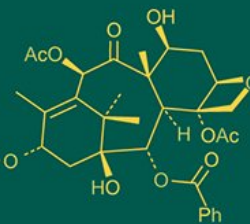
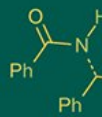


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1166-1176
www.biochemjournal.com
Received: 06-05-2026
Accepted: 08-06-2026

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Edible films and coatings: A sustainable approach to food packaging

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sn.8790>

Abstract

As food sector searches for environmentally friendly and sustainable substitutes for plastic packaging, interest in edible films and edible coatings is growing. These substances created from natural biopolymers including polysaccharides, lipids and proteins offer not only biodegradability but also functional benefits such as improved moisture control, oxygen regulation, and protection against microbial spoilage. Films made from proteins, particularly those derived from whey protein, these are recognized for their robust and strong structural properties, flexibility and valuable oxygen barrier performance. Polysaccharides and lipids enhance strength, transparency, compatibility with bioactive compounds and excellent water vapor resistance. Many researches shows that composite systems-combining two or more biopolymers can overcome the limitations of individual materials and provide more balanced, adaptable packaging solutions. As concerns about plastic waste, carbon emissions and food safety grow, edible films offer a promising approach that combines sustainability with technological utility.

Keywords: Renewable, Bio-polymer, Novel materials, Retention and Mechanical

1. Introduction

Food packaging ensures safety during processing, storage and distribution so that it maintains its physical, taste and sensory quality until it reaches the consumer. Food packaging has dominated the global market for decades due to its versatility. However, about 70% of the food used worldwide is petroleum, most of which are non-biodegradable and contain limited petroleum resources (Regaldo *et al.*, 2006) ^[70]. Their slow decomposition, accumulation in landfills and release of harmful gases like sulfur and nitrous oxide during incineration further increase environmental concerns (Hammam, 2019) ^[71]. These issues, coupled with awareness about climate impacts, are driving the search for healthier, renewable and sustainable alternatives to food packaging. Edible films are made of natural polymers that consists lipids and polysaccharides derived from plants, animals or marine organisms (Mohammad, 2020) ^[72]. These materials offer unique advantages such as biodegradability, renewable and in many cases, biodegradability. Edible films are not new, acting as selective barriers against moisture, gases and solute transfer, taste retention, food palatability, etc. Edible films are not new, proteins of fresh fruits and vegetables have been shown to be a good alternative to waxes due to their superior flexibility, viscosity and gas barrier properties. Among edible biopolymers, proteins have shown promise due to their varied amino acid compositions, ability to form intermolecular bonds and good gas barrier capabilities. Protein-based films can be produced from various sources including wheat gluten, wheat protein, casein, gelatin and other types of proteins have been shown to improve their structural strength, nutritional properties, and antimicrobial properties (Hammam, 2019) ^[71]. Hydrophilicity can reduce their vapor permeability. Researchers have developed chemical, enzymatic, and physical modification strategies to improve mechanical barrier performance (Nemati *et al.*, 2023 and Schmid *et al.*, 2023) ^[41]

Among protein sources, whey protein, a by-product of core production, has received increasing attention due to its excellent nutritional properties and its ability to enhance emulsification, gelation, and water-repellent capacity (Rocca-Smith, 2016) [48]. WPC (WPI) is converted to WPC, which is primarily composed of amines. (Parreidt, 2019 and Linden *et al.*, 2019) [33, 43]. This makes it ideal for products sensitive to oxidative spoilage. It can be stored and shelf-stable (Ramos *et al.*, 2012) [46]. Polysaccharides are another important type of food material. Plant-based polymers like zinc, pecan, cellulose, and gum arabic have been used for non-toxicity, transparency, and durability (Saklani *et al.*, 2019) [51]. Marine-based polysaccharides have additional functional properties such as gel formation and good cell integrity (Cazon *et al.*, 2017). Because polysaccharides are hard, their water resistance is often limited by lipid or wax coatings.

On the other hand, lipids are hydrophobic due to their hydrophobic properties. Because of this they provide an excellent moisture barrier. Edible waxes, resins and oils

provide a strong barrier to water vapor and generally improve performance (Cheng, 2021) [14]. Wax coatings may help delay aging (Aguirre-Joya, 2016) [3]. Edible films today use structures combining polysaccharides, proteins and lipids (Janjarasskul and Krochta, 2010) [26]. Multi-gelatin films, such as zinc-gelatin films, also inhibit microbial growth.

2. Classification of edible films and coatings

Edible films and coatings are used to lessen the environmental impact of traditional non-biodegradable packaging. Edible materials possessing potential to form films can be used to create edible films. Edible coating can be produced by directly adding coating solution to the food products's surface whereas, edible films are created by wrapping solid edible laminate around the food product. On the basis of material used for preparation for simple films and composite films are the two categories of edible films and coatings. (Fig.1).

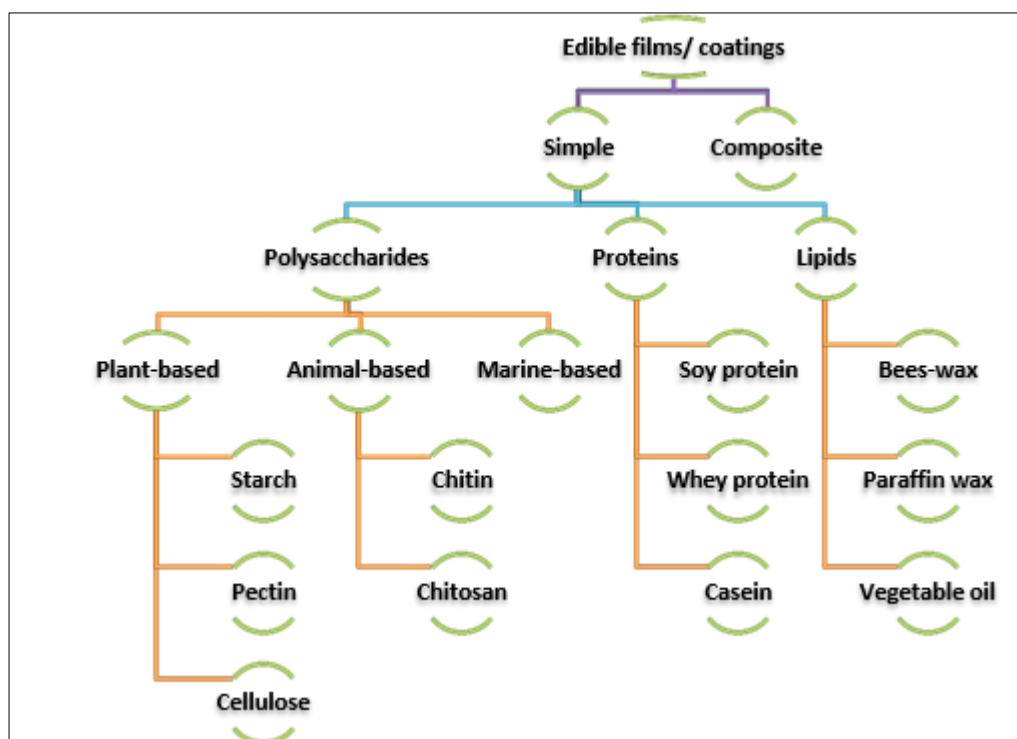


Fig 1: Classification of Edible/films on the basis of material used

3. Simple films/coatings

Films consists single material or phase, which results into specific properties inherent to that material alone. It can be further divided mainly into polysaccharides, protein and lipid (Fig.1) that can generate sustained coatings and films (Saklani *et al.*, 2019) [51].

a) Polysaccharides

Polysaccharides may originates from plant, animal or from marine sources. Plant-based polysaccharides includes starch, pectin and cellulose whereas marine-based includes carrageenan, alginate and agar and animal based derivatives are chitin and chitosan (Han JH, 2014) [21]. Polysaccharides are abundant in nature and generally non-toxic, reusable and because of their hydrophilicity, it can because of their hydrophilic nature, it can produce edible coatings with good mechanical properties to maintain the food's strength, flavor,

and shelf life. (Cazon *et al.*, 2017). Due to hydrophilicity, packaging may degrade under highly humid conditions. Addition of lipophilic substances like oils and waxes can reduced hydrophilicity (Kumar, *et al.*, 2022) [32].

i. Plant-based polysaccharides

- **Starch:** Starch is commonly found in grains such as corn and wheat, and its properties enable it to create films favours oxygen and fat barrier properties, making it useful for food packaging. It is mainly made up of two main components: amylose and amylopectin. For example, in potato packaging, using starch films can maintain quality and act as a barrier for oxidation after frying (Pelissari, 2019) [44], while corn starch is utilized for egg packaging to reduce moisture loss (Peterson,1999) [45]. Starch exists as granules and is hydrophilic, swell when contact with water to create a

gel-like consistency. It is a polymer of anhydroglucose units and varies in composition, with corn starch containing about 25% amylose and 75% amylopectin. Certain corn mutants can contain up to 85% amylose, which is beneficial for film production (Rodriguez *et al.*, 2006) [49].

- **Pectin:** Citrus and apple fruits contain pectin that is an ionic polysaccharide. Cross-linking with calcium ions can improve mechanical characteristics. Pectin polysaccharide films or coatings can be used to pack foods with low moisture content, including walnuts and chestnuts. Nuts contain high oil content and pectin act as an oxygen and lipid barrier.
- **Cellulose:** Cellulose is one of the most abundant biopolymer on Earth. D-glucose monomers polymerize with one another in a 1-4 linkage via glycosidic bond. Some cellulose derivatives, such as carboxymethylcellulose, hydroxypropyl and methylcellulose create less efficient edible films and require combination with fats for effectiveness (Hammam, 2019) [71].

In its natural crystalline form, cellulose has a compact structure that resists solubility in water. Through alkali treatment and reactions with compounds like chloroacetic acid, cellulose can be transformed into derivatives such as carboxymethyl cellulose, methyl cellulose, hydroxypropyl cellulose and hydroxypropyl cellulose. These derivatives exhibit beneficial characteristics, including good film-forming ability, being odorless and tasteless, as well as flexible and moderately strong. MC is noted for its low water solubility and hydrophobic nature. The article emphasizes the applications of MC and HPMC in creating thermally induced gelatinous coatings, which can minimize oil absorption in fried foods and act as barriers in confections. Additionally, research on composite films made from MC or HPMC mixed with materials like beeswax shows properties similar to low-density polyethylene like water vapor permeability (Bourtoom, 2008) [8].

ii. Animal-based polysaccharides

Chitin and chitosan are examples of biopolymers derived from animals. Chitin is second most abundant naturally occurring biopolymer and can be obtained from fungal exoskeleton. By deacetylating of chitin with alkali produces chitosan polysaccharide. Chitosan is made up of (β-(1-4)-2-acetamide-D-glucose and (β-(1-4)-2-acetamido-D-glucose and a cationic polysaccharide with good film-forming properties (Kadam *et al.*, 2021) [29]. Chitosan can be utilized as an antibacterial agent in other film-forming biopolymers due to its antimicrobial and antifungal qualities (Cazón *et al.*, 2017) [11]. Products of chitosan are very sticky similar to gum and their films exhibit cohesive characteristics providing resistance against gas and fat permeation (Alves, 2018) [5].

iii. Marine based polysaccharides

Because of their mechanical qualities and preservation capabilities, agar, which is derived from red algae combined with carrageenans from seaweed, can be used in edible films for meat, poultry, and fish, while alginates generated from brown marine algae have less water barrier properties (Cazón *et al.*, 2017) [11]. On the other hand, certain bacterial strains create pullulan, gellan and xanthan which are

microbial-based polysaccharides. Food products shelf life is extended by these coatings and packaging materials (Mohamed *et al.*, 2020) [72].

b) Proteins

Proteins are essential natural polymers made up of amino acids creating edible films. There are two types of natural proteins: globular proteins such as collagen protein having highly folded spherical shapes and fibrous protein like whey protein, soy protein and zein maize which aligned with the polypeptide chain. These proteins have shown excellent film and coating forming properties. Antioxidant agents and antimicrobial agents are also present in protein-based edible films (Saklanis *et al.*, 2019) [51]. Protein-based films to moderate water barriers and lose their integrity when exposed to high humidity because of their hydrophilicity nature. They provide excellent barrier against hydrophobic compounds like aroma and oil. Additionally, whey protein films shown comparatively better oxygen gas barrier properties than caseinate films (Mohamed *et al.*, 2020) [72].

c) Lipids

Many fatty compounds including plant fats, animal fats and waxes have been utilized for creating edible films. Lipids have attractive appearance and hydrophobicity properties. In fresh foods such as fruits and vegetables, waxes incorporated in the starch-based film to prevent the water permeability from the foods (Yoursuf, 2018) [68]. They have a semi-solid structure and a yellow to brown color. The tomatoes and green chilies have been covered with a resin-based substances to provide oxygen and water barrier with transparency and glossiness (Cheng *et al.* 2021) [14].

Many fruits coated with a variety of oils, such as soybean oil, cottonseed oil, corn oil, palm oil and olive oil are used to coat many fruits because they exhibit good water vapor holding to their low polarity which extends the shelf-life (Yoursuf, 2018) [68]. They are hydrophobic and volatile. An essential oil has antibacterial characteristics. Thyme, clove, and lemon peel essential oils are added to the biological polymer matrix to improve the antimicrobial qualities of the packaging materials (Hassan *et al.* 2018) [22]. By lowering intermolecular forces, plasticizers improve the flexibility of polymer matrices and increase the permeability of water and oxygen. Emulsifiers mitigate phase separation in lipids and hydrocolloids used in edible packaging by reducing surface tension between hydrophilic and lipophilic compounds. Emulsifiers, which are made from phospholipids produced from plants and animals, also reduce the separation between their phases. (Liu *et al.* 2020) [35].

3. Composite films

These films derived from proteins or polysaccharides having appropriate mechanical properties suitable for edible packaging. But, these films are permeable to moisture. Incorporation of lipids in composite films can overcome this limitation and improve packaging properties. To overcome this limitation and to improve packaging properties, addition of lipids in the composite films improve barrier properties against water vapor and oxygen.

An effective technique for fabricating composite films is the bilayer method, where one layer is hydrocolloid-based and the other is composed of lipid. Therefore, the solubility and

permeability of films to water vapor are decreased when fats and proteins are combined (Kim, 2001) ^[30]. When two or more compounds were combined, the tensile strength of the films made from WPC, kappa carrageen, and gum increased from 4.67 MPa to 23.89 MPa are employed in comparison to films made from a single compound, while for the composite films, elongation increased from 0.16% to 3.03% (Villagómez-Zavala, 2008) ^[64].

4. Novel materials

Innovative sources for advanced edible films and edible coating materials are currently being explored and developed. It includes sources such as whole grain flours like amaranth, quinoa and chia, as well as legume flours like lentil and chickpea and starches from root plants such as yam, achira, canna, ulluco and water chestnut are gaining attention. Fruits and vegetables by-products and residues like orange, passion fruit, watermelon, lettuce and potato peels demonstrate promising capabilities for forming films and providing protection, contributing to more sustainable packaging solutions.

Moreover, researchers are harnessing plant gums, particularly gum arabic, almond gum, and gums sourced from various wild plants and seeds including *Opuntia cactus*, *Pereskia* leaves, *Shirazi balangu* seed mucilage, and seaweed extracts. Combination of these novel materials with polysaccharides, proteins and fibers, create as biodegradable, flexible coatings that are capable of prolonging food shelf life while preserving sensory and nutritional quality.

5. Methods of preparation of edible films and coatings

5.1. Techniques for making edible films

Edible films serve as the main edible packaging by being directly put to the food's surface. The ability of additives to dissolve in biopolymers is essential because it affects how the biopolymers adhere to one another and alters the film's overall mechanical characteristics. There are two basic methods for producing edible films: Hot melt extrusion (dry method) and solvent casting (wet method).

a) Wet method (Solvent Casting)

One commonly used cost-effective film preparation method is solvent casting. This method comprises of four steps: solubilization, heat treatment, casting and drying (Ak K, 2022) ^[4].

In initial stage, while solubilization dissolving of biopolymers in edible and non- poisonous solvents such as ethyl alcohol and water is done (Velega, 2018; Kumar, 2022) ^[32, 63]. In second step i.e., homogenization of mixture, where pouring of casting solution on the predefined mold to make an edible film with the required shape. In third step, to desiccate the film, the solvent is allowed to evaporate. The evaporation process protects the edible layer from structural damage and severe desiccation occurs in the controlled oven environment, where are maintained below 60 °C. The last step involves dehydration of the casted solution where, after additional drying, the cast film's solvent evaporates, causing polysaccharides to form a gel-like structure. After the

drying, film can be delaminated and utilized (Kumar, 2022) ^[32].

It is essential to allow the drying process to extend between 12 to 24 h to optimize solvent evaporation increased functional performance may result from the introduction of edible coatings with improved mechanical and structural qualities enhances functional performance; a rapid drying period at elevated temperatures may not yield films with superior properties (Polnaya, Tharanathan).

Advantages

- Polymers dissolve uniformly in a solvent gives precise control over film microstructure, thickness and incorporation of bioactives.
- It is ideal for heat-sensitive biopolymers (low temperature).

Disadvantages

- This methods requires long drying time as well as high energy demand
- Solvent residue & environmental concerns

b) Dry Formation (Hot melt extrusion method)

Since there is no liquid component in the hot melt extrusion method, very little amounts of substances other than the main component must be present (Britti, 2017). This dry extrusion process eliminates the waiting time associated with solvent evaporation, effectively reducing the drying phase.

There are three primary zones in an extruder. The extruder is fed biopolymer and additives in the first zone. The kneading zone comes in second, where an extruder screw blend the ingredients. Finally, the heating zone applies heat with the help of the oven facilitate melting and mixing of biopolymer with any additives. The shape and thickness of the extruded film are determined by a die that is positioned at the end of the extruder.

High temperatures play an important role in altering biopolymer's structure and enhancing the film's overall properties. To accelerate the compaction process, a plasticizer is usually used in this step. The heat treatment starts at temperatures between 75 and 100 °C and continues for the defined period of time (Chevalier, 2018) ^[15]. At high temperature extrusion of temperature sensitive is difficult (Suhag *et al.*, 2020; Cheng *et al.*, 2021) ^[14, 59].

5.2. Advantages

- It offers high throughput, energy-efficient, and compatible with existing plastic-processing machinery, allows mass production
- It produces strong and cohesive films

Disadvantages

- High temperature (80-160 °C) may cause: protein denaturation, loss of bioactive compounds
- Additives volatilize at high temperature residue & environmental concerns

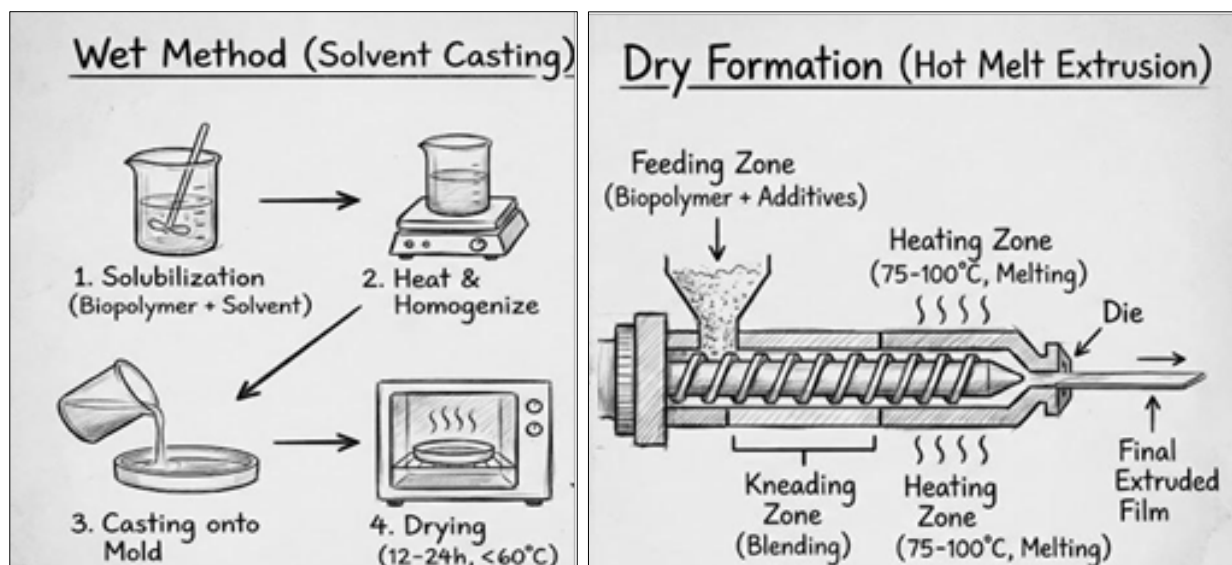


Fig 2: Different methods of preparation of edible films and coatings

5.3. Edible coating method

Edible coating serve as basic form of edible packaging that is applied directly on the surface of fruits, vegetables and other food products. After harvesting, fruits and vegetables experience solutes loss due to biological activity processes leads to weight loss, color and structural changes that are easily damaged by the use of cold storage. To assist postpone ripening processes such respiration rate, softening, color changes, and ethylene generation weight loss and to enhance antifungal activity, various measures are necessary (L. Saidi, 2021) ^[50].

Dipping, spraying, fluidized bed, and panning are the four primary coating methods. A number of elements, such as the food product's surface characteristics and the coating layer's intended purpose, influence the choice of coating technique. The materials initially diffuse on the food's surface during the coating process, and then the coating material adheres to the food's surface (Cerqueira *et al.*, 2017) ^[12].

a) Dipping method

The technique involve submerging the particle of food into a container filled with solution of coating. This technique is particularly helpful for foods that need a full coating (nutritional, antioxidant, antimicrobial, etc.) and those with complex or rough surface like fruits and vegetables. After dipping the food is dipped and removing the excess coating, it is air dried at room temperature or using a special dryer. The procedure can be divided into three stages:

- The food product is fully submerged in the coating solution
- the application of a coating on the food product's surface
- The coating's solvent evaporates, leaving the product's surface with a thin covering

Various Broccoli, star fruit, salmon, persimmons, and walnuts have all been dyed. (Vika Andriani, 2023) and strawberries (Guerreiro *et al.* 2015). Applying dipping method, coating of chitosan is applied on the salmon fish

(frozen) that stops the growth of harmful microorganisms and enhance the fish's storage life (Soares *et al.*, 2016) ^[58]. Firmness of fresh-cut mangoes can be enhanced by coating with alginate and malic acid which reduces the quality during storage (Salinas-Roca *et al.* 2016) ^[53].

b) Spraying Coatings Method

Spraying coatings of the solutions can be used to make a consistent layer on fruit and vegetable surfaces, enabling coatings with a particular composition, thickness, and purpose. Liquid sprayed transforms the liquid solution into small droplets that increase the liquid solution's surface area for the same volume (G. Hernández-López, 2020) ^[23]. Depending on the formation of the small droplets, the method is classified into air spray atomization (high-speed air converts the liquid into the droplets) and pressure atomization which utilizes high pressure.

c) Panning method

This technique works well for covering food and sweets. A large circular vessel called a pan is rotated, and a variety of oval or round food items can be coated simultaneously within it. The coating solution is sprayed onto the surface of the food items while the pan continues to rotate. Thickness of final coating on the food is determined by the amount of solution applied. Air circulation aids in solvent evaporation, causing the coating to dry (Campos *et al.*, 2010) ^[10].

d) Fluidized bed processing method

This method enables application of a thin layer of coating on the surface of dry foods like almonds or wheat. The coating atomized through nozzles, allowing smaller food particles to be covered with the applied solution for coating and after that drying is performed. Compared to other approaches, this one is more costly (Chawala *et al.*, 2021). However, this procedure reduces the likelihood of agglomeration and aids in lowering the rate at which active chemicals are released. (Lipin and Lipin 2021) ^[34].

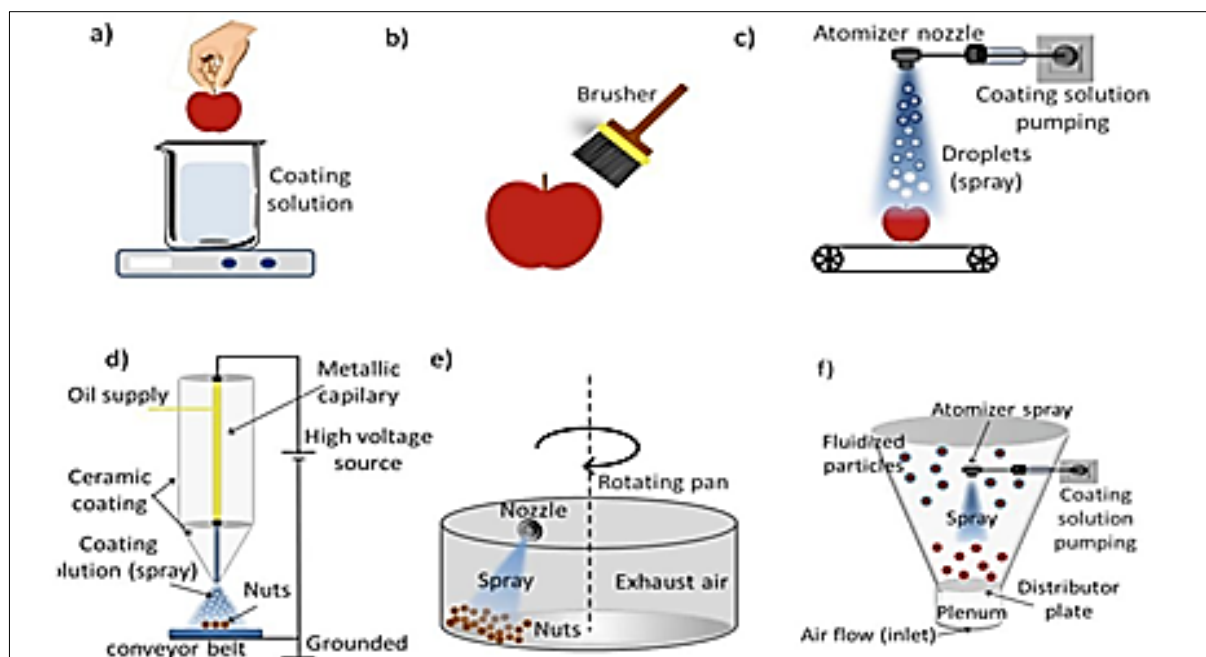


Fig 3: Different methods of edible coating application a) Dipping; b) Brushing; c) Spray Coating, d) Electrospray-method; e) Panning Method; f) Fluidized-bed

6. Applications in food

Edible films and coatings are biodegradable and sustainable. Eco-friendly packaging is in greater demand due to environmental issues. They can be used for all food materials including fresh produces, dairy products, meat and poultry products. When compared to traditional plastic packaging, edible packaging provides a selective barrier against oxygen and water, extending the shelf life of food items (Cerqueira *et al.*, 2017) ^[12].

i. Fruits and vegetables

Post-harvest losses occur in fruits and vegetables due to biological activity. Key factors responsible for these losses and quality deterioration are respiration, ethylene production, microbial growth and moisture loss (Kumar *et al.*, 2021c) ^[31]. For food sector, assuring the quality of minimally processed or cut fruits and vegetables are essential. Fruits and vegetables degrade at temperatures below 12 °C, therefore cold storage alone is insufficient to keep their quality at ideal levels during marketing (Andriani,

V., 2023). Therefore, it is necessary to implement efficient renewal techniques, such as edible coatings, to maintain low production losses and increase postharvest life (Table 1). The weight of the food product and aids in lowering the respiration rate of fresh produce.

ii. Meat, poultry and seafood

Due to high amount of moisture content, meat, poultry and seafood are more perishable. Edible films and coatings create a protective barrier to them. Variety of edible biopolymers are used to coat meat products, which help to inhibit shrinkage, control microbial growth, and reduces discoloration, along with minimizing oxidative off-flavors (Gaikwad *et al.* 2020) ^[18]. The best meat categorized into red meat and white meat. Beef, pork, lamb, and goat are examples of red meat, whereas chicken, duck, turkey, and rabbit are examples of white meat. High-grade flesh products exhibit superior quality attributes, including high UV resistance, texture, color, taste, and nutritional value (A.A.F. Fallah, 2022; R. Zhao, 2022) ^[17, 69].

Table 1: Application of coating for fruits/vegetables

S.no.	Fruits/vegetables	Materials	Result	References
1.	Apple	Zein- based formulations incorporated with beeswax(compared with conventional petroleum wax)	Application of water-soluble zein coatings demonstrated significant anti-microbial activity. Specially, it accelerated the reduction of <i>L. monocytogenes</i> populations on fresh produce surfaces	Oliveira, G.M., 2021 ^[42]
2.	Litchi (<i>Litchi chinensis</i>)	Composite coating of Chitosan, pomelo extract and citric acid	Formulation inhibited fungal growth and extended the fruits's post-harvest longevity while maintaining original sensory attributes	C. Yang, 2023 ^[67]
3.	Tomatoes	Whey protein isolate, Glycerol monostearate, Clove oil, Xanthan gum	Biodegradable coating functioned as a barrier to respiration, effectively delaying the metabolic conversion of starch into sugar and reducing physiological degradation	Kumar, A., 2021 ^[31]
4.	Peeled garlic	Zein, whey protein, glycerol	Coating utilizing milk proteins and zein provided a protective barrier that prolonged the storage life of peeled cloves to 10-15 days when stored at 15 °C	Torun, M., 2021 ^[62]
5.	Green banana	Silk fibroin (SF) enriched with curcumin	Coating enhances the effective shelf-life (up to 8-9days) by maintaining weight and retaining firmness. Edible coating also provided added nutritional value.	Singh, D.P., 2022

Table 2: Application of coating for meat products

S.no.	Meat Products	Materials	Result	References
1.	Ready-to-eat Carbonado chicken	Gelatin, Chitosan, Rosemary extract, e-poly-L-lysine (e-PL), Essential oils	Shows increased safety and quality of ready-to-eat chicken carbonated products extends for six days, antimicrobial and antioxidant	Huang, M., 2020 ^[24]
2.	Salmon Fillets	Fish bone gelatin, Clove oil, Gallic acid, Chitosan	It provides antioxidant and antimicrobial protection. Result states improvement in fillet quality and prolonged storage viability	Xiong, Y., 2021 ^[65]
3.	Pork	Pectin-based nanoemulsions enriched with oregano essential oil and resveratrol	Coating founds highly effective in stabilizing pork at 4 °C for 1 week. It acted by retarding and protein oxidation, preventing discoloration and maintaining meat tenderness. Smaller particle size of the nano-emulsion contributed to superior preservative stability	Xiong, Y., 2023 ^[66]
4.	Rabbit meat	Chitosan and rosemary essential oil	Application of this coating helped maintain the physicochemical integrity of the meat during cold storage, specifically reducing the quality deterioration typically caused by refrigeration	Mahmoud, A.F.A., 2023

iii. Dairy products

A daily diet must include dairy products including cheese, yogurt, and milk. Cheese is high in proteins, vitamins and lipids. Edible coatings and films over dairy products regulate ripening, lessen mass transfer, and increase shelf life. When compared to polysaccharides and other protein-based films, whey protein-based edible films have better gas barrier properties (Leandro *et al*). The film-forming capability of whey protein can be improved through heat treatment, which allows its structure to open up, promoting

more inter- and intra-molecular bonding. Additives such as plasticizer glycerol and pH adjustment agents combine with whey protein. Film-forming solution is made with a solvent. The film-forming solution is made with a solvent. After the films have been dried for eighteen hours at around 35 °C in a hot oven, cheese slices can be sandwiched between them. Additionally, the consumer can observe the quality of the cheese since whey protein-based films are transparent (Costa *et al*). Antimicrobial substances are added to the whey protein matrix.

Table 3: Application of coating for dairy products

S.no.	Dairy Products	Materials	Result	References
1.	Soft/white cheeses (e.g., Iranian white cheese, brined cheeses)	Whey-protein concentrate (WPC) (WPC + EO on Iranian white cheese)	Reduced surface microbial counts, delayed growth of spoilage organisms, maintained prolonged shelf life	Nemati <i>et al.</i> , 2023 ^[41]
2.	Fresh/soft cheese (home-made, natural cheeses)	Sodium alginate- based edible film	Acted as a moisture/gas barrier, reduced weight loss and surface spoilage, improved visual appearance	Mahcene <i>et al.</i> , 2020 ^[37]
3.	Paneer (Indian cottage cheese, high moisture)	Chitosan-based films & chitosan + essential oil (e.g., oregano)	Lower total plate counts and yeast/mould counts during storage, reduced moisture loss	Asif Ali T S, 2025 ^[6]
4.	Yogurt (cup surface, stirred yogurt)	Protein or polysaccharide coatings as carriers of probiotics/antioxidant s	Enhance functional value and help control surface syneresis	Salama <i>et al.</i> 2022 ^[52]

7. Mechanical properties

Improving the mechanical qualities of films, which depend on their structural cohesiveness, is crucial to ensuring the mechanical safety of food during manufacture and transit (Adedeji, 2009) ^[2]. The polymers' ability to form multiple molecular interactions between polymer chains determines the films' uniformity and durability (Gontard, 1994) ^[20]. Protein-to-protein interactions within polymer sequences are used in mechanical measurements of edible films to reveal important details about the mechanical film's characteristics, like tensile strength. The strength and elasticity of polymers differ and are influenced by factors such as molecular weight, polarization, and bonding strength (Javanmard M., 2009) ^[27].

8. Features of edible film retention

Application of edible films with suitable properties is required in a large number of food applications (Regalado, 2006) ^[47]. Gas retention, water and lipid permeability and

odor all have a major impact on how effective these films are. These factors are dependent on the chemical composition, polymer structure, product attributes, and storage circumstances (Skurtys, 2014) ^[57]. Films made from lipids demonstrate excellent moisture retention and high oxygen permeability, whereas films composed of polysaccharides and proteins exhibit lower moisture retention, particularly in high humidity, alongside superior gas barrier capabilities and favorable transparency and shine (Jooyandeh, 2011) ^[11].

Mechanism of movement of molecules through the film done by 3 steps:

1. Adsorption
2. Diffusion
3. Desorption

Addition of food additives such as food antioxidants, plasticizers etc improves functional properties and retention properties of film.

Table 4: Addition of food additives in edible films

S.no.	Films Material	Additive Used	Result	References
1.	Whey Protein	Ascorbic acid	Oxygen retention increased	Murillo-Martínez, 2013 [39]
2.	Whey Protein	Glucose oxidase and Nisin	Water vapor permeability at pH 5 is effective against gram-positive and gram-negative microorganisms. Lowered as a result of more molecules becoming cross-linked	Azeredo, 2009 [7]
3.	Banana puree	0.2% chitosan nanoparticles	Water vapor's permeability reduced as molecules became more cross-linked	Martelli MR, 2013 [38]

8. Active edible films and coatings

8.1. Antimicrobial activities

Food spoiling can be caused by a variety of bacteria and yeast, which poses a financial challenge to the food supply chain. Microbial contamination causes about 25% of food to be destroyed. This decay is strongly influenced by parameters include food pH, moisture content, oxygen availability and temperature. (Chawla *et al.* 2021) [13].

Antimicrobial packaging, which includes antimicrobial agents into the biopolymer matrix of food packaging, prolongs food shelf life by reducing the growth of bacteria and protecting food quality by preventing food products from deteriorating (Singh *et al.* 2018) [55]. Enzymes, essential oils, plant extracts and other antimicrobial agents are available for use in packaging (Chawla *et al.* 2021) [13].

The conventional method of directly applying antimicrobial chemicals to food is replaced by incorporating antimicrobial agents into the biopolymer matrix. Films or coatings made from antimicrobial biopolymers regulate the release of these agents. Natural and safe antimicrobial agents used include essential oils like eugenol, carvacrol, citral, thymol,

rosemary, and cinnamaldehyde. For instance, the antibacterial activity of apple-based edible films containing carvacrol and cinnamaldehyde essential oil is demonstrated. *Escherichia coli* and *Staphylococcus aureus* are effectively combatted by edible films made of whey protein isolates, glycerol as a plasticizer, and essential oils from lemon and bergamot as antibacterial agents (Çakmak *et al.* 2020) [9].

8.1.2. Antioxidants

Antioxidants are stable substances that donate electrons to unstable molecules. These antioxidants effectively halt the chain reaction that could lead to food products deteriorating by interacting with unstable molecules known as free radicals and reactive oxygen species (ROS) (Lobo *et al.* 2010) [36]. According to Ghidelli *et al.* (2013) [19] and Tanwar *et al.* (2021) [61], active films and coatings that include active antioxidant agents prolong the shelf life of food, delay the enzymatic browning of cut fruits, and boost customer acceptance. Enzymatic browning is a key indicator of any freshly cut fruit's commercial success.

Table 5: Addition of antioxidants in edible films/coatings

S.no.	Plant	Edible film	Active compounds	References
1.	Thyme	Chitosan and starch matrix- based	Flavonoid glycosides and terpenoids	Talón <i>et al.</i> , 2017 [60]
2.	<i>Ocimum sanctum</i>	Arabic gum-based guava fruit coating	Polyphenols and flavonoids	Murmu and Mishra 2017 [40]

8.1.3 Nutraceuticals

Nutraceuticals improve food's nutrient content, particularly when processing at high temperatures, which can cause nutrient loss. These are incorporated into the food packaging materials' composite matrix. Milk proteins are also used in edible food coating as a nutraceutical component (Daniloski *et al.* 2021) [16]. It has better tensile strength, is more flexible, acts as an oxygen barrier, and delays moisture loss. However, some nutraceuticals can have a favorable impact on human health. For instance, beta carotene influences age-related health problems, pectin supports cardiovascular health, and ascorbic acid acts as an antioxidant.

8.1.4. Active nanoedible packaging

In active packaging, bioactive encapsulation substances are incorporated into the package, which releases active elements and enhances the shelf life of food. Food-grade additives that are generally regarded as safe (GRAS) in their nanoforms, such as nanoparticles or nanoemulsions, are present in the edible food coating solution. Another name for these is "nanoadditives." (Chawla *et al.* 2021) [13]. When the food packaging needs to serve several purposes, a combination of nanoparticles is used.

Table 6: Addition of nanoparticles in edible films/coatings

S.no.	Nanoparticle	Edible Film	Inhibition microorganisms	References
1.	Chitosan nanoparticles	starch film	<i>Escherichia coli</i> <i>Staphylococcus aureus</i>	Shapi <i>et al.</i> , 2020 [54]
2.	Thyme essential oil and Montmorillonite Nanoclay	sweet potato	<i>Escherichia coli</i> <i>Salmonella Typhimurium</i>	Issa <i>et al.</i> , 2017 [25]

Nanoparticle vary from 1-100 nm; however, smaller nanoparticles carry a bigger risk as move freely within the body and they may readily penetrate the cell.

Due to their nano size, nanoparticles can enter human cells and destroy the life material of the cell. Nanoparticle use must adhere to food regulatory regulations. For instance,

compared to 100 nm silver nanoparticles, 20 nm silver nanoparticles are more harmful to human lung tissue. (Chawla *et al.* 2021) [13].

Food-grade materials are used to make thin, nanoscale nanolaminates for packaging. Polysaccharides exhibit excellent properties against gas and water. They can range

in thickness from microscale to nanoscale. Based on the thickness of the laminate, adsorption stage can take time from 1 min to 1 h (Acevedo Fani *et al.* 2017) ^[1]. At present time, the nanolaminates include active chemicals. Active chemicals are released in response to changes in external factors like as temperature, pH, and light.

Conclusion

Conventional packaging poses significant environmental concerns, encourage packaging industry to explore alternatives such as edible films/coatings derived from polysaccharides, lipids and proteins. These films not only aim to enhance the shelf life of food products but also to incorporate antimicrobial and antioxidant agents, beneficial ingredients like vitamins, flavors, probiotics and nutritional additives. Consumer demands for sustainable and eco-friendly solutions and development of edible packaging has gained momentum, with all constituents adhering to food safety regulations from authorities like the FDA and EFSA. The potential of nanotechnology is also being explored to enhance the performance of edible packaging; specifically, nanomaterials can improve the stability and solubility of active ingredients, facilitating their controlled release. Despite its promising advantages, edible packaging is at an early developmental stage. Challenges such as limited barrier capabilities, insufficient mechanical strength and high production costs continue to hinder its widespread industrial adoption. To advance commercialization, further research is essential to enhance the quality and reduce the costs associated with edible packaging solutions.

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