatings and films used for edible applications are classified into three main categories, namely hydrocolloids, lipids and composites, including polysaccharide-, protein- and lipid-based formulations for food preservation and quality improvement, as elucidated in Fig. 4.

Hydrocolloids

Hydrocolloids are formed via the dispersion of colloids that are composed of long-chain polymers. Hydrocolloids can be fully or partially dispersed and swell up in contact with water. Dispersion of hydrocolloids leads to altered physicochemical properties either by forming a stable gel or through associated properties such as viscosity, thickness, emulsification and stability (32). Hydrophilic

groups in biomacromolecules are involved in hydrogen bond interactions that are significant towards the formation of a stable hydrocolloid system. Polysaccharides are commonly used for the preparation of hydrocolloids because the basis of these interactions is the occurrence of hydroxyl functional groups in their molecular structure. But not all polysaccharides are utilised for hydrocolloid production due to water insolubility. In fact, due to their low molecular weight, sugars are considered a poor source of hydrocolloids (33). The hydrophilic behaviour and polydispersity of protein colloids allow proteins to be categorised as hydrocolloids. Stable hydrocolloids are formed from protein sources such as milk, eggs, gelatin and protein extracts obtained from vegetables (34).

Some of the cellulose derivatives which have been used for testing as food-grade hydrocolloids are hydroxypropyl methylcellulose (HPMC), nanofibrillated cellulose (NFC), hydroxyethyl cellulose (HEC), CMC and methylcellulose (MC). Low methyl ether pectin has been prepared from fruits and vegetables by esterification of the naturally occurring pectin. The high methyl ether pectin was commercialised as a thickening and gelling agent (35).

Edible coating technologies for fruits and vegetables make up lots with a range of high/low molecular weight hydrocolloids. They may have thixotropic properties. In aqueous media, polysaccharides, as a result of solvent-polymer hydrogen bonds, form micelles in the gums. The formation of stable gum-based polymer-water systems are influenced by the level of hydrogen bonding and intermolecular interactions with water molecules (36).

The hydrocolloids system of polysaccharides, hydrogels and gums results in extremely high-viscosity, shear-thinning colloidal dispersion, which is good for coating and film formation applications. Hydrocolloids offer benefits in terms of process convenience and flexibility when continuous and batch processing are involved. But formulation parameters like concentration, drying conditions and solidification mode (in case of evaporation) play a vital role in the production of high-quality edible films and coatings. These coatings and films obtained from polysaccharide molecules can re-shape during drying; drying of polysaccharide-based coatings and films leads to molecular reorganisation and the formation of distinctive semi-crystalline structures. The degree of semi-crystallinity is responsible for important functional properties like stability, solubility, durability, visco-elasticity, mechanical, optical

Table 1. Edible coating performance for fruits and vegetables

Coating material	Examples	Barrier properties	Mechanical strength	Oxygen permeability	Cost	Industrial applicability	References
Polysaccharides	Chitosan, gums, starch, alginate, pectin, cellulose	Moderate water vapour and excellent oxygen barrier	Moderate	Regulates respiration; low oxygen permeability	Low	Good film-forming ability used for fresh fruits and vegetables	(28)
Proteins	Egg albumin, gelatin, soy and whey protein, zein, wheat gluten, casein	Poor moisture and excellent oxygen barrier	High	Very low	Moderate	Suitable for high value produce	(28)
Lipids	Carnauba wax, beeswax, vegetable oils, fatty acids	Excellent moisture and limited gas barrier	Low-moderate	Moderate	Low-moderate	Commercially used for citrus, mango, cucumbers, apples etc.	(29)
Composite coatings	Pectin-lipid, chitosan-alginate, polysaccharide-protein, starch-protein	Excellent gas and moisture barrier	High	Low oxygen permeability with balanced exchange of gases	Moderate	Suitable for commercial applications because of multifunctional properties	(30)

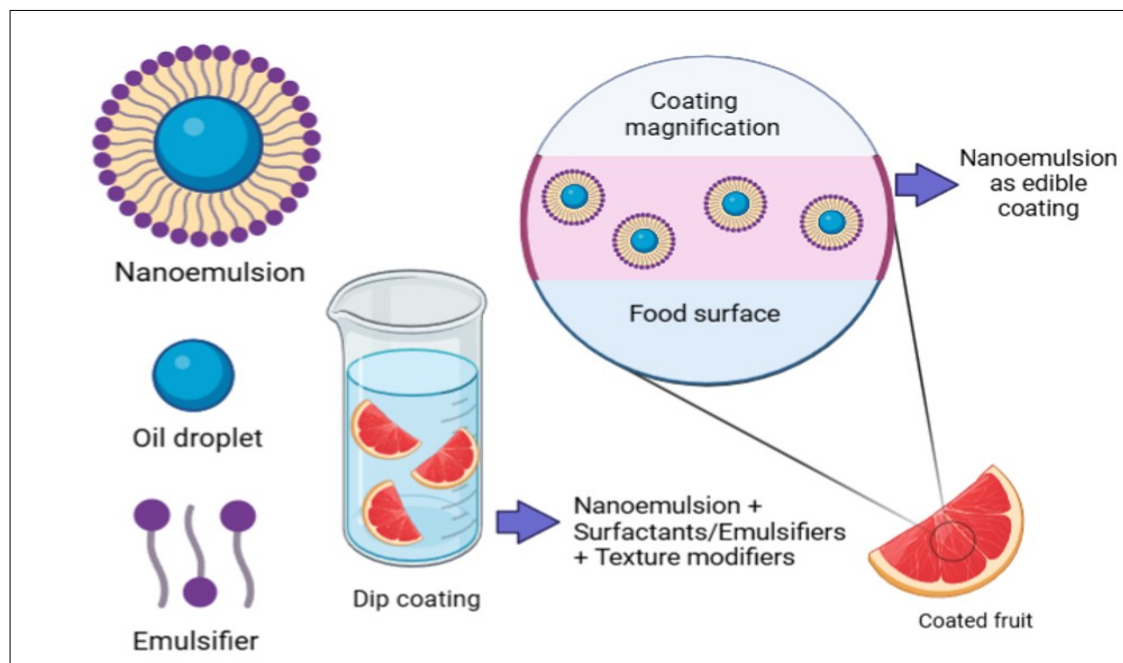


Fig. 3. Mechanism of nanoemulsion formation and coating deposition on fruit surfaces.

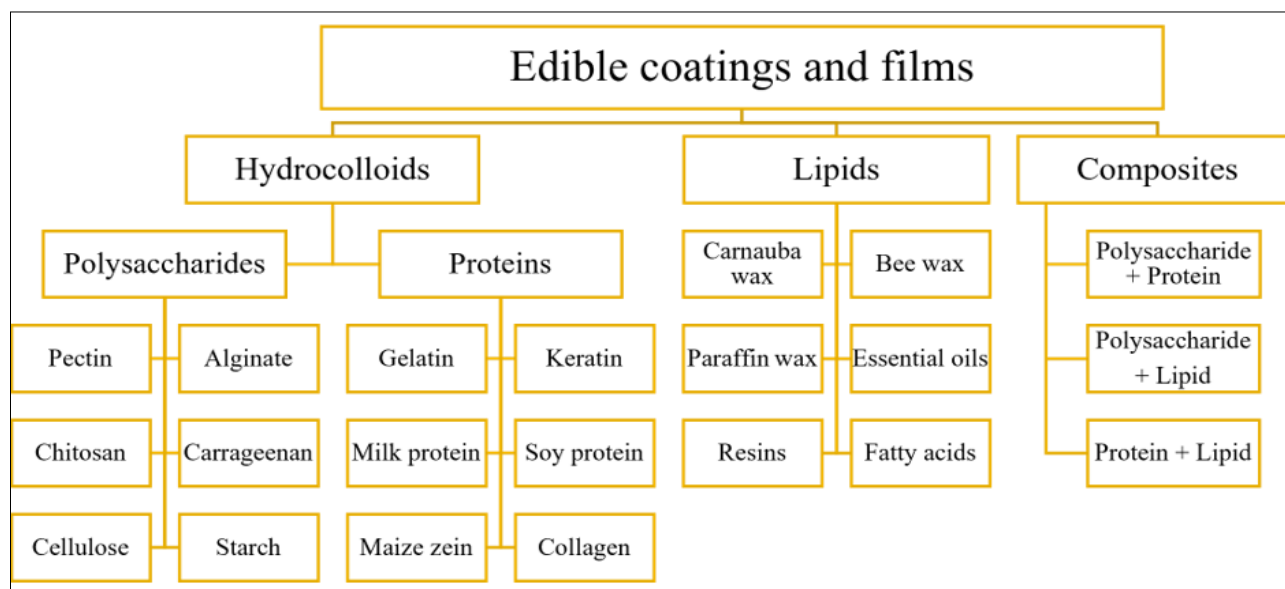


Fig. 4. Classification of edible coatings and films.

and barrier properties (37).

Polysaccharide edible coatings

The upcoming trends of polysaccharide-based edible coating are to be concentrated on the preparation of bioactive, nano-structured and multilayered composites of high functionality materials with different combinations. This will result in new multifunctional edible coatings that not only contribute to food quality but also show beneficial bioactivities towards human health (38). Materials derived from polysaccharides including alginate, chitosan and starch are commonly used owing to their biodegradable nature, compatibility, strong mechanical properties and effective O_2 barrier characteristics. Chitosan is a derivative of chitin, which is considered an antimicrobial compound; thus, it is preferred for enhancing the storage life of perishable food (39). One compound produced by brown seaweed and used to make films is alginate, which prevents fruits from gaining water and deteriorating in nutritional quality. On the other hand, the excellent moisture barrier properties of lipid-based coatings contrast with the inadequate water vapour barrier performance of polysaccharide-based films and coatings.

Polysaccharide edible coatings and films are well suited for fruits and vegetables because of their colorless appearance and superior barrier characteristics. Indeed, the existence of moisture and lack of appropriate water barriers are primary challenges in quality retention of fruits and vegetables. Although, they are efficient in controlling the environment by changing the moderate permeability of polysaccharides to O_2 and CO_2 , which enables them to regulate respiration and maintain the internal atmosphere (40). The active components (vitamins, antioxidants, preservatives, antimicrobials, bactericides, etc.) were introduced into the polysaccharide matrices in recent research. Einfache Verpackungs-Konstruktion (EVK) design of enhanced postharvest preserving qualities, controlled release behaviour, bioactive properties, protection and barrier to water in polysaccharide solutions involves active edible films and coatings (41).

Even if polysaccharides are economical, as a budget-friendly preservation method used to make very short storage life products, which naturally have good peel protection, they will still be feasible

for fruit and vegetable applications.

Advantages: Low cost, excellent O₂ barrier and biodegradable.

Disadvantage: Poor moisture barrier.

Protein edible coatings

Protein-based coatings and films can be of either animal or plant origin. Proteins, solvents and plasticisers are the key components of protein-based edible coatings and films. Proteins used in the packaging applications of food products are mostly water-soluble globular proteins and water-insoluble fibrous proteins. The edible films prepared from these proteins in the human body can act as bioactive peptides to regulate hypertension and oxygen free radical levels (42). The quality and functionality of these edible coatings and films are associated with composition, components and processes. The structural properties include crystallinity, amino acid content, hydrophilicity/hydrophobicity, variation in molecular weight, plasticizer content, surface charge type, spatial shape and additives (43).

Proteins like casein, gelatin and isolate whey protein provide a strong film-forming capacity and are rich in protein. All these materials build up a porous layer covering the surface of the fruit, thereby promoting gas permeability and maintaining the freshness of the fruit while providing nutritional value (44).

Advantages: Good film-forming ability, high mechanical strength.

Disadvantage: Poor water resistance.

Lipid edible coatings

Lipids are important in creating edible coating materials to control moisture loss. In addition, they are hydrophobic films. In the case of fruits and vegetables, moisture control offers preservation and increases shelf life by preventing desiccation. Also, they can be used as carriers for the active component, preserving the texture and taste of fruits and vegetables. Lipids are blended with hydrocolloids such as polysaccharides, proteins, starch, cellulose and its derivatives in composites. Lipids and hydrocolloids can be blended and mixed via solvent homogenisation and blending. Other ways of preparing composites are film-forming and casting methods, along with forming bilayer and multilayer films. Absorption of water in a hydrocolloid-lipid composite is mostly due to the hydrocolloid matrix and the lipids regulate moisture. Lipids can be doped with various additives to impart functionality to coatings and films. Lipid functionalisation aids in the development of film-forming suspension matrices and colloidal emulsion helps in film and coating adherence to a food product. Furthermore, lipids serve as emulsifiers, antioxidants, antimicrobials, enzymes, flavour enhancers, processing and gelling agents. Oils like sunflower, high oleic linseed, rapeseed, palm and soybean were found to be investigated for the development of edible coatings and films due to their moisture barrier characteristics, availability, lesser effect on flavour attributes and cost effectiveness (45).

The hydrophobic property of lipid coatings like carnauba wax and beeswax is utilised and this coating creates a moisture barrier which greatly decreases the transpiration rate through the surface of the fruit. Usually, these are combined when producing composite films with appropriate mechanical stability and barrier characteristics with proteins or polysaccharides (46).

Advantages: Reduces weight loss and provides an excellent moisture barrier.

Disadvantages: Poor gas permeability; may cause anaerobic respiration.

Composite edible coatings

Composite films are characterised by a heterogeneous structure and a combination of biopolymers is used to get a different feature of each component. The hydrophobicity of several materials is combined in order to get better functional properties. The materials most often include lipids, carbohydrates, biopolymers and proteins (47). According to the number of biopolymeric components utilised, composite edible films and coatings are divided into binary and ternary types (48). Fats are usually utilised to limit moisture exchange; protein helps in maintaining the film's mechanical properties and carbohydrates alter the gas exchange. Natural and synthetic polymers are also used in combination to prepare composites.

The integration of various material classes has resulted in composite edible films and coatings. Composite materials utilise the unique characteristic properties of each constituent component and consequently provide improved barrier properties, mechanical and functional properties, including enhanced antimicrobial activity (49).

Advantages: Improved mechanical properties, balanced moisture and gas barrier, controlled release of bioactive compounds.

Disadvantages: More complex formulation and high production cost.

Active compounds and additives in edible coatings

Additives and active ingredients can greatly enhance the performance of coatings. Additives include many types of compounds, including emulsifiers, flavourings, plasticizers and anti-browning compounds. The coating was enriched with bioactive agents, which contribute to its antioxidant and antimicrobial properties. They use either natural or synthetic bioactive components such as nisin, plant extracts, natamycin, EOs, organic acids, sorbates and butylated hydroxyanisole (BHA). These agents help to enhance the properties of fruits and vegetables and consumer acceptability.

Plasticizers

Natural polymers are brittle because they have weak intermolecular forces and are very branched. These compounds decrease the rigidity of the polymer, viscosity, deformation tension, increase the flexibility, dielectric constant and the electrostatic charge. At the same time, they lower odour emission resistance (50). The adaptable character of the coating enables it to change in accordance with the modifications in fruit produce. Plasticizers are introduced to achieve better compatibility and functional properties of biopolymer systems in composite coating systems (51).

The commonly used plasticizers include acetylated monoglyceride, xylitol, sucrose, glycerol, mannitol and polyethylene glycol (10). Because of their hygroscopic properties, they help to clear the way for more water uptake, which decreases intermolecular interactions between polymer chains and prevents excessive softening, flakes, cracks and blisters (52). The effectiveness of a polymer network in being plasticized by its solvent is determined by the physicochemical properties of the polymer network, such as physical state, frequency of active functional groups, polarity, chemical structure, shape and the chain length. The changes in Zein films leading to increased film flexibility are possible through adding glycerin to the Zein film materials (53). Plasticizer is a chemical

additive that can be applied through edible coatings to make them soft, which is more malleable (53).

Emulsifiers and surfactants

Certainly, specified emulsifiers and surfactants can be used to improve the homogeneity and wettability of coatings. Since, poor adhesion and wettability are the factors responsible for the degradation of the coating, many substances have been used as surfactants to improve this property, including spans, fatty acid salts, lecithin, tweens and vegetable oils (28). The emulsifiers such as sodium lauryl sulfate, soy lecithin, sucrose fatty acid esters and polysorbates have a critical function in the preparation of protein–lipid and polysaccharide–lipid composite coatings, which give uniform water-based solutions. When used in edible solutions, the emulsifiers help to incorporate hydrophobic lipids into the solution and help to stabilise the emulsion and ensure uniformity of particle distribution. Some polymers have emulsifying properties, so it is not necessary to add emulsifiers (25).

Bioactive compounds

These compounds, which are sometimes referred to as “extra-nutritional components” (54), as they are present in trace amounts in the food and are obtained from plants, microorganisms, animals and sea organisms, can improve edible coatings for their positive properties in food quality conservation (55).

Organic acids

Organic acids (citric and ascorbic acid) have been used to improve the quality and storage of stone fruits. Citric acid is safe to use as a food additive in organic fruits and vegetables, not only as a bacteriological and fungicidal growth promoter but also a promoter of disease resistance in vegetables. By reducing postharvest fruit respiration, it prevents browning and fruit diseases and is effective. Furthermore, it is employed as an optional ingredient to increase the level of acidity and flavour in foods, which could help to boost the quality and inhibit spoilage (56).

Plant extracts

In recent years, food losses in fruits and vegetables have begun to raise an increasing interest in plant extracts to replace the use of synthetic chemical compounds for handling postharvest losses. Extraction of plants is an important source of bioactive compounds from different parts of plants. Edible coatings containing a combination of different plant-based extracts, which are rich in antimicrobial and antioxidant substances, in edible coatings will increase their effectiveness (57).

Essential oils

Essential oils (EOs) are a group of secondary metabolites that occur in nature and are selectively extracted by steam distillation or by cold pressing from various parts of a plant such as the leaves, flowers, fruits, seeds, bark and roots. Owing to their antimicrobial, antifungal, antiviral, antioxidant and bioactive properties, they are widely used as natural active ingredients in edible coatings. Many EOs are recognised as GRAS by the U S Food and Drug Administration (FDA) for food applications (58). Essential oils can be added to edible coating matrices, which improves the functional properties of the coating by decreasing microbial growth, slowing oxidation and improving the quality and shelf life of fruits and vegetables.

Bioactive components like phenolics, aldehydes, alcohols and terpenes are key contributors to the antimicrobial activity of EOs. They are hydrophobic and can penetrate into the membranes

of microorganisms, thereby causing cell death by disrupting the integrity of membranes and making them permeable to leakage of the intracellular components. Gram-negative bacteria tend to be more resistant than Gram-positive bacteria as their outer layer is composed of lipopolysaccharide, an added barrier against hydrophobic compounds (59). However, excessive concentrations of Eos may adversely affect the flavour and aroma of coated produce. Thus, the use of encapsulation methods through nano emulsions is necessary to obtain effective antimicrobial activity without compromising their desirable sensory qualities. Table 2 outlines the different constituents of fruits and vegetables used for preservation using edible coatings.

Emerging innovations in edible coatings/films

Based on the literature, emerging trends indicate that fruits and vegetables have a promising direction for the incorporation of nanotechnology, which can provide new possibilities for increasing the bioactive functionalities, physical barrier and mechanical integrity of edible films and coatings (81). Smart and active packaging systems can detect and record the quality of the fruit and communicate with the surroundings, marking a modern era of advanced smart preserving technologies. Employment of natural and value-added recycled materials for edible coatings and film materialisation is in line with the international agenda for sustainability and waste reduction. These agro-industrial byproducts provide benefits for reducing waste and for the creation of value from discarded products in favour of a circular economy. The food packaging industry was anticipated to be worth USD 346.5 billion, whereas the bioplastics industry was forecasted to achieve USD 2.87 million by 2025, showing a 36 % increase from 2020 levels (82). Multifunctional coatings that combine antimicrobial, antioxidant and nutritional properties are a comprehensive strategy in food preservation. This can drive great changes in nutritional and public health as it can lead to more nutritious and safe fruits. The improvement of edible self-healing coatings using sodium alginate (SA) and L-menthol-beta-cyclodextrin-graft-chitosan can enhance the postharvest shelf life of fruits and vegetables. The improved materials exhibited good properties, indicating that coatings containing L-menthol exhibited increased thickness, smoothness, transparency, mechanical properties and self-healing performance (83). Natural antioxidants like ascorbic acid, plant extracts and tocopherols, as well as biopolymers like alginate and chitosan, nanomaterials like nanofibres, nanoemulsions and various composites are being added to enhance material performance. Integrating these innovations has improved barrier, antimicrobial and controlled-release properties, reducing the impact of oxidative stress and microbial deterioration (84).

Finally, edible coatings and film technologies combine with personalised nutrition and functional foods to create a window of opportunity for personalised health solutions. This is in parallel with the general growing consumer appetite for a diet that has a beneficial effect on their perceived state of health, establishing edible films and coatings as an effective method for providing consumers with desired targeted health benefits.

Nanotechnology

Nanotechnology has been recognised as an effective strategy to extend the storage life of foods in recent years. Using nano-scale particles offers different and enhanced properties compared with

Table 2. Various constituents of edible coatings in fruits and vegetables

Coating matrix	Active component	Fruits and vegetables	Method of application	Properties	Reference
Alginate + α -tocopherol acetate	-	Carrots	Dipping	Preservative tool for prolonging the life of the food product	(60)
Beeswax	-	Mandarin	Spreading	Maintains various fruit quality parameters and sensory attributes	(61)
Alginate/Oil nanoemulsion	Oil nanoemulsion	Sweet cherries	Cross-linked coating	Increased cracking tolerance by 53 % and enhancing firmness	(62)
Chitosan	-	Zucchini	Dipping	Extending post-harvest shelf life and enhancing the overall quality	(63)
Chitosan fortified with lemongrass essential oil	Lemongrass essential oil	Green bell pepper	Dipping	Maintained physicochemical quality during storage	(18)
Chitosan combined with Eugenol and <i>Aloe vera</i>	Eugenol + <i>Aloe vera</i>	Pineapple	Spraying	Maintained the quality of their fruit and extended their shelf life.	(64)
Carnauba wax	-	Papaya	Spreading	Fruit firmness was reduced by more than 3 times and acted as a gas barrier to reduce fruit respiration.	(65)
Cassava starch incorporated with cinnamon essential oil	Cinnamon essential oil	Guava	Dipping	Enhance the quality of guava and its shelf life in storage processes.	(66)
Whey protein-based nanofibrils	-	Apples	Dipping	Decrease in browning, phenolics and weight loss.	(67)
Alginate with pectin	Pectin	Blueberry	Dipping	Stronger firmness and better control of microorganisms in the blueberry.	(68)
Carboxymethyl cellulose (CMC)	-	Mandarin	Spreading	Improved a longer freeze storage time; less spoilage measured by firmness loss.	(61)
Ethylene scavenging coatings incorporated with zein-Artemisia Sphaerocephala krasch Gum (ASKG)	Ethylene scavenger	Banana	Electrospraying	Reduced browning, higher hardness and extended shelf life.	(69)
Carnauba wax	-	Sweet potatoes	Dipping	Maintain quality and storage life of sweet potato.	(70)
Alginate incorporated with chitosan	Chitosan	Pear	Layer-by-layer	Decreased respiration rate, ethylene production, firmness loss and peel colour changes.	(71)
Alginate/Chitosan	Chitosan	Mandarin fruits	Layer-by-layer	Maintained fruit bioactive contents and organic acids	(72)
Arabic gum	-	Persimmon fruits	Dipping	Higher amounts of phenolics, antioxidants, ascorbic acid and acidity.	(73)
Aloe vera gel	-	Grapes	Dipping and spraying	Improved storage stability and quality of table grapes.	(74)
Locust bean gum combined with Carboxy cellulose nanocrystals	Cellulose nanocrystals	Cherry tomatoes and strawberry	Dipping	Prolonged the shelf life of cherry tomatoes and strawberries.	(75)
Xanthan gum	-	Apple	3D food printing	Greater hardness, stiffness, gumminess and structural strength.	(76)
Carboxymethyl cellulose (CMC) incorporated with chitosan	Chitosan	Citrus fruit	Layer-by-layer	Improved the appearance of fruit and glossiness	(77)
Carnauba wax	-	Tomato	Dipping	Increased fruit glossy appearance and improved tomato quality	(78)
Guar gum-protein blend with mango puree/calcium chloride	Mango puree/CaCl ₂	Fresh-cut mango	Cross-linked coating	Less decay of fresh-cut mangoes and quality during cold storage.	(79)
Maltodextrin- whey protein solate (WPI) stabilised water-in-oil (w/o) emulsions	-	Strawberry	Electrospraying	Significantly reduced moisture loss during storage	(80)

bulkier particles. Nanotechnology has developed many implementations of edible coatings and films in the food industry owing to the enhancement of their properties (85).

Nanotechnology is a new and novel field which provides a potential new way to produce an emulsion-based coating with better properties and better functionality. The coatings may be produced by either macro- or microemulsion (traditional technology) or by nanoemulsions, which are essential conventional emulsions with significantly smaller (nano) emulsion droplet sizes. Nanoemulsions are formed when the particles are suspended at the nanometre level in an aqueous phase (less than 100 nm radius of the particle). This results in changes in the physical characteristics of the covering by further decreasing the movement of moisture, oxidative reactions, oxygenation and inhibition of mould occurrence, nutritive disorder prevention and forestalling of product damage (86). Moreover, nanoemulsion-based coatings have also been found to be promising delivery systems for several active compounds including, antimicrobials, flavours and nutraceuticals which can also be used in maintaining the quality attributes of food products (87). Schematic representation of the nano-coating architecture for fruits and vegetables is elucidated in Fig. 5.

Bionanocomposites

Bionanocomposites emerged as a new technology, which offers multiple benefits in the application of biomolecules in the coating process. It also helps in preserving food properties, including aroma and flavour, which enhance the barrier properties (88).

Bionanocomposites may be perceived as multiphase materials that are made of a biopolymeric matrix and nanofillers (less than 100 nm) that provide antimicrobial properties, barrier attributes and structural strength (89). Nanofillers include silicate, titanium dioxide, chitin, starch nanocrystals, graphene, carbon nanotubes, clay nanoplatelets as well as cellulose-based nanofibers. The gas barrier efficiency and thermal stability are also enhanced by the integration of these into the biopolymer matrix (90).

Nanosized metals incorporated into the matrix of biopolymers give stability to the biopolymer and the ability to control the antimicrobial effect. Indicatively, chitosan nanocomposite films that contain silver NPs have excellent antimicrobial activity (85).

Active packaging

The implementation of bioactive compounds within the edible coating/film framework to actively contribute to the food product is called active edible coating. Antioxidants and antimicrobials, among other compounds, are active agents that interact with the fruit itself, allowing it to maintain both shelf life and safety. The integration of plant extracts, essential oils and natural preservatives is typical, allowing the performance of two different functions: preservation and improvement of the sensory properties (91).

Smart packaging

Smart edible coatings and films can modify their characteristics when exposed to environmental variations or change with different stages of fruit ripeness. Such smart materials are able to regulate the ripening rate of bioactive compounds and permeability to them depending upon the requirements of the fruit at the production stage through to the final consumer, ensuring that major emphasis is given to effective preservation environment throughout the supply chain process (92).

Bioprinting

Three-dimensional bioprinting (3D bioprinting) is a new additive manufacturing technique that makes it possible to create personalised edible coatings and films for fruits and vegetables with precise control. Technology employs food-grade bioinks (polysaccharides, proteins, lipids and composites) for the deposition of uniform and multifunctional coatings. The coatings can be loaded with various bioactive compounds such as antimicrobial agents, antioxidants, EOs, probiotics and NPs to enhance the functional properties. In this method, a uniformly thick coating is obtained which has improved mechanical strength, barrier capacity and capability to control the migration of active ingredients, thus minimising microbial growth, moisture loss and oxidative degradation, while preserving the nutritional and sensory attributes of fresh produce (93).

In recent developments, 3D bioprinting has been combined with nanotechnology and smart packaging to create an intelligent edible coating that will respond to changes in the relevant environmental conditions, including pH, temperature and microbial activity. These coatings can enhance food safety, increase shelf life and contribute to the reduction of plastic packaging in the food supply chain, promoting sustainable postharvest management.

Incorporation of natural substances

Utilising natural materials in edible films and coatings has become a significant innovation in the preservation of harvested produce, which is mainly attributed to the antimicrobial and antioxidant characteristics of the natural materials. These natural compounds boost both the barrier and protective capacity of coatings and films with an increasing demand for eco-friendly and safe preservation methods.

Natural antimicrobials

Different plant extracts and essential oils are exploited as natural antimicrobial agents and added to the formulation process and have been extensively studied as inhibitors or preventers of pathogenic and deteriorating microorganisms multiplying on the surface of the fruit. The incorporation of bioactive EOs into the edible coating or film, such as oregano, cinnamon and thyme, has demonstrated strong antimicrobial effectiveness, which helps to reduce microbial loads and prolong the storage life of various fruits (94). In addition, chitosan films supplemented with *Thymus capitatus* L. oil exhibited a very strong fungicidal activity against strawberries, which resulted in better preservation of freshness and delayed spoilage. Likewise, grapefruit seed extract as an antimicrobial additive for chitosan-based coatings has been able to control the growth of *Salmonella* bacteria in cherry tomatoes and keep the cherry tomatoes safe during the storage period (95).

Natural antioxidants

The detrimental effect of enzymatic discoloration and oxidative stress on fruit quality and storage life makes antioxidants integral to preservation effects and plays an important role. The use of naturally derived antioxidants, including ascorbic acid, plant polyphenols and vitamin E, as coatings or films has been achieved with favourable protection properties. An alginate coating rich in ascorbic acid and citric acid has been applied for antioxidant activity retention of fresh-cut apples to avoid apple cut surface browning and enhance its visual appeal (96). Chitosan coatings containing green tea extract have additionally been recognised as an effective antimicrobial treatment for extending kiwi storage life by preventing the

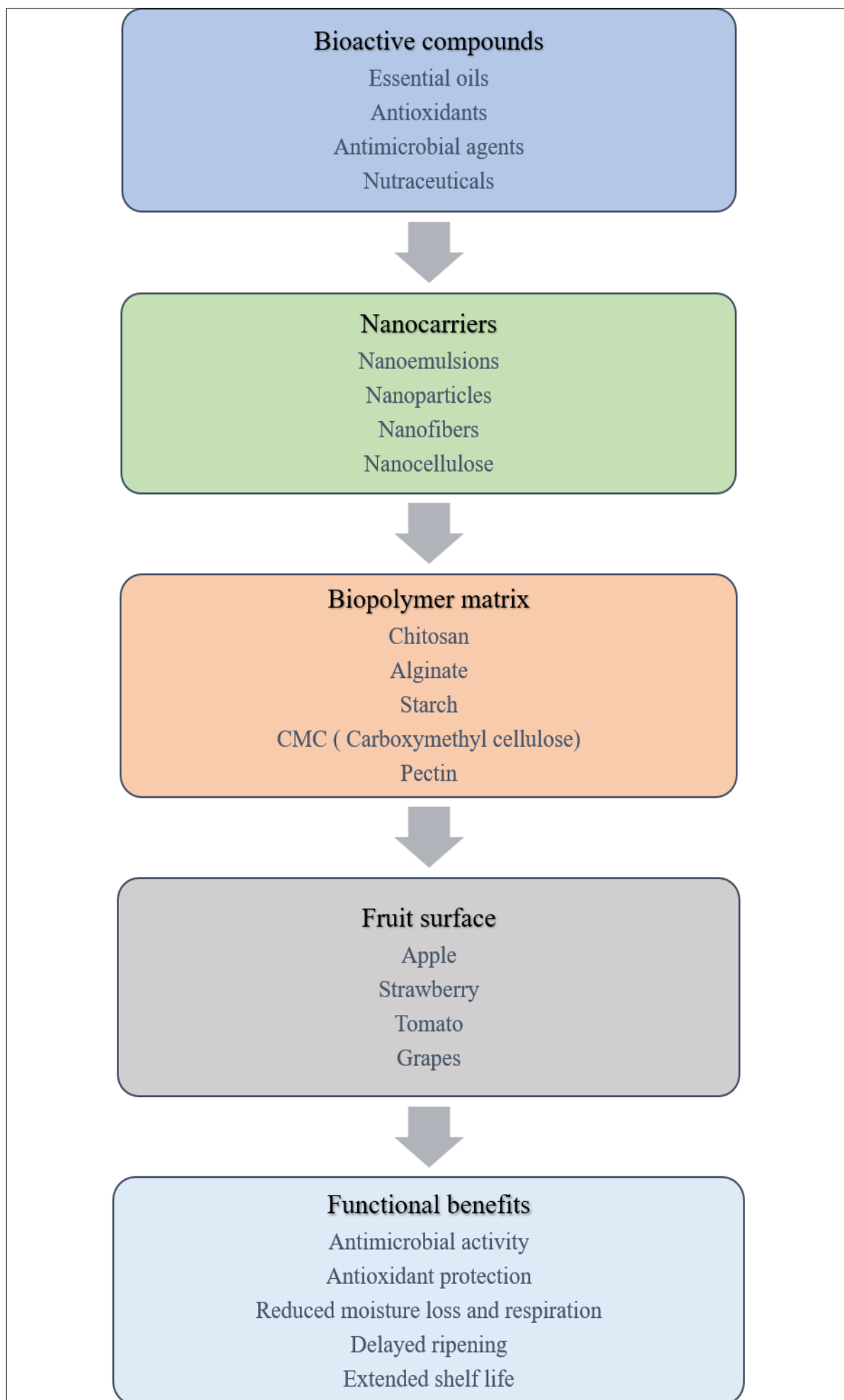


Fig. 5. Schematic representation of nano-coating architecture for fruits and vegetables.

emergence of senescence. Also, certain EOs are added to edible films and coatings to improve the antioxidant protection (97).

From the present network analysis of natural substances, it can be concluded that EOs are developed to respond to their antimicrobial and antioxidant properties, as they are mostly applied in edible films and coatings. For instance, extensive research has been carried out on EOs for their antioxidant properties, including cinnamon, clove and lemon oils (98).

Research gaps and future directions

As sustainability gains traction in food preservation research, exploration of edible coatings and films poised for an important transformation in the science field. Although this is a significant area of advancement at present, there are several critical research areas that require additional research for perishables.

Research gaps

Edible coatings and edible films have manifested great potential for food preservation and the extension of shelf life for fresh fruits and vegetables. However, there are some challenges to successful commercialisation of edible coatings (99). The performance of edible coatings is primarily dependent on the antimicrobial, antioxidant, water barrier, mechanical and gas barrier properties of the biopolymer and bioactive materials used (100). One of the major research gaps is the limited information on the long-term environmental impact of edible coatings and films. These materials are considered to be a sustainable alternative to conventional packaging, but there is a lack of comprehensive life cycle assessment (LCA) studies. For future research, biodegradability properties and carbon footprints should be assessed in commercial applications of coating materials, as well as the overall environmental sustainability. There is another challenge in the limited harmonisation of regulations on edible coatings and films. Differences in standards, acceptance mechanisms and regulations in various countries restrict their international market availability. Thus, there is a need for guidelines for safety evaluation and/or labelling as well as quality norms which are accepted by the international community to boost public acceptance and market interest for using various biofortified staple crops.

Moreover, the majority of investigations have been carried out on the laboratory scale and there is only limited data on industrial-scale production. Future work could be directed towards optimising the production efficiency, utilising a less expensive manufacturing process, identifying the best application methods for coating and testing the economic viability of commercialisation of coating. However, there is a need for more research on consumer acceptance. Consumer preference studies should be used to assess the effect of edible coatings on sensory properties related to the visual, flavour/taste, odour, tactile and general characteristics of fruits and vegetables. Optimising coating formulations based on consumer perceptions will help to achieve enhanced product quality while satisfying market requirements. The recent developments of the edible coating technologies enabled with nanotechnology, smart materials and bioactive compounds represent new potential solutions for postharvest preservation technologies. However, their large-scale and commercial adoption will need further research in order to assess their safety, legal compliance, scaling up and feasibility.

Optimisation of controlled-release systems with sustained and targeted delivery of antimicrobial, antioxidant and other

bioactive compounds during storage, which could be of interest to future research, is also suggested. Furthermore, the development of multilayer edible coatings deserves more attention, as they have the potential to integrate the best properties of various biopolymers to optimise gas barrier properties, moisture barrier, mechanical properties and coating stability. Moreover, biodegradable nanocomposite coatings, which are reinforced by natural nanomaterials, have the potential to improve coating functionality without harming the environment.

Artificial intelligence (AI) and machine learning are also becoming more significant in accelerating the formulation of edible coatings, as they can help in predicting the most suitable combination of biopolymer, bioactive agents and processing conditions based on the characteristics of different fruits and vegetables. In addition, standardised methods for testing the performance of coatings such as gas permeability, moisture barrier properties, mechanical strength, controlled release behaviour, antimicrobial activity and extension of shelf life are needed. The standardisation will help to ensure the ability to compare the results and the implementation of research in the industry and allow the commercialisation of the edible coating technology.

Future directions

Going forward, the market potential of edible coatings and films is predicted to increase owing to continuous research and innovation in improving functionality, affordability and public acceptance of these preservation technologies. Opportunities are being further researched for dividing food into smart materials incorporating edible coatings and films to allow instant tracking of food quality and safety while encouraging the creation of advanced smart materials and novel formulations with enhanced barrier, biodegradable and nutrient properties. Smart edible coatings provide protection while also delivering intelligent sensing capabilities to track the quality and freshness of fruits and vegetables. These include pH sensors, natural colourants (such as anthocyanins, curcumin and betalains), freshness sensors as well as biosensors for monitoring ripening and microbial spoilage. New developments have combined these coatings with sensors for setting and assessing the conditions of storage and the shelf life in real-time by applying intelligent packaging and Internet of Things (IoT) technologies. While promising, additional research is required to increase sensor stability, to lower costs in manufacturing, to assure regulatory acceptance and to scale industrial processes to commercial application. Besides, investment and attention should be given to scaling up the edible coatings and film technologies to industrial applications and studying the regulatory path for their acceptance. Moreover, the use of environmental friendly materials which can be recycled or are quickly biodegradable in edible coatings and films would be valuable and could present interesting opportunities in the contentious and burgeoning field of "green" food packaging, which would appeal to eco-conscious consumers as well as satisfy regulatory standards for environmental responsibility. Finally, the toxic activity of these naturally occurring substances should also be determined accurately to ensure their harmlessness to consumers. Therefore, while edible coatings and films may be an effective and sustainable approach to prolong the quality of fruit, a few challenges still exist and further research is needed to overcome existing limitations and knowledge gaps.

Limitations and perspectives

Edible coating technology has performed well in the preservation of

fruits and vegetables, but there are several limitations to commercial applications. They are effective depending on the type of produce, application technique, storage conditions and the composition of their coating. In addition, issues related to consumer acceptance, mechanical stability, regulatory approval, safety of nanomaterials and high production costs need to be addressed. Large-scale production processes and standardised application techniques are also needed for achieving success in commercialisation. Moving on, further studies are needed to improve biodegradability and smart edible coatings with enhanced antimicrobial, antioxidant and barrier properties as multifunctional systems. New technologies such as nanotechnology, active packaging and biopolymers would be expected to improve coating functionality, food quality and shelf life. The potential of edible coatings for sustainable postharvest preservation and global food security underscores the need for further research focused on safety, industrial-scale feasibility, environmental footprint and consumer acceptance.

Conclusion

Edible coatings and films are technologies developed to preserve the quality, safety and shelf life of fruits and vegetables and now they have been effectively developed into sustainable postharvest preservation technology. They possess the physicochemical capacity to control moisture loss, gas exchange, microbial growth and oxidative deterioration, which aids in maintaining the nutritional and sensory quality of fresh produce. There have been important developments with biopolymer coatings, bioactive compounds, nano-formulated and smart edible coatings, which have enhanced the functional properties and have extensive application potential. Though, these developments have been made, some obstacles need to be addressed, such as mass production, cost, acceptance, regulatory clearance and a detailed safety study of advanced coating materials. These challenges can be overcome through multidisciplinary research and standardisation of regulations to enable the commercialisation of edible coating technology. Future work could be directed towards further optimising multifunctional coating systems that are biodegradable, intelligent, with barrier properties and increased industrial applicability. Overall, edible coatings offer a sustainable and promising solution for food packaging, aiming to ensure food security, decrease food losses and waste, lower the environmental footprint and protect the food chain from postharvest losses.

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Authors' contributions

SYM and KK wrote the original draft and conceptualised the manuscript, revised the original draft and included the figures and

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During the preparation of this manuscript, the authors used QuillBot to assist with paraphrasing the text and BioRender to prepare scientific figures. After using these tools, the authors reviewed, edited and verified all content and figures as needed and take full responsibility for the content of the publication.

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