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Plant-based edible films and coatings for food-packaging applications: recent advances, applications, and trends

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Recent research has focused on using plant-based polysaccharides, proteins, and lipids to create functional films and coatings with desirable properties. Adding bioactive compounds and antimicrobial agents as well as employing nanotechnological approaches has improved the functional properties of plant-based materials, extending their shelf life and preserving food quality. This review explores the various applications of plant-based materials as coatings for fresh produce, meat, dairy, and bakery products, thus offering sustainable packaging solutions. Researchers have studied polysaccharides derived from fruits, roots, and traditional crops to make edible films and coatings. They have found that whole grains and legume flours with a high starch content can be used to create such films. Bio-based polymers and modern manufacturing methods are appealing for creating innovative food-packaging solutions. This paper explores novel film-forming materials with an aim to reduce food waste in the fruit and vegetable industry by promoting the use of edible films and coatings. It also discusses the challenges and opportunities associated with scaling up production and consumer acceptance. This review outlines future trends and research directions, emphasizing the potential for innovation in designing edible film and coating polymers, processing techniques, and interdisciplinary collaborations to advance the development of plant-based edible films and coatings for a sustainable food-packaging industry.

Sustainability spotlight

In the pursuit of sustainable food-packaging solutions, plant-based edible films and coatings have emerged as promising alternatives, as presented in the review paper titled "Plant-based edible films and coatings for food-packaging applications: recent advances, applications, and future trends." This comprehensive analysis illuminates the recent strides made in harnessing natural resources to create innovative packaging materials that reduce environmental impact. By leveraging plant-derived materials, such as polysaccharides, proteins, and lipids, these edible films and coatings offer biodegradability, renewability, and compostability, thereby addressing concerns associated with traditional petroleum-based packaging. Moreover, their ability to extend the shelf life of perishable goods and reduce food waste underscores their practical utility in the food industry. As we delve into future prospects, this paper not only identifies current challenges but also charts a course for ongoing research and development, fostering a paradigm shift towards sustainable food-packaging practices. Through collaboration and innovation, the journey towards eco-friendly packaging solutions is indeed within reach.

1 Introduction

Food is a necessity for the survival of living beings, and therefore, it becomes necessary to store and pack it to keep the product properties preserved and demands fulfilled. Food emerges from a long process involving various steps, which typically include growth, harvesting, and processing, as a consumable entity; hence, to keep it edible for longer durations, it is essential to pack and store it in such a way that it is prevented from spoilage and deterioration and its sensory profile is maintained.[1] In developed nations, 20–25% of the harvested produce is expected to spoil during handling due to post-harvest infections. However, the situation is even worse in developing countries because of their insufficient transportation infrastructure and storage facilities.[2] This deterioration generally includes changes related to the respiration rate, acidity, softening, ripening, ethylene production, pigment composition, and sensory properties and decrease in weight.[3,4]

Glass, metal, paper, plastic, and laminated polymers are commonly used as packaging materials, each with its own advantages and disadvantages.[5] Meanwhile, many of these options have sustainability issues associated with them, including the use of petroleum derivatives, such as

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polypropylene, polyethylene, and polyethylene terephthalate, and being hazardous to the environment.[6] They are mainly used to manufacture disposable single-use plastic packs and containers, which are rarely recycled. They are also the major contributor to urban solid wastes.[5] Furthermore, poisonous chemical additives and chlorofluorocarbons released while burning these plastics significantly contribute to global warming and ozone depletion.

The modern consumer, aware of these issues and concerns, is shifting towards plant-based sustainable packaging materials. This has made researchers and manufacturers continuously develop novel plant-based packaging materials and technologies to meet these demands, which are in sync with the circular economy. Nowadays, researchers create edible films and coatings with enhanced characteristics comparable to synthetic materials, such as mechanical strength, transparency, lightness, softness, and water resistance.[1,4] By acting as a barrier to decrease moisture, solute migration, respiration, gas exchange, and oxidative reaction rates, edible coatings can help prolong the shelf life of fresh produce.[7] Consequently, the market share of edible packaging has shown an upsurge in compound annual growth rate (CAGR) of 6.81% from 2017 to 2023, and from being valued at $697 million in 2016, it had upscaled to $1097 million by 2023.[2,8]

The materials used in edible packaging are synthesized from plants, animals, microorganisms, or biopolymers derived from foods like proteins, lipids, and polysaccharides. Edible packaging is a sustainable and advanced approach to reducing the waste generated due to food spoilage and the disposal of packaging materials to some extent. With continuously emerging technologies, edible materials can now be converted into coatings that can be deposited on the surface of food products. Also, films can be made into preform wraps or pouches to contain/store the food products.[8,9] Edible coatings act as an additional barrier layer over the stomata in various fruits and vegetables, reducing their transpiration and ultimately contributing to a reduction in their weight loss. In the case of animal produce, edible films and coatings can act as an additional barrier over the surface and help reduce weight loss.[4]

In this perspective, plant-based biopolymers, being biodegradable and recyclable, have high utilization potential. Furthermore, their barrier properties can be improved by incorporating additives to enhance flexibility, biodegradability, and the barrier and mechanical properties. The addition of plasticizers, like sorbitol or glycerol, can further enhance flexibility, while adding active ingredients like essential oils, generally recognized as safe (GRAS) compounds, microbial antagonists, and antioxidants can impart these properties into the developed films.[7] The supplementation of these ingredients is important as edible films alone cannot offer all the barrier properties required.[8] Therefore, applying multi-layer films or coatings with many properties can counterbalance the advantages and disadvantages of different edible films or coatings. In this regard, nanoparticles have been proven effective at improving the barrier properties and mechanical strength.[10]

The technology of commercially packaging fruits, vegetables, and animal products by edible packaging is gaining increasing attention, and different plant-based materials are being explored for their compatibility with these foods. Different inherent properties of food and the effect of the storage conditions, temperature, relative humidity, and certain compatibilities on the food, must be studied while designing edible packaging and selecting appropriate ingredients and additives. Edible packaging may not wholly replace plastic but it can be an alternative in many situations. Sustainable plant-based edible polymers can also help align the industry towards sustainable packaging goals. Due to the direct contact during exposure to potential environmental hazards during handling, edible packaging materials cannot be utilized as secondary packaging materials for transportation and storage.[1]

This review will, therefore, discuss the role and importance of plant-based edible films and coatings in the food-packaging sector. A brief introduction about plant-based edible packaging, the materials, functions, and technologies for its formation and application, followed by the future scope in this area, is provided in this paper. In continuation, recent research studies, applications, trends, and safety concerns are also discussed.

2 Importance of plant-based edible coatings

Edible coatings are considered eco-friendly as they can replace plastic packaging and minimize food waste by prolonging the shelf life of food products. Moreover, the barrier limits of the plant-based coatings reduce the contact of the product with the environment; therefore, they can alter the functional properties of the food and reinforce the regulation of surface moisture by hindering the attrition of the food. The world's population has surged in modern times and it has been estimated that it will reach approximately 9.7 billion by 2050 and 11 billion by 2100.[11] It has been anticipated that the current global demand for animal-based proteins will be redoubled by 2050 with a likely contingent increasing demand for food proteins in the upcoming years, which could likely be met by consuming protein from economical and sustainable origins.[11]

Plant extracts are considered safe for incorporation in food-grade coating/film formulations.[12] With the recent advancements in techniques, various kinds of antifungal, antibacterial, and antioxidant compounds have been integrated into these edible compounds to reduce the oxidation of fatty acids and elevate their microbial resistance, which can ultimately result in reducing alterations in their texture and enzymatic browning during their preservation period.[13] Plant-based edible coatings are considered alternatives to traditional plastic food packaging as they can effortlessly reduce the respiration rate and loss of water from fruits and vegetables, minimize physical damage and microbial spoilage, and prevent post-harvest loss.

2.1 Natural antioxidants

The appropriate choice of antioxidants for incorporation into food products is pivotal. Natural antioxidants are an alternative to synthetic ones, primarily as they contribute more advanced consistency and proficiency, as well as having good economics and accessibility. Furthermore, the utilization of synthetic antioxidants by food industries has significantly risen in recent years and has been suggested to have health implications, such as gastrointestinal tract issues and other skin allergies.[14] Additionally, it has been suggested that consumers should abstain from these synthetic compounds in their daily intake, and they should generally opt for natural ones. High levels of synthetic antioxidants might result in deoxyribonucleic acid (DNA) impairment and induce premature senescence.[15] Besides, the natural antioxidants present in plant materials contribute to food-grade augmentation and are positive well-being components of the materials. Therefore, plant extracts are naturally occurring compounds usually found in spices, herbs, and essential oils acquired from edible plants and added in coatings/films for food preservation. These have attracted immense interest, not just recently but in earlier times as well.[12]

Lopes *et al.* reported that plant extracts are natural substances with interesting bioactivities but have some limitations. They collected plant extracts from sage, thyme, liquorice, and eucalyptus and characterized them. The extracts exhibited exceptional bioactive properties. Edible alginate-based coatings and films were prepared incorporated with these plant extracts (2% w/v), and their antioxidant properties were determined. The results revealed that these coatings could reduce and inhibit bacterial growth (E. coli, P. aeruginosa, B. cereus, S. aureus, and L. monocytogenes), with the only exception being the coating with sage extract. The films incorporated with eucalyptus and liquorice inhibited the growth of Gram-positive bacteria. Still, none of these films could inhibit the growth of Gram-negative bacteria. The film incorporated with sage extract demonstrated excellent antifungal properties.[16]

2.2 Waste valorization

Agricultural waste is a huge global waste form, yet it is also an advantageous resource that can be utilized as a natural source for many applications. Its use could minimize food industry costs substantially. Moreover, it can ameliorate the quality of the packed foodstuff. Essential oils are biological materials that cannot be implemented directly into food formulation. Among recently created packaging, adopting edible films and coatings has exceptional positive outcomes. Furthermore, it has acquired considerable research attention owing to the advantages of eco-friendliness and cost-effectiveness. The application of these compounds plays a pivotal role in food packaging. It has the potential to be an appropriate approach to address the present challenge of the waste utilization of varied edible coatings and films in this arena. Despite that, numerous agrarian and food-based wastes should be considered for their potential application in the food-packaging industry.[13]

Kumar *et al.* reported that the peel of the pomegranate fruit contains a high amount of flavonoid and phenolic compounds, yet it is commonly considered an agricultural waste product. Moreover, pomegranate peel extract within the edible matrix offers excellent compatibility between the matrix and the peel particles and can improve a coating's mechanical, biochemical, antimicrobial, and antioxidant activity. The researchers also studied the incorporation of pomegranate peel extract in an edible matrix that could be applied on food products and found it could also facilitate lipid oxidation, prevent microbial contamination and the retardation of natural pigments, and improve the shelf life by preserving the organoleptic properties of the food products.[17]

2.3 Biocompatibility

In the present-day scenario, plant-based coatings are gaining prominence due to their biocompatibility. Their minimal unintended effects on living tissues and organisms make them suitable for use in food-packaging applications. In addition to the contribution of multifaceted approaches to preserving food, edible coatings are generally developed from compounds like polysaccharides, proteins, and fats, specifically those generally recognized as safe (GRAS) according to the US FDA. Their primary positive aspect is that they retard microbial growth, thus prolonging the shelf life of the food product. Implementing edible coatings can prevent weight reduction and preserve the fruit firmness throughout prolonged storage. In addition to polysaccharides, plants are specifically compromised by their natural polymers derived from their sap. Their biocompatibility, excellent film-forming characteristics, and edibility make such edible coatings stellar options for food packaging.[18]

Backed up by relevant data on their biocompatibility, renewability, and biodegradability, plant-based biopolymers are gaining recognition as the prime selection material for edible film/coating formulations in the food-packaging industry. This shift is additionally reinforced by competitive analysis of the costs of these biopolymers associated with their diverse functional properties, which shows their good economics. Furthermore, plant-based biopolymers can contribute to regulating gas (moisture and oxygen) permeability, prolonging shelf life, and preserving food quality and ensuring it can meet relevant food standards. In addition, they can potentially protect volatile aroma compounds and encapsulate them, assuring the sensory allurement of the product. Furthermore, these films/coatings can be applied as carriers for natural additives and botanical preservatives, thereby allowing improving food handling safety and alleviating deterioration of the food. Conspicuously, the biocompatible aspect of these plant-based materials outscores their susceptibility to imparting distasteful flavour or textures as a paramount factor for customer endorsement. This confluence of positive aspects sees plant-based biopolymers gaining prominence as a versatile and sustainable alternative solution for edible film/coating formulations, facilitating the development and application of more eco-friendly food-packaging systems today and in the future.[19]

2.4 Preventing enzymatic reactions

The safety and quality of fresh and cut fruits and vegetables generally deteriorate during storage due to them undergoing several physical, chemical, and microbial changes; most importantly enzymatic reactions, which can minimize the shelf life and increase food wastage. Therefore, edible films and coatings are used to prolong the shelf life and preserve the quality of fresh-cut fruits.[20]

Maringgal *et al.* reported that apples contain different enzymes that carry out critical biochemical functions within the living fruit. Later when the fruit is picked and stored, many of these enzymes continue to catalyze biochemical reactions. In addition, there are cellular compartments within apples that are disrupted when spoiled or cut, exposing enzymes to different molecules in the surroundings or environment. Specifically, the susceptibility of polyphenol oxidase to polyphenols and oxygen results in enzymatic browning reactions that negatively impact the desirable visual appearance of apples. In particular, softening occurs caused by a reduction in turgor pressure, accompanied by moisture loss, resulting in the shrivelling of the plant tissue.[21]

3 Sources of plant-based edible coatings and films

The increasing attention towards food surplus and waste has driven significant exploration of novel preservation methods for fruits and vegetables. Amongst these developments, edible films/coatings have emerged as a promising and eco-friendly strategy. Besides, the use of bio-based and plant-based compounds represents a sustainable alternative to traditional plastic packaging, which also aligns with the increasing demand nowadays for eco-friendly solutions. Additionally, the function of edible films/coatings is to create a second layer of skin around the food product. This secondary barrier is generally formulated by utilizing natural biopolymers, such as proteins, polysaccharides, and lipids, which may be plant derived as well.[22] The food-packaging industry faces great challenges in dealing with the waste produced or generated from traditional and non-biodegradable packaging materials. One innovative novel approach to address this concern is to improve packaging materials, *e.g.* by implement biodegradable packaging materials formulated using plant by-products. These plant-based, readily available materials, generally derived from sources such as fruits, grains, vegetables, legumes, and seeds, offer an eco-friendly and sustainable alternative to conventional packaging.[23]

3.1 Polysaccharides

Polysaccharides, commonly known as complex carbohydrates, are the most abundant carbohydrates in food. These macromolecules comprise long chains formed by linking/coupling smaller sugar units, called monosaccharides, through glycosidic bonds or linkages. Polysaccharides exhibit a substantial degree of heterogeneity. Sugar units exhibit distinctive properties based on their structure, arrangement, and slight alterations of these repetitions. The vast majority and diversity of food polysaccharides are plant-derived, both terrestrial and aquatic.[24]

Majeed *et al.* reported that starch, recognized for its economical and non-toxic nature, and easily accessible biopolymers, has great potential for developing edible films and coatings. Besides, starch has potential as an eco-friendly and natural replacement for conventional packaging materials. Majeed *et al.*'s research also highlighted the potentiality of starch-based films as the most promising alternatives with desirable characteristics, including transparency, good barrier properties, transparency, and mechanical strength. However, the hydrophilicity and retrogradation effect of starch restrict the application of starch-based films.[25] Maan *et al.* investigated the minerals, bioactive compounds, and phenolics substances present in the gel, which offer significant potential for use in active film and coatings. In this regard, blending aloe vera gel with other biopolymers can improve the functionality of coatings/films.[26]

Cellulose is the major component and macromolecular polysaccharide of the plant cell wall, formed by connecting D-glucopyranose with a β-1,4 glycosidic bond. Cellulose is moisture-proof and biodegradable and offers excellent film-forming properties. Panahirad *et al.* reported that carboxymethyl cellulose (CMC) edible films and coatings are generally bendy, tasteless, transparent, and offer a moderate barrier to oxygen and moisture, and resistance to fat and oil.[27]

3.2 Lipids

Food lipids, or dietary lipids/fatty acids, are usually fats and oils in food; indeed, fats and oils are the solid and liquid forms of lipids. Chemical lipids are the polymers of fatty acids, comprised of long chains and non-polar hydrocarbons with a small polar oxygen region. In one study, the researcher investigated the use of lipid materials as an edible film and found they could provide hydrophobicity, flexibility, and cohesion in the film. In addition, the lipid edible coatings could serve as a remarkable barrier against oxygen and moisture and thereby sustain the food quality for a prolonged period. These lipid edible films and coatings have nutritional and functional properties as well. The lipid films comprise a hydrophobic barrier that enhances the barrier function and reduces water vapour permeability.[28] For instance, Milani and Nemati reported that carnauba wax, generally obtained from Brazilian palm tree leaves, is solid and white, soluble in boiling ethanol, and insoluble in water. Additionally, candelilla, extracted from plants and known as GRAS wax, is considered the hardest wax. In another study, researchers studied in-depth rice bran wax extracted from rice bran oil during waxing, which can be produced in both soft and hard forms and purified and bleached to make white wax. This rice bran wax can be used as a filler compound and coating in food products such as gum, chocolate, and fruit vegetable coating.[28]

3.3 Proteins

Proteins are macromolecules composed of amino acids, commonly known as the building blocks of proteins. Indeed, proteins are polymers made up of numerous amino acids linked by peptide bonds with each other. These compounds exist naturally in the form of globular or fibrous proteins. Generally, amino acids comprise carboxyl, R groups, and hydrogen.[29] Panahirad *et al.* investigated proteins and reported they have good mechanical properties compared to polysaccharides and distinct structures with excellent barrier properties for oils and aromas. Whey proteins, soy isolates, and wheat proteins can be used as films and coatings.[27] Several edible films and coatings use gluten, whey, casein, soy protein, and peanut protein for their manufacturing. Since these substances are formed from proteins and can cause allergic responses, they are classified as allergens. In order to avoid confusion, the labels should clearly indicate if certain allergenic substances are used in the production of edible films and coatings.[30]

Erdem and Kaya reported on soy protein isolate (SPI) isolated from soybeans, and described it as a biodegradable globular protein with good oxygen and oil barrier properties and remarkable forming properties; offering films with smooth and flexible textures. SPI coatings can be applied to fruits and vegetables due to their high permeability to water. It was observed that the elongation at break (EB) and tensile strength (TS) of SPI-derived films rapidly increased with the addition of 2.5% of chitosan, while the surface of the edible film was also smoother and denser with fewer pores and cracks.[31] Seiwert *et al.* reported that whey protein isolate (WPI) is a cheese whey-derived protein with good absorption and a high nutritional value. WPI-derived films and coatings are odourless and transparent, colourless, and offer oil and oxygen resistance.[32] However, WPI is hydrophilic with a poor moisture barrier and requires plasticizers to overcome the brittleness of WPI-based films and coatings.[33]

4 Functional properties of plant-based coatings and films

Edible coatings/films made from biopolymers are being increasingly explored for sustainable packaging. These films now amalgamate boundaries between packaging, preservation, and food.[34] Packaging foods into edible, biodegradable, moisture-resistant films prevent colour fading, lipid oxidation, and off-odours, while adding improved functionality to animal products is now a reality. Moreover, the addition of certain active compounds, like organic acids, phenolic compounds, flavourings, vitamins, enzymes, and nutraceuticals, has further expanded the applicability of these films and coatings in real food systems.[3] We have covered the various properties and functions of plant-based edible coatings in detail.

4.1 Antimicrobial properties

Food preservation by preventing microbial damage is a priority after the food processing and packaging. It is also one of the major concerns in the fast-growing food industry. Fruits and vegetables can be contaminated at various production and supply chain points, like during the growing season, harvesting, handling, transport, storage, and sales. Contamination can occur even after the consumer makes a purchase. Moreover, the number of microbes growing on fresh produce can vary depending on its nature, the cultivation technique, geographical area, and climate before harvest.[35]

Spoilage by microbes can induce changes in texture, colour, aroma, flavour, and nutritional quality of food. Depending on the type of food, various microbes can be responsible for spoilage, in which bacteria, fungi, yeasts, and moulds are the most prominent. Other factors responsible for microbial growth may include moisture, temperature, nutrient profile, pH, osmotic pressure, salinity, and gaseous composition in the surroundings. Incorporating antimicrobial compounds in food packaging is a significant solution in active packaging technology. These compounds are homogeneous with the polymer matrix to develop films/coatings, which can help to combat spoilage-causing microbes.[36] They interact with the surface of the food and, therefore, need to be in direct contact with it. Due to increasing awareness of the harmful effects of synthetic antimicrobials, sulfite-based compounds or benzoic acid and its derivative salts are constantly facing rejection by consumers, who are increasingly demanding a shift towards plant-based sustainable materials. Also, sulfites have been found to cause the degradation of vitamin B1 (thiamine) in foods.[37,38]

Incorporating compounds into coatings is advantageous over other application methods, like dipping, panning, or spraying. However, it may also pave the way towards the development of resistance in microbes, for which the antimicrobials must be developed and tested constantly in foods. Hence, continuous development and improvisation must be done to tackle this permanent issue. However, a few common problems may arise in using natural antimicrobials, including instability, dispersibility in food matrices, and unacceptable flavours;[39] therefore, exhaustive research is ongoing to identify and utilize potential plant sources for antimicrobials,[40,41] and has found that plant derivatives are generally safer than their synthetic counterparts. They also fit into the umbrella of food safety measures. Antimicrobials derived from plants work on the general mechanism shown in Fig. 1. Polyphenols and essential oils from plants use this mechanism against food-borne bacteria.[42]

The possible sources of plant-based antimicrobial compounds may include nutraceuticals, broadly classified into terpenoids, like carnosic acid, polyphenols, like quercetin, and thiols, like allicin. Meanwhile, various parts of some plants, like flowers, buds, stems, leaves, roots, branches, bark, and seeds, are also found to be rich in essential oils, like carvacrol, citral, linalool, and geraniol. A typical example is the essential oil from rosemary (*Rosmarinus officinalis*), which contains mono-terpenes, like α & β pinene, borneol, camphor, myrcene, and verbenone. Carnosic acid, rosmarinic acid, and carnosol are also potent antimicrobials.[43] Polyphenols derived from industrial by-products, like coffee pulp, green tea, olive pomace, pomegranate aril/peels, mango seeds, and walnut husk, are also rich in flavonoids, carotenoids, saponins, tocopherols, rutin, and quercitin derivatives, which are effective against the common spoilage-causing microbes, like *Escherichia coli*, *S. aureus*, *Pseudomonas* fluorescence, *Salmonella typhimurium*, and *Bacillus* spp.[44] The significant advantage of incorporating plant phenolics into edible coatings is the increased stability against oxidation. The properties of edible films and the coating and application of antimicrobial films incorporated with an

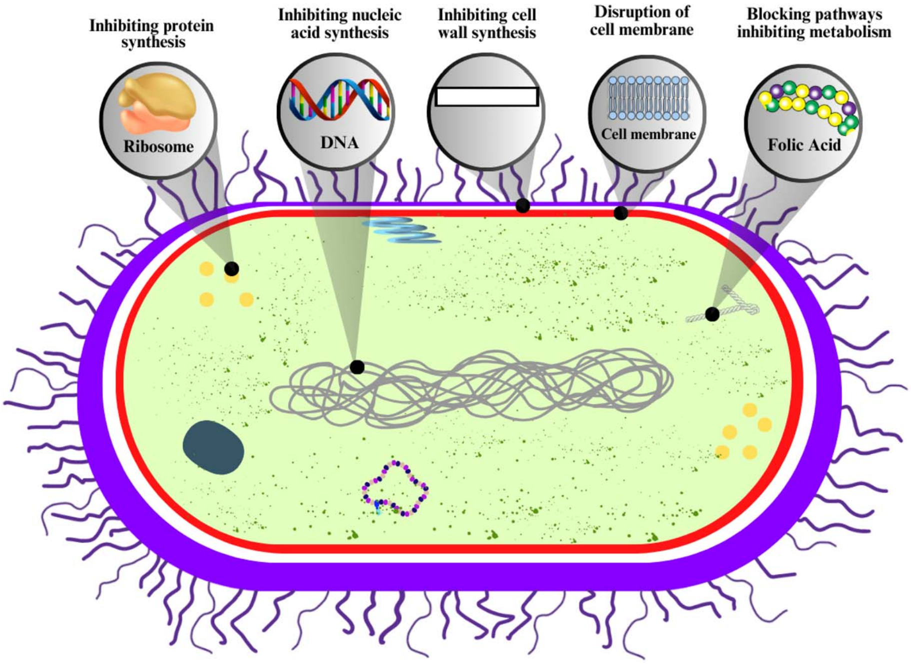

Fig. 1 Working mechanism of antimicrobial agents against pathogens by inhibiting protein or nucleic acid synthesis, cell wall synthesis, disruption of the cell membrane, and blockage of metabolic pathways.

antimicrobial agent for improving the shelf life of food are shown in Fig. 2.

Antibacterial liquid-based preservatives were discussed in 2019 by Wang and Xue, when they designed a lacquer wax composite nanometre silver liquid incorporated with ginkgo lead lipid compounds that displayed a strong antibacterial effect against *S. aureus*, *B. subtilis*, and other fungal species.[45] Next to this, plant-based antimicrobials have their advantages too, like easy availability, low cost, biodegradability, and sustainability. Sourcing them from the non-edible portions of food crops can contribute to the economics of growing that plant. The common concern of diffusability can also tackled with plant-based edible coatings, and the controlled release of active compounds is also possible. The primary problem with these properties in edible coatings is that they are all highly susceptible to external humidity conditions and the storage temperature. If not appropriately stored, there can be a decrease in antimicrobial properties due to the instability and development of degradation products. Furthermore, high temperature will enhance the diffusion rate of molecules, whereas humidity, if permeated through the barrier layer, will increase the spoilage rate.[1]

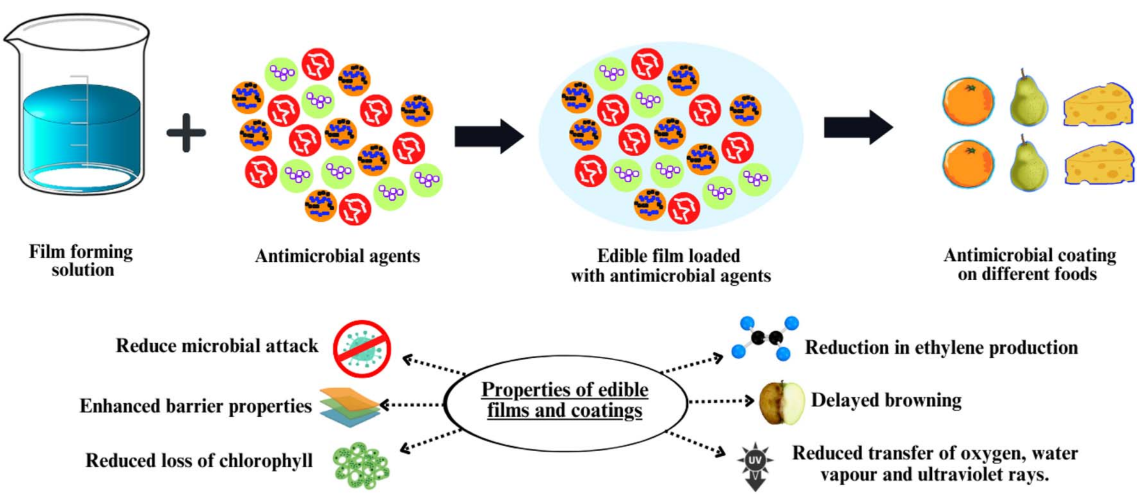

Fig. 2 Process for incorporating antimicrobial active compounds into edible films and coatings for application on the surface of the foods (*e.g.*, oranges, pears, and cheese).

4.2 Shelf-life extension

In the food processing and preservation sector, managing and extending the shelf life of food products is the main concern. The daily needs and lifestyles of consumers have changed drastically in recent years, and nowadays people have less time to prepare food due to their work-life imbalance. Therefore, the need for shelf-stable foods has significantly increased.[46,47] With active packaging solutions, the shelf life of foods can be increased and with better organoleptic properties.[48] Food products rich in nutrients are excellent media for the growth of microbes, which, upon achieving higher populations due to uncontrolled growth, can produce toxins and cause spoilage of the food. Plant-based edible coatings are gaining more attention among the constant new technologies and developments to tackle this problem.

Naturally sourced coatings act as a barrier layer, forming a protective shield over food surfaces, and provide an eco-friendly solution by acting as a barrier to gaseous exchange and moisture loss. They can also be incorporated with antimicrobial agents and antioxidants, further extending the shelf life of food as they slow down deteriorative changes, like enzymatic browning. These coatings can effectively maintain the coated food products' quality, freshness, and nutritional value. An additional advantage is their biodegradable nature, which aligns with the growing trend for sustainable solutions, including in packaging. Moreover, adding slow-release active ingredients to inhibit pathogens at the food surface is advantageous over the direct addition of preservatives.[49]

The active ingredients may include flavouring compounds, nutrients, colourants/pigments, antioxidants, and antimicrobial compounds, which help prolong the shelf life and modify the nutritional and organoleptic properties of the end product.[19] These active ingredients in packaging are usually carried by cohesive structured biopolymers, solvents, or additives. Essential oils, phenolic compounds, plant extracts, and vitamins can be incorporated into edible film and coatings, as shown in Fig. 3.

From this perspective, gums are also excellent carriers for active substances that can control the maturation of fruits and vegetables.[50] Biocompatibility and affordability are additional advantages of gums.[4] Continuous research in this field is ongoing to formulate novel ingredients and application techniques along with other preservation techniques to improve the efficiency and functionality of plant-based edible coatings and further increase their mechanical barrier, antioxidant, and antimicrobial properties. All this sums up to providing better

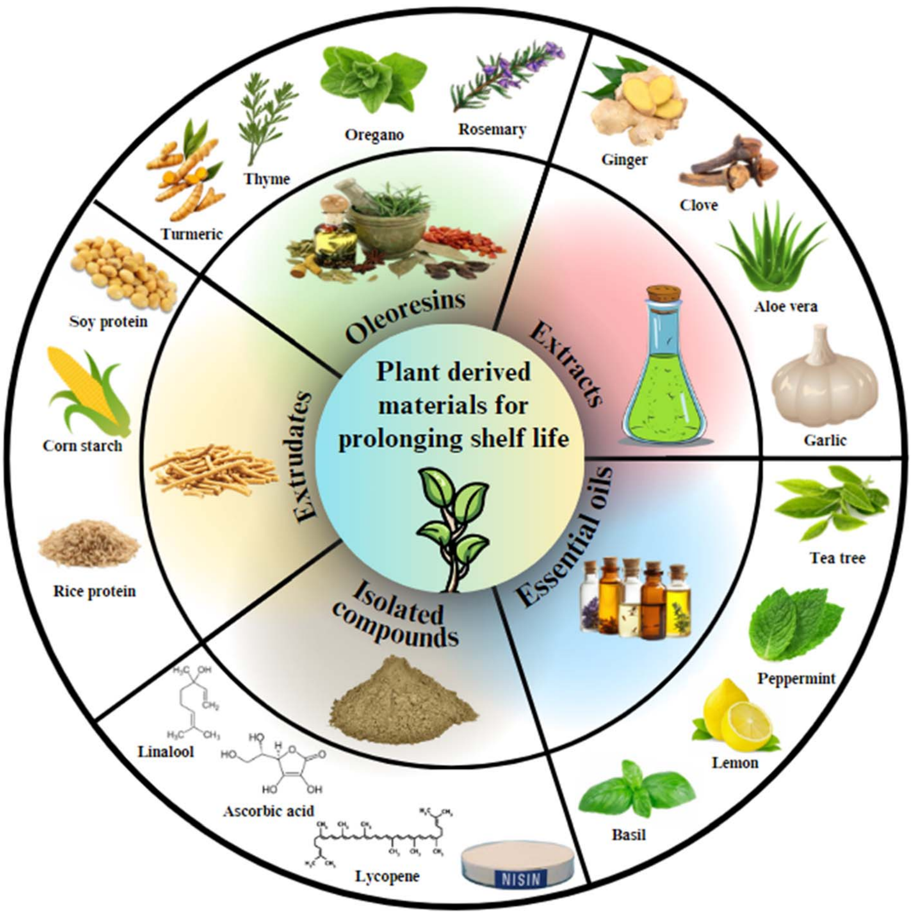

Fig. 3 Plant-derived materials, such as plant extracts, essential oils, isolated compounds, extrudates, and oleoresins, used for prolonging shelf life, which can be incorporated into edible films and coatings.

shelf-lives for foods through the use of plant-based-edible coatings. Heras-Mozos *et al.* utilized garlic (*Allium sativum*) extract as an antimicrobial agent to combat the spoilage-causing microbe *Penicillium expansum* in sliced bread loaves. A polyethylene film coated with zein and 0.5% garlic extract prevented bread from contracting mould infection for 30 days.[49]

Furthermore, Zaidi *et al.* found that guava fruits have a shorter shelf life due to their climacteric nature, but when coated with garlic and ginger extract along with gum Arabic and aloe vera (and subjected to an environment of 25 ± 3 °C temperature and RH of 85 ± 2% for 15 days) they showed comparatively lower weight loss than the control.[51] According to experiments conducted by Galus *et al.*, uncoated strawberries had a comparatively 66% lower shelf life than starch-coated ones. Studies conducted on lime fruit showed that uncoated fruits had increased shrivelling, wilting, and loss of green colour at elevated temperatures. At the same time, the coated ones showed comparatively less respiration, and a lower weight loss.[52]

4.3 Moisture barrier

Food products must be packaged properly to maintain their flavour, quality, shelf life, and marketability. In order to reduce food waste and increase the product shelf life, high-quality packaging that keeps moisture from penetrating or entering should be used. The canning industry and the packaging of alcoholic beverages both make extensive use of glass and metal containers due to their superior gas- and water-barrier qualities. Nevertheless, they do not break down in landfills and incur significant energy expenditures for recycling as well as high transportation expenses.[53] Materials made of polysaccharides absorb or release moisture till they achieve an equilibrium moisture content, which depends on the temperature and relative humidity. Harvested fruits and vegetables continue to show biological activities even after harvesting, which causes a constant loss of water and solutes to the surrounding environment. This affects the post-harvest quality due to their loss in weight, shrivelling, and considerably lower shelf life.[54]

Fresh fruit and vegetables usually have more than 80% moisture at their harvested state, and a decrease in moisture level can significantly accelerate their susceptibility to post-harvest physiological disorders.[55] Hence, applying an edible coating soon after the harvesting of fresh produce is a popular approach. Providing an additional barrier layer over the surface of foods is the primary function of edible packaging. Edible coatings have been applied on food products for a long time to reduce mass transfer between the atmosphere and the food. Indeed, fruit waxing was utilized in the 12th century in China, while later on in the 16th century, meat larding became popular in England.[56] These preservation methods significantly help to delay senescence by reducing water loss. Moreover, active antimicrobial and antioxidant compounds would have additional advantages.

The coatings form a semi-permeable layer that permits a controlled exchange of moisture and gases to delay over-ripening and senescence while avoiding anaerobic conditions that may cause deterioration. The barrier layer helps retain the internal gas composition and has effects similar to those of modified atmospheric packaging (MAP). They also help prevent oxidative browning, combat early maturation, and control the respiratory rate.[57] The environment provides all the necessary conditions for spoilage microorganisms to grow, including temperature, water vapour, and gaseous composition. Among them, humidity is the most important since all enzymic reactions and microbial growth require humid conditions. That is why foods with a lower water activity have a longer shelf life. Therefore, innovative approaches to edible coatings with enhanced moisture barriers need to be continuously developed to extend the shelf life of foods. These coatings serve as a crucial interface between food items and the environment and regulate the ingress and egress of gases and moisture.

Pająk *et al.* studied polysaccharides extracted from starch-rich pumpkin fruits, lentils, and quinoa seeds. They examined the application of these polysaccharides in edible films and observed that the films created had higher water vapour permeability compared to polystyrene.[58] With the increasing consumer confidence, there is an emerging shift from chemical-based to plant-derived compounds utilized in edible coatings. Based on their source, the barrier properties of plant-based edible coatings are listed in Table 1 below.[1]

Tainting is also a significant concern when storing fruits and vegetables with sharp and pungent aromas. The bipolar matrix of edible coatings is also effective against aromas. Non-polar aromatic compounds have a lower affinity towards hydrophilic proteins and polysaccharides. This property also renders them effective against grease and oils. Edible coatings, hence, can be considered natural, sustainable, biodegradable, and compostable materials, which align with the goals of a sustainable food system.[59] Being plant-based, these coatings have fewer risks of toxicity, and they are "Generally Recognized As Safe (GRAS)" for human consumption. By increasing the shelf life of foods, they contribute towards preventing food spoilage and

Table 1 Barrier properties of plant-based edible coatings

Property	Polysaccharides and proteins	Lipids and waxes
Affinity to water	Hydrophilic	Hydrophobic
Water vapor permeability	High	Low
Ideal relative humidity	Low	High
Moisture absorption	Absorbs water, reduces oxygen barrier	Minimal moisture absorption
Oxygen barrier	High in low humidity conditions, reduced with moisture	Effective oxygen barrier even in high humidity
Gas barrier	High in low humidity conditions	High in all humidity conditions

wastage. The coatings have also been shown to improve the appearance and glossiness of food, ultimately improving the visual appeal of the products.

While plant-based coatings are a sustainable alternative to synthetic coatings, they also have some disadvantages, including their effectiveness in comparison to synthetic alternatives. Plant-based polymers may offer good barrier properties but may not be suitable for all food systems, narrowing down their applications in real-life scenarios. For instance, the polar compounds in these materials will pose a problem with solubility, making them less effective for high-water-content foods. Plant-based coatings composed of wax may have reduced flexibility at low temperatures and can become brittle. This will compromise the coating integrity, eventually leading to an increased moisture loss. Moreover, coatings with lower melting points can soften at elevated storage temperatures, compromising their effectiveness as a barrier layer. Da Silva *et al.* explored nine edible coatings formulated from pectin, cellulose nanocrystals, glycerol, and lemongrass essential oil for application on strawberries. Examination of refrigerated fruits over different storage periods with these coatings demonstrated that these coatings could moderate weight loss and decrease the anthocyanin content while preserving the pH levels, which meant they could effectively minimize weight loss of the fruit without compromising the strawberries' physical and chemical properties.[60]

Liu *et al.* studied the impact of plant-based edible coatings with asparagus waste extract on the quality of strawberry fruit. The coatings showed antifungal activity against *Penicillium italicum*, and could delay colour change of the fruit, reduce weight loss, and preserve the phenolic and flavonoid contents, suggesting that these coatings can be an effective, safe, and eco-friendly way to extend the shelf life of strawberry fruit.[61]

4.4 Antioxidant properties

Plant-based coatings used for food-packaging applications can be incorporated with antioxidant compounds directly into the film or coating matrix, offering a controlled release mechanism to protect the food product.[62,63] Such incorporation in the coatings further enhances their functionality and increases the shelf life of food products. These added antioxidants help inhibit oxidation reactions responsible for food deterioration, like changes in texture, aroma, flavour, colour, and mouthfeel. The stable compounds can donate their negative charge to free radicals and reactive oxygen species (ROS). These radicals, if not neutralized, tend to damage essential food components, like lipids, proteins, and pigments, which can adversely affect the food quality and safety.[64]

Commonly used antioxidants in plant-based edible coatings include vitamin E, vitamin C, polyphenols, carotenoids, tannins, and anthocyanins.[65–67] They can be derived from soybean, sunflower, citrus fruits, green leafy vegetables, edible roots, tea leaves, tree bark, *etc.* Ascorbic acid (vitamin C), a powerful antioxidant derived from citrus fruits and berries, helps to protect against oxidative stresses by its scavenging action and regeneration of other antioxidants, like α-tocopherol. α-Tocopherol (vitamin E or vit-E), commonly used in food-packaging applications, helps to prevent lipid oxidation and sustain the stability of fats and oils. It is also the most biologically active form of vit-E. Polyphenols are diverse compounds and include flavonoids (*e.g.* quercetin, catechins), phenolic acids (*e.g.* gallic acid, caffeic acid), and resveratrol. Carotenoid pigments, including β-carotene, lycopene, and lutein, also possess antioxidant properties. Tannins found in nuts, seeds, fruits, and bark exhibit antioxidant properties and can help to inhibit lipid oxidation and microbial growth in food products.

The concentration and stability of the antioxidants and the extraction methods should be carefully optimized to ensure the coated food products' have the desired functionality and shelf-life extension. Synthetic antioxidants have been traditionally used because they have higher stability and performance, lower cost, and easy availability. The most widely utilized synthetic antioxidants in the food industry are butylated hydroxytoluene (BHT), butylated hydroxy anisole (BHA), propyl gallate (PG), and *tert*-butyl hydroquinone (TBHQ). The ones primarily used in fruits and vegetables include 2-naphthol (2NL), 4-phenylphenol (OPP), and 2,4-dichlorophenoxyacetic acid (2,4-DA).[68]

Oyom *et al.* developed an edible film and coating using modified sweet potato starch incorporated with 0.2–0.4% (v/v) cumin essential oil.[69] They found that including essential oils could improve the colour, barrier characteristics, and mechanical strength of starch films. The edible coating treatment helped in delaying fruit pulp degradation and retarded the enzyme activity during ambient storage for 28 days. The coating further improved the activity of the antioxidant enzymes, like the peroxidases, phenylalanine ammonia-lyase, superoxide dismutase, and catalase, and endowed the fruit with resistance against softening compared to the control fruits.

Also, a study conducted by Ezati *et al.* showed that coating tangerines and strawberries with cellulose nanofiber/N-functionalized carbon dots synthesized from glucose could extend their shelf life by more than 10 and 2 days, respectively, due to inhibiting fungal growth.[70] The carbon dots enhanced the UV-blocking properties of the coatings and maintained their transparency. At the same time, the coatings showed an increased water vapour permeability and contact angle and exhibited high antioxidant activity.[71] Further, applying active carboxymethyl cellulose-based coatings enriched with functional ingredients from spent coffee grounds prolonged the shelf life of fresh goldenberries. The goldenberries' antioxidant activity was enhanced because of the additional phenolic compounds, like flavonoids, contained in SCG and the polysaccharide-rich extract present in the edible coating, with the coatings showing good potential for extending goldenberries' shelf life under different storage conditions.

4.5 Biodegradable

Globally, the food industry is the major contributor to the total plastic waste produced.[72] Nowadays, there is increasing interest in biodegradable packaging due to the increasing knowledge of the environmental impact of synthetic materials. Attempts have been made to investigate novel sources of biodegradable packing materials. Researchers are mainly focusing on making edible films with improved characteristics and desired features, like softness, high mechanical strength, lightness, transparency, and water resistance. Biopolymers derived from polysaccharides, lipids, and proteins are emerging as an alternative to many existing plastic packages, with seed gum one of the key emerging sources of interest. Various seed gums, like dracocephalummoldavica, balangu, basil, durian, *Lepidium perfoliatum*, cress, wild sage, qodumeshirazi (*Alyssum homolocarpum*), tamarind, cassia, psyllium, chia, flax, and mesquite have shown to have desired mechanical, physical, thermal, and microstructural characteristics along with biodegradability.[73]

4.6 Target delivery of nutrients

Essential nutrition is provided by consuming nutritious food, yet some of the good ingredients of foods may not be well absorbed. Low or non-solubility, chemical instability, and disagreeable taste are some of the drawbacks of nutraceuticals, including curcumin, carotenoids, and omega-3 fatty acids. These substances may also be degraded by digestive enzymes and intestinal walls. Nutraceuticals are dietary supplements proven to alleviate health, support proper functioning, and prevent diseases in the body. Recently, they have been gaining attention in the public domain due to their nutritional and therapeutic advantages. They can be classified as dietary supplements and herbal bioactive compounds. This category of nutritive compounds has enormous applications beyond just their basic nutritional profile.

Over the years, many bioactive compounds extracted from food and phytochemicals have been developed and marketed as pharmaceutical formulations, such as capsules, powders, gels, and solutions.[74] Epidemiological studies have confirmed that plant-derived bioactive compounds can have a beneficial effect on health. These are specifically linked to plant polyphenols.[75] In addition to this category, vitamins, probiotics, polysaccharides, and peptides are also commonly used. However, the direct consumption of nutraceuticals is not advised. Therefore, they must be incorporated into some food items for consumption.[1] Also, various systems of nutrient delivery are used in the food and pharmaceutical industries, such as pH-responsive,[76] enzyme-responsive,[77] temperature-responsive,[76] and time-responsive[78] systems.

Edible coatings and films tend to hold active compounds that can eventually help enhance the nutritional value of food products.[79] Studies have reported the integration of nutraceutical ingredients into coatings or films, and research is still being done to identify the possible concentrations of ingredients to be added into the films or coatings that would not affect the other characteristic properties of films, like the barrier or mechanical properties. Hence, they can be used as excellent carriers of low concentrations of nutrients in food products. The micro- and nanoencapsulation of these active compounds can further increase their stability for application in various food categories.[10]

4.7 Improvement of appearance and strength

The wax coating on fruits and vegetables has the added advantage of improving glossiness and shine apart from providing a moisture and gas barrier.[80] The use of this coating method started with a paraffin wax coating applied in 1930 in the United States for citrus fruits, and later carnauba wax in 1950 for fresh fruits and vegetables.[81] Due to the current shift towards sustainable, biodegradable, and, more specifically, edible packaging, new plant-derived coatings are being researched to provide these properties in addition to a gas and moisture barrier. Coatings of soy protein, starch, wheat gluten, casein, and cellulose have been studied for these properties. These films can improve the physical appearance of foods by adding colour, gloss, and greater visual appeal.[82] Mango kernel starch-based pouches for packing red chilli powder were reported to show better colour values (lowest reduction in capsaicinoid content) than LDPE pouches.[83]

4.8 Physical and mechanical properties

Ensuring good handling is one of the major problems when developing edible films. Plastic films are an excellent barrier along with good physical strength, rigidity, and handling properties. These films also retain these properties up to several micron thicknesses. With the increasing interest in applying packaging materials made from edible and biodegradable sources, like polysaccharides, lipids, and proteins, natural polysaccharides are emerging as an excellent, sustainable, inexpensive, and fully biodegradable source offering good film-casting properties. However, edible films often have a higher cost, lower tensile strength, and poor barrier properties, making them more difficult to process than plastic-based packaging films, but they do have good elongation compared to plastic films.[1] Temperature is also an important factor that can affect edible films' physical and mechanical properties, and the physical strength of materials is known to decrease when the temperature increases beyond the glass transition point.

Starch isolated from potato, corn, cassava, wheat, and rice has been used in edible packaging due to its thermoplastic properties. With polymers extracted from the seeds of lotus and pinhão, litchi kernel, mango, okenia, and banana, the scope and application of these research studies are broadening daily. Pająk *et al.* studied polysaccharides extracted from starch-rich pumpkin fruits, lentils, and quinoa seeds for their application in edible films and tested their physicochemical, thermal, and mechanical properties. They observed that the tensile strength and elongation at break increased from 8.98–13.85 MPa and 3.35–4.44%, respectively, for such films, which displayed elastic characteristics while acting like solid materials. Furthermore, researchers concluded that films developed from non-traditional starches can be an alternative to conventional synthetic polymer films.[58] Behrestaghi *et al.* also reported the satisfactory physical and mechanical properties of carboxymethyl cellulose (CMC) film when *Artemisia sieberi* essential oil was added.[84]

5 Methods for fabricating edible films and coatings

Edible packaging comes in two forms: applying an edible coating directly onto the food product or using preformed films that can be wrapped around the food.[8] Edible film-forming methods can be further classified into wet (casting) and dry (compression/extrusion moulding) processes. Dipping, fluidized-bed coating, spraying, and panning are usually used to deposit edible coatings on the surface of food products. We briefly discuss these in the following section.

5.1 Edible film-forming methods

Edible films provide an additional protective layer around the food surface by wrapping around it. Other additives, like antimicrobial agents, antioxidants, colourants, and flavours, may be added to the film to improve its functionality and utility.[19] The solubility of these compounds in the biopolymer matrix ensures their active dispersion throughout the film. Hence, their interaction with polymeric substances and food surfaces is crucial in determining the film's effectiveness. The mechanical properties of films are greatly influenced by the cohesive forces between the biopolymers. These forces include hydrogen bonding, electrostatic interactions, and hydrophobic interactions. They help determine the film's strength and flexibility.[85]

Dry compression/extrusion (moulding) and wet (casting) methods for preparing edible films are explained below.

5.1.1 Solution-casting method. Casting is the easiest and most widely used method for film formation, and is usually used for manufacturing films at the laboratory and pilot scales. It involves manufacturing films from biopolymers, and includes the following steps: (i) solubilizing the biopolymer in a suitable edible and non-toxic solvent, such as ethyl alcohol or water. The solubilization step ensures an even dispersion of the biopolymer in the solvent. This solubilization step is crucial as the film formation depends on the polymer's solubility rather than melting; (ii) casting of the solution in a predefined mould, where it forms a gel structure (cohesive film adhering to the mould) as the solvent evaporates with time; (iii) drying the cast solution layer, which is necessary to form a cohesive film, but with the moisture content maintained at 5% to 8% to prevent wrinkling and tearing of the film during peeling.[86]

Different drying methods, like hot air ovens, microwaves, or vacuum dryers, can be used to ensure proper film formation and to maintain structural integrity. The drying process is important to establish strong intramolecular bonds between

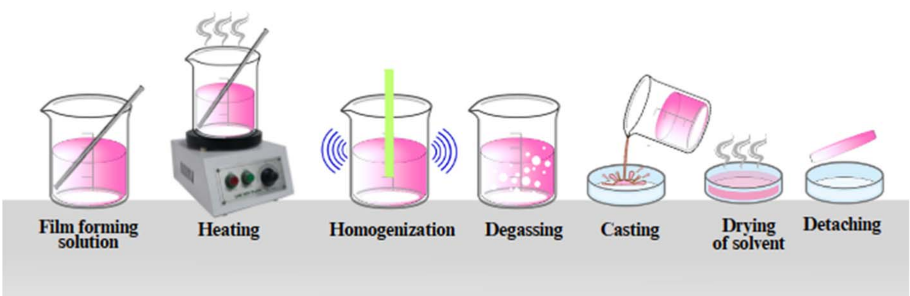

Fig. 4 Different steps involved in preparing an edible film using a solution-casting method, with the film-forming solution subjected to heating, homogenization, degassing, and then cast into films by pouring over a Petri plate, and then slowly drying.

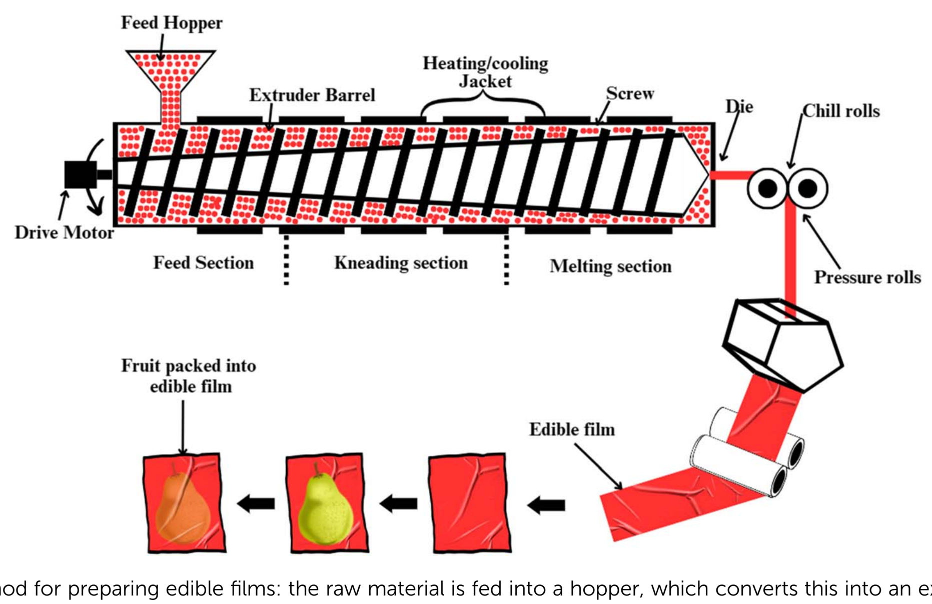

Fig. 5 Extrusion method for preparing edible films: the raw material is fed into a hopper, which converts this into an extruded mass, which is made into sheets using cold pressure rolls to make films to wrap or pack fruit.

the polymeric chains to achieve the desired microstructure of the film. Slow drying is usually preferred, as quick drying methods can negatively impact the film's physical, structural, and integral properties.[8] Optimization of the drying temperatures and methods for a particular film is done to produce high-quality edible films. As this is a low-temperature long-time (LTLT) method, molecule degradation is impossible. However, this is also one of the major disadvantages of the method as it decreases its application on a commercial scale. Beneficially, the film's mechanical properties can be tailored by controlling the casting and drying processes to meet specific packaging needs. Fig. 4 shows the different stages of the casting process.

5.1.2 Hot melt extrusion method. The extrusion method is one of the underexplored techniques for manufacturing edible films, but is now attracting more attention, particularly for starch/protein combinations. Traditionally, starch and protein have been investigated for film formation by solution casting. However, the potential of extrusion in this domain remains underexploited. Further research into different extrusion techniques is required to enhance the processability and properties of starch and protein blend combinations. Extrusion forms films through a thermomechanical process, completely different from the conventional solution-casting method, which relies solely on solvent addition. This even eliminates the need for solvents. Also, the addition of solid lipids makes the solution-casting process challenging since a high temperature is needed to melt them.[87] This method also changes the structure of the raw materials and improves their physiochemical properties.

Blown-film extrusion, one of the commercial methods for producing plastic films, presents a viable alternative to solution casting. This eliminates the need for long drying durations, which provides additional advantages, especially for achieving industrial-scale film production, which is impossible with the solvent-casting method. This method involves subjecting the raw materials to a thermomechanical extrusion treatment to convert the crystalline starch into its amorphous state, facilitating the film formation. After extrusion, the formed edible plastic tubes undergo heat-sealing to produce pouch-like packaging materials, which can filled with a product and closed by top heat-sealing. A major concern in extrusion is the high temperatures required for melting the starch, as this may induce material degradation. Hence, a plasticization step is needed to produce the extruded materials with thermoplastic properties that can be transformed into different shapes without thermal degradation.[88]

Stickiness and moisture sensitivity during the blowing process pose substantial processing challenges for thermoplastic starch. Therefore, blending the starch with other polymers offers a practical strategy for enhancing film formability and improving the mechanical, barrier, and thermal properties. The extruder unit used typically has three distinct zones: feed, knead, and melting zones, each serving a distinct role in material transformation. In the feed zone, biopolymers and additives are added. In the kneading zone, ingredients are mixed properly with the help of an extruder screw. In the melting zone, some additional heat is provided (if needed) with the help of heating plates/coils. A die is fixed at the end, and the extruded film's shape and thickness can be varied. Elevated temperatures can be applied to change the biopolymer's structure and alter the film's overall properties. Typically extrusion machinery for the preparation of edible film is shown in Fig. 5. In this process, the moisture content, die diameter, barrel temperature, screw speed, pressure, and solvent (if added) influence the outcome. Meanwhile, the composition of the feed, type, and the quantity of plasticizer can also significantly impact the film properties.

Single- and twin-screw extruder assemblies may be utilized and offer discrete advantages in edible film fabrication. The twin-screw extruder has enhanced mixing and conveying capabilities through various interchangeable screw profiles. Co-extrusion techniques further enable the production of multi-layer films with distinct properties and functionality. The final co-extruded film will have the collective and improved properties from the multi-layers compared to a single-layer extruded film. However, challenges like deformities and starch retrogradation can sometimes occur, which must be mitigated against by careful process optimization and material selection. Also, extrusion machinery can be capital-intensive initially, but is often still considered superior to casting on a commercial

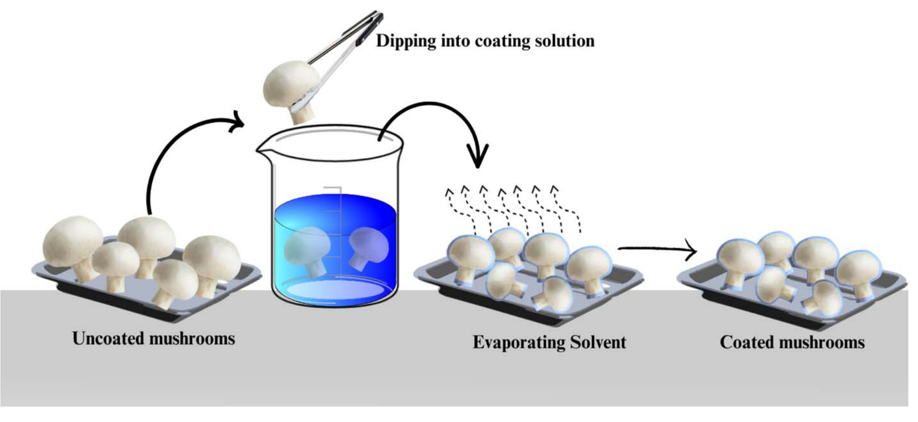

Fig. 6 Different steps involved in the dipping process for depositing an edible coating on white button mushrooms, which were then air-dried.

scale.[8] Moreover, its application for heat-sensitive foods is still questionable.

6 Edible coating application methods

An edible coating, after application, acts as the primary packaging, as it is in direct contact with the food surface. Different coating techniques, such as dipping, spraying, fluidized bed, panning, layer-by-layer deposition, and cross-linking, can be used to apply edible coatings directly onto fruits, vegetables, and other food items. The selection of the appropriate method for a particular food depends on various factors, such as the intended purpose of the coating layer and the surface properties. Considering the food product's ripening and spoilage pattern is essential before coating. Methods can vary in effectiveness and most come with their own advantages and disadvantages. The different coating application methods are discussed briefly below.

6.1 Dipping method

The dipping method is characterized by its simplicity and is the most commonly used method. It comprises three primary steps: (i) immersion and dwelling, in which the food is submerged in the coating solution and allowed to dwell for a specified duration; (ii) deposition, which involves the adherence of the coating solution to the food surface; and (iii) solvent evaporation, which leaves a thin coating on the food product's surface. Fig. 6 displays a typical dipping process for edible coating formation on white button mushrooms. Many factors can influence the quality characteristics of the coating formed through dipping, including the number of coating cycles, the speed at which the food is withdrawn from the solution, and the duration of immersion. Also, parameters related to the coating solution, such as its density, viscosity, and surface tension, can affect the quality of the coating. Moreover, the drying conditions and substrate surface properties are important in determining the coating density and morphology. One of the main drawbacks of the dipping method is the uneven coating, which can lead to areas of fruit respiration and surface damage. Another limitation is the high volume of coating solution required per unit mass of product to achieve an optimal coating.

The contact duration with the coating solution is also important, as prolonged exposure can result in excessive moisture absorption, whereas an insufficient contact time can lead to uneven coating. The coating can also be applied in the form of foam, which can facilitate a uniform distribution over the food surface. The foam application method can also ensure a consistent coating thickness. With the help of the dipping method, it was reported that an aloe vera coating incorporated with salicylic acid could maintain the phenolic content, firmness, and weight of oranges, while also providing antimicrobial properties.[89] Also, a lotus leaf extract-incorporated composite coating was found to be able to increase the shelf life, maintain the ascorbic acid content, and reduce the decay rate and malondialdehyde content of fresh Goji (*Lycium barbarum* L.) fruit;[90] while pineapples coated with sodium alginate and citral nano-emulsions showed reduced microbiological growth, a lower respiration rate, and improved colour retention.[91]

6.2 Spraying method

In the spraying method, a fine layer of liquid coating is dispersed over the food sample using a small nozzle called an atomizer, with sizes ranging from micrometres to nanometres. When passed through this atomizer, the coating solution converts the liquid into tiny droplets that cover most of the food's surface area. Fig. 7 shows the typical method for spraying an edible coating on paneer and cheese. The effectiveness of the spray coating pivots on the fluid rheological properties, like the surface tension temperature and viscosity. The use of spraying technology allows for even multi-layer applications, like inter-layer solutions, and forms a consistent coating with homogeneous thickness. The coated sample then undergoes a drying period, which is directly influenced by the drying method, time, and temperature.[92] Several techniques are employed in various

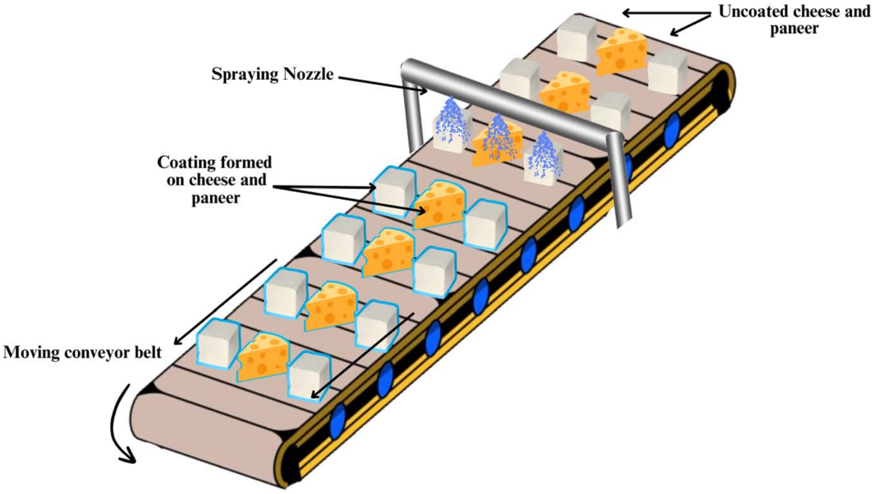

Fig. 7 Spraying method for depositing an edible coating on paneer and cheese using spray nozzles: The food material (paneer and cheese) passes through a series of spray nozzles *via* a conveyor belt, depositing an edible coating on the surface of the food.

industries, including pressure atomization, air spray atomization, and air-assisted airless atomization, each with distinct mechanisms and outcomes. Pneumatic and hydraulic atomizing nozzles are the most commonly used.

Electrospraying is a recently emerged specialized technique that uses a strong electric field to produce charged droplets with accurate size control, representing a cutting-edge approach for achieving micro- and sub-micro droplets. This method permits the customization of the droplet specifications by changing the flow rate and solution viscosity, thereby offering precise control over the coating thickness and uniformity. A xanthan gum-based edible coating, along with citric acid and glycerol, was applied to fresh-cut lotus roots by spray coating, which showed a considerable reduction in the colour changes of coated lotus roots upon storage. Moreover, it also inhibited enzymatic browning and the growth of *Bacillus subtilis*.[93]

6.3 Panning method

Panning is usually used for round- or oval-shaped food and confectionary items. It originated from Greek/Arabian society and has been used for drug-coating applications. It supports obtaining small and high-quality food products and offers efficient batch-processing capabilities. The process involves using a large spherical rotating pan in which the food items to be coated are placed. Numerous spray nozzles are fitted inside the coating chamber to disperse the coating solution over the food products. During this process, the pan is kept rotating, ensuring a uniform distribution of the coating material, with the thickness

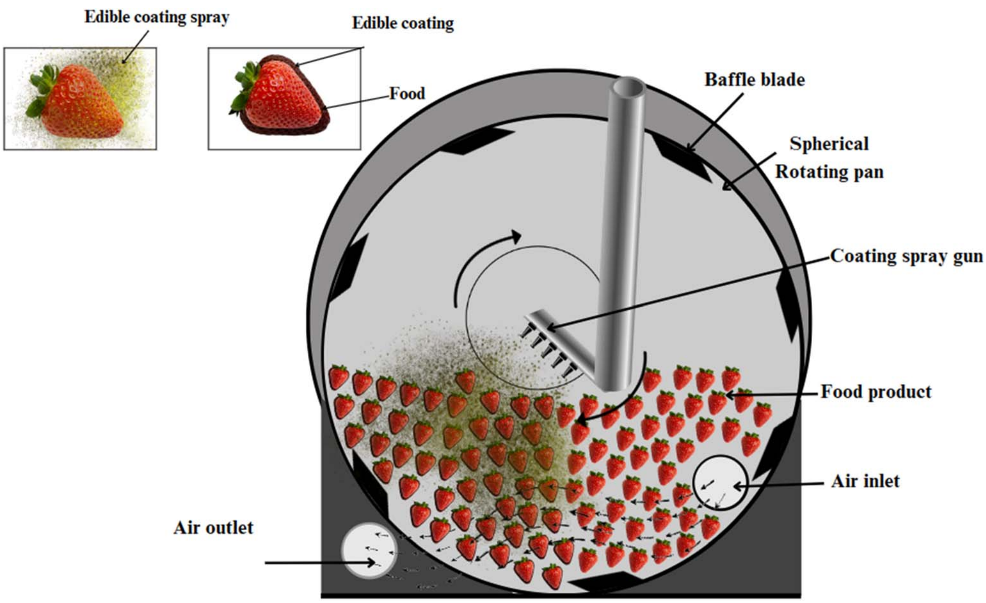

Fig. 8 Panning method for depositing an even layer of an edible coating on oval- or spherical-shaped foods, such as strawberries, utilizing a spherical rotating pan into which air circulation is provided, helping to evaporate the solvent and leaving an even coating on the food products.

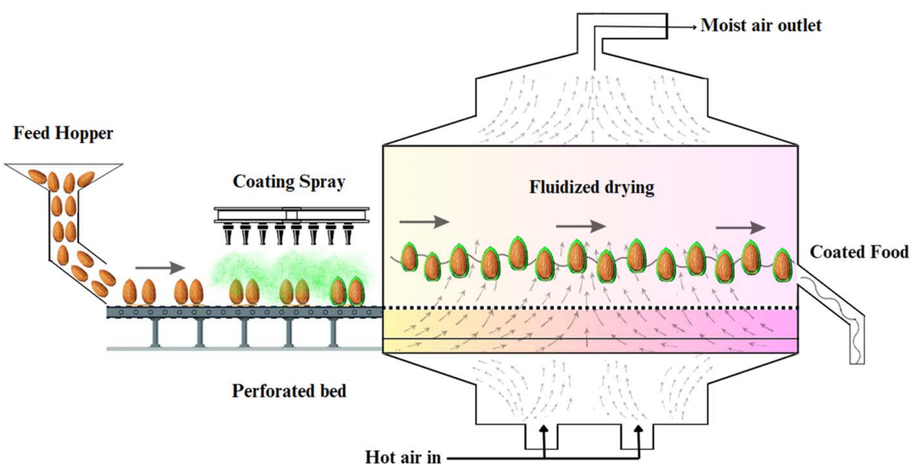

Fig. 9 Steps involved in the fluidized-bed-coating method for the application of edible coatings on small food items, such as almonds: the coating is initially deposited through spray nozzles, after which the food materials, *e.g.*, almonds, are subjected to fluidized drying to evaporate the solvent, giving an even coating quickly.

of the final coat being determined by the quantity of coating solution sprayed.[1] During this process, heat is generated by friction with the cold air. The typical panning method for the application of an edible coating on strawberries is depicted in Fig. 8. The pan's rotation speed influences the food items' coverage with the coating material throughout the coating cycle. After panning, the coated products are subjected to a drying cycle, where hot air is circulated to evaporate the solvent and promote drying. This drying process is crucial for achieving a stable and dry coating on the food items. Overall, the panning method can effectively coat foods that have round or oval shapes, ensuring a uniform and controlled coating thickness.[92]

6.4 Fluidized-bed-processing method

The fluidized-bed-coating process, known as the Wurster process, was pioneered in the 1950s. This is a modified version of the fluidized-bed drier that is widely used in food industries to dry small items. This method helps apply a thin coating on to small, dry food products, like wheat, cereals, or different types of nuts, at low pressure. This method requires the largest amount of coating solution compared to other coating methods. Among the different fluidized-bed methods, namely the top, rotary, and bottom spray, the top-spray type is the most efficient method.[92] This method facilitates the flow of smaller-sized foods, allowing the coating solution to form a shell that gradually transforms into the desired coating, as shown in Fig. 9. While effective, this method tends to be costlier than the other coating techniques.[36]

The major advantages of this method are the prevention of agglomeration and the controlled release rate of the active compounds, which can enhance the product quality and its shelf life.[94] In the food industry, fluidized bedding is already utilized to encapsulate various foods, including puffed wheat, nuts, and peanuts. There is also a possibility to increase the crispness of ready-to-eat foods coated using the fluidized coating method. However, there are certain challenges associated with this method, which include solution loss due to adherence of the coating on to the unit's side walls and the potential for premature evaporation leading to an uneven coating on food. Despite these challenges, the fluidized-bed-coating method can be efficiently utilized with commercial-scale formulations.

6.5 Layer-by-layer deposition

The layer-by-layer deposition method depends on the electrostatic interactions between the food surface and the charged polyelectrolytes. These interactions can enhance the coating adhesion and permit the creation of coatings with several thin layers linked physically or chemically. Such multi-layer coatings can also showed improved coating effectiveness in comparison to conventional coatings.[95] This method has been effectively used to enhance fruit preservation during post-harvest storage, exploiting polysaccharides and charged polyelectrolytes capable of hydrogen and covalent bonding to increase the coating tightness. The layer-by-layer (LBL) deposition of an edible coating on mangoes is depicted in Fig. 10.

6.6 Cross-linking

Cross-linking combines polymer chains through both covalent and non-covalent linkages. In real food systems, cross-linked

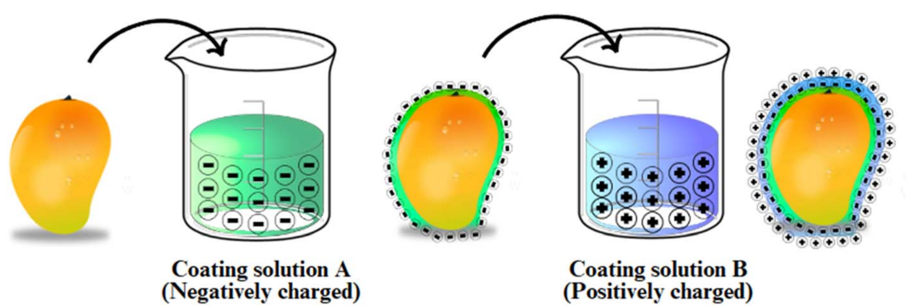

Fig. 10 Steps involved in the layer-by-layer (LBL) deposition of an edible coating on mangoes, whereby washed and cleaned mangoes are initially coated by a negatively charged solution, after which a positively charged coating is deposited on the surface of the fruit.

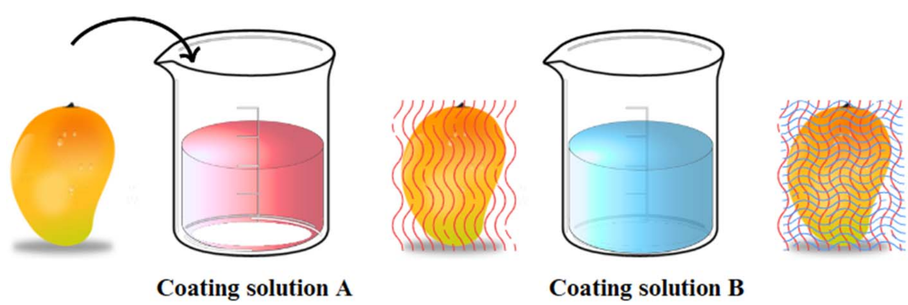

Fig. 11 Developing an edible coating on mangoes by employing a cross-linking method, whereby a matrix of coating A is first deposited on the fruit, after which the matrix of coating B is deposited, leading to the formation of cross-links between the coatings.

Table 2 Plant-based edible coating for fruits and vegetables for extending their shelf life

Plant-based edible material	Additives	Food product	Effect on the product	Reference
Cellulose nanofibers	Nitrogen-formulated carbon dots	Tangerine and strawberry	Extend the shelf life of strawberries, show high antioxidant activity	70
Cellulose nanofibers	Chitosan, curcumin	Kiwifruit	Reduce weight loss, respiration rate, and microbial count, improve physiological characteristics	99
Carboxymethyl cellulose	Astragalus honey	Pistachio kernel	Improves physiological chemical and sensory properties, increases shelf life	100
Potato starch	Calcium gluconate salt	Papaya	Reduces moisture content, water activity, and colour loss	101
Pectin from cacao shell	Gallic acid	Tomato	Retains physiochemical properties	102
Modified starch	Gelatin, peppermint essential oils	Guava fruit	Extends the shelf life of guava fruits by 15 days	103
Sweet potato starch	Cumin essential oil	Zaosu pears	Preserves the sensory properties, shows high antioxidant activity	69
Pectin	Ascorbic acid, ethylene-diamine-tetra acetic acid (EDTA), glycerol	White button mushroom	Extends the shelf life and retains the quality parameters	104
Gum Arabic	Aqueous extracts of *Syzygium aqueum*, *Diploglottis bracteata*, and *Tasmannia lanceolata*	Fresh-cut capsicum	Reduces bacterial load and extends the shelf life	105
Guar gum and almond gum	Essential oils	Okra	Preserve the physicochemical characteristics, show antimicrobial activity against *A. niger*, *E. coli*, and *S. aureus*, and show antioxidant activity	106
Carnauba wax	—	Orange	Minimizes fruit decay and extends the shelf life of the fruits by up to 80 days	107
Pomegranate seed oil	Gelatin	Mexican lime	Delays the reduction in weight and increases the shelf life	108
Mentha and *piperita* L. essential oil	Glyceryl palmitostearate	Strawberry	Preserve the nutritional content and extend the shelf life of strawberries	109
Carboxymethyl cellulose	Glycerol and coffee ground extract	Golden berries	Inhibits microbial growth and increases antioxidant activity	71
Potato starch	Glycerol and glyceryl monostearate	'Fino' lemons	Reduces citrus sour rot, maintains the post-harvest quality, reduces weight loss and gas exchange; also, extends shelf life for up to 4 weeks	110
Apple pectin	Cellulose nanocrystals, glycerol, and essential oil of lemongrass	Strawberries	Reduces and minimizes weight loss	111
Hydroxyethyl cellulose	Sodium alginate and asparagus waste extraction	Strawberries	Shows antifungal activity against *Penicillium italicum*, delays colour change, reduces weight loss, and extends the shelf life	61
Carboxymethyl cellulose	*Morus alba* root extracts	Banana	Reduces the rate of changes in weight loss, texture,	112

Table 2 (*Contd.*)

Plant-based edible material	Additives	Food product	Effect on the product	Reference
			sucrose content, total chlorophyll content, and CO_2 evolution; also, delays the browning index	
Carboxymethyl cellulose (CMC)	Glycerol	Plum fruits	Enhances the shelf life, effective at maintaining firmness and titratable acidity	113
Cellulose from Brewer's spent grain	—	Strawberries	Gives better appearance and extends the shelf life	114
Aloe vera gel	Orange peel essential oils and glycerol	Button mushroom	Slows down the respiration rate, inhibits the browning index and moisture loss, gives better firmness, total phenolic content, antioxidant activity, and total flavonoid content, retards the microbial load, and extends the shelf life for up to 16 days	115

coatings are applied by dipping, spraying, or spreading the coating on the surface. To further enhance its stability and compactness, a cross-linking agent is typically incorporated. These cross-linked coatings provide significant advantages, including improved chemical and thermal stability, mechanical properties, and enhanced molecular migration. The deposition of an edible coating on mangoes by cross-linking is depicted in Fig. 11. This is an effective coating method for biopolymer materials derived from polysaccharides or proteins, with proteins being ideal due to their higher number of functional groups than polysaccharides.[95]

7 Food-packaging applications

The current global pollution situation has made society more aware of the pollution from plastic waste and the need to find sustainable alternatives to traditional plastic packaging. Over time, there has been increasing demand for safe, natural, and eco-friendly products, which has prompted efforts towards the development of safe preservation technologies for food for both human consumption and environmental considerations and that will not affect the sensory and nutritional characteristics of the foods. Green sources, like materials from plant sources, can improve the food coating quality and performance. In the coating, the use of plant-based extracts has become popular due to their availability, low cost, and ability to be used as an additive to improve polymer coatings.[96]

7.1 Fruits and vegetables

Post-harvest quality loss is a significant problem for fruits and vegetables, because they are living tissues and highly perishable. Such losses also depend on post-harvest handling and climatic conditions. There is thus a need to develop advanced technologies that can increase production, optimize distribution, and minimize quality loss, and extend the shelf life of produce.[22] After harvesting, the primary reason for the short shelf life of fruits is their high respiration rate, presence of microbial agents, and degradation of moisture; therefore, a biodegradable coating that includes antimicrobial agents, antioxidants, and anti-browning agents would be a good option to minimize moisture loss, slow the ripening rate, protect the produce from microbial invasion, and extend the shelf life.[97] For example, Sarkar and Grift studied aloe vera as a readily available option as a coating material that has activity against microorganisms, oxidation, moisture loss, and gas exchange, and that can also preserve the colour, firmness, and flavour of the produce, helping to extend the shelf life of fruits and vegetables.[98] Some plant-based coating materials and their effects on fruits and vegetables are listed in Table 2.

7.2 Meat, poultry, and seafood

Meat and fish are also perishable food items that can quickly decay if not handled and stored properly. Edible coatings and films are an excellent medium to preserve this type of food because they are made from biopolymers, such as polysaccharides, proteins, or lipids, that are edible and can serve as a medium for natural active agents. The coating extends the shelf life of food products by inhibiting the growth of microorganisms, decreasing moisture loss and purging accumulations, slowing the oxidation of lipids, proteins, and pigments, and increasing the time that the products remain sensibly acceptable.[116] Some plant-based coating materials and their effects on meat, poultry, and seafood foods are listed in Table 3 below. Nowadays, the demand for polymers based on plants and plants themselves for the development of novel edible coatings has increased because of their availability and low cost.

Table 3 Plant-based edible coatings for meat, poultry and seafood

Plant-based edible material	Additives	Food product studied	Effect on the product	Reference
Tomato plant extract	Chitosan	Pork stored at 4 °C	Reduces the microbial load, shows high antioxidant activity, and increases the shelf life by up to 21 days	117
Zataria multiflora Boiss. essential oil	Sodium caseinate	Veal meat stored at 4 °C	Reduces the microbial load, preserves the sensory and chemical characterization, and increases shelf life for two weeks	118
Basil (*Ocimum* spp.) extracts	Alginate	Beef	Show greater antioxidant activity, reduce the lipid oxidation of meat, decrease weight loss, and extend the shelf life	119
Fennel essential oil	Cinnamaldehyde nanoemulsion	Pork meat patties	Inhibits the growth of *E. coli*, *Staphylococcus aureus*, and other microbes like yeast and mould, maintains the moisture state, flavour, and texture, and extends shelf life for up to 10 days	120
Konjac glucomannan and camellia oil	Kappa-carrageenan	Chicken meat stored at 4 °C	Restrict the oxidation of lipids and protein, reduce microbial growth, and extend the shelf life for up to 10 days	121
Plantago major seed mucilage	Citrus limon essential oil	Buffalo meat	Reduces the progression of lipid oxidation and microbial growth, maintains the hardness and sensory properties, and extends shelf life for up to 10 days	122
Pomegranate peels	Gelatin and k-carrageenan	Fish fillets	Reduce the microbial count of aerobics, psychrotrophs, yeast, moulds, and Enterobacteriaceae groups, hinder the rate of increasing chemical parameters, and prolong the storage by up to 30 days	123
Lepidium sativum seed mucilage	*Heracleum lasiopetalum* essential oil	Fresh beef	Increases the physiochemical, oxidative, and microbiological activities, and extends shelf life for up to 9 days	124
Oregano essential oil	Chitosan	Chicken fillet	Decreases the microbial population and increases the shelf life by up to 12 days	125
Ocimum basilicum seed mucilage	*Mentha pulegium* essential oil	Veal stored at 4 °C	Increase the resistance of meat products against microorganisms and the oxidation of fat	126
Portulaca oleracea extract	Sturgeon gelatin	Fish sausage	Controls microbial growth, preserves the chemical properties and sensory acceptance, and extends the shelf life	127
Qodume shirazi seed mucilage	Lavender essential oil	Ostrich meat stored at 4 °C	Reduces the microbiological effect on the shelf life of meat and extends the shelf life for up to 9 days	128
Lepidium perfoliatum seed mucilage	Chicory essential oil	Beef slices stored at 4 °C	Has inhibitory effect on lipid oxidation, microbial growth,	129

Table 3 (*Contd.*)

Plant-based edible material	Additives	Food product studied	Effect on the product	Reference
			weight and texture loss, and extends the shelf life	
Flaxseed oil	Chitosan and green tea extract	Fresh beef	Delays lipid oxidation, reduces total viable count, decreases the change of colour of the beef, and maintains the hardness, adhesiveness, and springiness	130
Basil essential oil	Chitosan and beeswax	Eggs	Linalool present in basil essential oil shows bacteriostatic activity against *E. coli* and *S. aureus* and extends the shelf life	131
Malva sylvestris seed mucilage	*Cinnamomum zeylani* essential oil	Lamb meat slices	Inhibits the growth of microorganisms, preserves the pH value, moisture content, and hardness, activity, reduces the lipid oxidation of meat slices, and decreases the oxidation products	132
Lallemantia iberica seed mucilage	*Malva sylvestris* extract	Turkey meat	Delays oxidative deterioration and maintains the odour, colour, texture, and preference	133
Aloe vera gel	Aloe vera leaf skin extracts	Cooked ground chicken meat stored at 4 °C	Inhibits lipid oxidation, maintains the quality characteristics, and extends the shelf life for up to 14 days	134
Malva sylvestris mucilage	Postbiotics (PSB) from *Saccharomyces cerevisiae* var. Boulardii	Lamb meat	Displays antibacterial activity, maintains the pH value, moisture content, hardness of meat, and sensory characteristics, inhibits lipid oxidation, and decreases the production of oxidation intermediates; also, extends the shelf life for up to 14 days	135
Rice protein concentrate	Brazilian green propolis	Eggs	Avoids moisture loss through the pores of the shell, maintains the internal quality, and extends the shelf life for 6 weeks	136
Shahribalangu seed mucilage	Cumin essential oil	Beef slice	Reduces the microbial load and lipid oxidation, and extends the shelf life for up to 9 days	137
Cinnamon essential oil nanocapsules	Sodium alginate and nisin	Beef slices	Reduce the microbial growth, lipid oxidation, and water loss, improve the colour, texture, odour, purge quality, and extends the shelf life for up to 15 days	138

For example, Khojah studied the effect of pomegranate peel extract in an edible coating based on careen-green and gelatin because it is rich in phenolics and tannins that enable it to show antioxidant activity and antimicrobial activity against aerobics, psychrotrophs, yeast, molds, and Enterobacteriaceae groups and also because it is easily available as fruit waste.[123]

Table 4 Plant-based edible coating for dairy products

Plant-based edible material	Additives	Food product studied	Effect on the product	Reference
Cinnamon bark CO_2 extract	Glycerol and whey protein concentrate	Eastern European curd cheese	Coating affects the appearance and colour by preserving moisture, inhibiting the growth of yeasts and moulds, and extending the shelf life of both package-free and packaged cheese	139
Carboxymethyl cellulose	Chitosan and sodium alginate	UF soft cheese	Shows high antimicrobial activity and extends the shelf life for 45 days	140
Carboxymethyl cellulose	Natamycin	Mozzarella cheese stored at 7 °C	Shows inhibitory effects on *Aspergillus flavus*, *A. fumigatus*, *A. niger*, *Penicillium citrinum*, and *Candida albicans* and yeast and mould, and doubles the shelf life	141
Galactomannan from *Caesalpinia pulcherrima*	*Cymbopogon citratus* essential oil	Coalho cheese	Microbial reduction, physicochemical stability, and sensory characteristics within the acceptance zone, and extends the shelf life for up to 30 days	142
Pectin extracted from banana peel	Starch and glycerol	Mozzarella cheese	Highly antioxidant shows antimicrobial activity against *Staphylococcus aureus* and extends the shelf life for up to 21 days	143
Cumin essential oil	Whey protein concentrate and glycerol	Iranian white cheese	Maintains the moisture content, decreases the counts of *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, yeast, and mould, and extends the shelf life from 10 to 28 days	144

7.3 Plant-based edible coatings for dairy products

In dairy products, the two most frequent contaminants are yeast and moulds, which may result in both odour and taste complications as well as visible defects. Edible coatings and films are thin layers that are applied manually by dipping, spraying, or wrapping, and they may contain antioxidant and antimicrobial agents. Some plant-based coating materials for diabetes and their effects are listed in Table 4. To provide safe and wholesome dairy products to consumers, dairy businesses should find a creative way to increase the quality and safety of their dairy products.[139]

8 Challenges

Food items can be improved in terms of quality, safety, and appeal by using edible coatings and films. Even though this novel technology has many potential benefits, there are still some obstacles that currently prevent it from being commercially viable. More research and analysis are necessary to overcome these obstacles. Because the polymeric materials used in such coatings and films come from sustainable and natural sources, they frequently have an unappealing flavour and colour that can make the food product unpleasant. Further, compounds derived from natural sources are often costly to isolate and exhibit batch-to-batch quality fluctuations that inhibit their commercialization. While an even thickness can be achieved with conventional coating application procedures, which can be managed with sophisticated technology, it generally requires more natural active compounds than conventional synthetic ones. The additional cost of a few of the processing technologies, such as the spraying method for edible coatings, may not be justifiable for some foods. The next challenge is to develop systems based on essential oils derived from plant sources for edible coatings and to study these as sources of antimicrobials and antioxidants. Consumers would increasingly prefer natural additives over synthetic and chemical additives because they are aware of the adverse effects of conventional additives. Essential oils are very effective against various microbial spoilage, but there is a need for more studies on their impact on sensory food profiles, as other than their positive effects, essential oils have some negative impacts on sensory properties. Also, when essential oils are used in greater quantities, they show toxic effects, high volatility, and low solubility in water.[145]

The other challenge for plant-based edible coatings is the selection of appropriate polymer and coating methods. Edible coatings obtained by a single edible polymer may be insufficient because of the requirement for active agents and the functions they can provide. There is thus a need to prepare composite coatings that are created using a variety of polymers and techniques; yet nearly all of these have some drawbacks at present. More work is still needed on the compatibility of polymers, like whether they work well together, how they interact with other ingredients like plasticizers and emulsifiers, and whether or not they can enhance the quality and shelf life of the food item. For composite coating films, the choice of the appropriate coating is another difficult consideration. For tomatoes, the typically used coating method is the dipping method, but it does not guarantee a consistent coating thickness across the whole surface of the tomato. There is thus a need for further investigation of feasible, innovative coating techniques that could address the drawback of the widely used coating techniques, together with offering economic viability with the food material to be coated.[146]

A major challenge with plant-based coatings is consumer acceptance. Consumers are concerned about the coating material type, the coating material's safety, the sensory characteristics of the finished food products, the shelf life of food products, and the price of packaged food items. "Freshness," "texture," and "nutritive value" are important parameters considered by consumers at the time of purchasing.[147] In a study, Bucher found that edible coatings were removed from apples due to consumer demands, and suggested that Australian customers rejected the coated apples because they lacked an understanding of the food coating and its benefits. Therefore, combining information about the food product and its coating on the label, together with the coating ingredients, may reduce the risk perception and thus consumer acceptance.

9 Conclusion

The field of plant-based edible films and coatings shows promise for sustainable food packaging. Recent advances in materials science have enabled the development of eco-friendly alternatives to traditional packaging. A variety of plant-derived materials have been explored, highlighting their versatility and potential to enhance food quality and safety. These innovative packaging solutions have diverse benefits, including barrier properties, antimicrobial activity, and flavour retention. Edible coatings and films can enhance food quality, safety, and appeal, but many still face challenges that need to be overcome, such as unappealing flavours and colours from their natural sources. Also, issues with achieving a suitable coating thickness, which needs to be addressed with advanced technology. Plant-derived essential oils are popular for their antimicrobial and antioxidant properties, although excessive use should be avoided due to potential issues with their toxicity level, volatility, and low solubility in water. Selecting the right polymer and coating methods for plant-based coatings is challenging. More research is needed to improve the techniques and ensure consistent results for smooth-surfaced fruits. Consumers are concerned about the type and safety of the coating material, sensory characteristics, shelf life, and price of food products. Providing clear information about the coating and its ingredients on the label may improve consumer acceptance. Future research should focus on optimizing the material properties, processing techniques, and scalability for widespread adoption. Collaboration between academia, industry, and policymakers is essential to address current challenges, such as cost-effectiveness, regulatory compliance, and consumer acceptance. "By utilizing collective expertise and resources, we can accelerate the shift to sustainable food packaging with plant-based films and coatings, paving the way for a healthier, greener, and more resilient food system."

Data availability

All data generated or analysed during this study are included in this published article.

Author contributions

Divyanshu Gupta: manuscript writing- original draft, visualization, data curation, formatting, graphics. Arshiya Lall: manuscript writing- original draft, visualization, data curation. Sachin Kumar manuscript writing, tables. Tejaswini Dhanaji Patil: manuscript writing- original draft, formatting, revision of manuscript. Kirtiraj K. Gaikwad: conceptualization, manuscript editing and review, supervision, project administration, funding acquisition.

Conflicts of interest

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

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