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Utilization of Agro-Industrial Wastes as Edible Coating and Films for Food Packaging Materials

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Abstract

Mostly, food packaging employs synthetic materials obtained from nonrenewable sources. These packaging materials are based on petrochemicals and cause substantial environmental problems by producing massive amounts of non-biodegradable solid wastes. Edible coatings and films are considered as the potential solution to these problems of non-biodegradable packaging solid wastes for maintaining food-environment interactions, retaining food quality, and extending shelf life. In addition, edible coatings and films offer prevention from microbial spoilage of packed foods by controlling moisture and gas barrier characteristics. Increasing environmental concerns and consumer demands for high-quality eco-friendly packaging have fueled the advancement of innovative packaging technologies, for instance, the development of biodegradable films from renewable agricultural and food processing industry wastes. Therefore, the current chapter presents the application of edible coatings and films as an alternative to conventional packaging, emphasizing the fundamental characterization that these biodegradable packaging should hold for specific applications such as food preservation and shelf life enhancement. The primary employed components (e.g., biopolymers, bioactive, and additives components), manufacturing processes (for edible films or coatings), and their application to specific foods have all been given special consideration in this chapter. Besides, a future vision for the use of edible films and coatings as quality indicators for perishable foods is presented.

Keywords: agro-industrial wastes, edible films, edible coatings, food packaging, biopolymers

1. Introduction

Majority of food packaging are made of synthetic materials derived from nonrenewable sources and based on petrochemicals, having advantages of being available in large quantities at a low cost and having excellent barrier and resistance properties. Nevertheless, these are causing serious environmental issues due to the

production of large amounts of non-biodegradable solid wastes [1]. Apart from its primary function of containing food, delaying deterioration, and extending shelf life, packaging also plays a critical role in regulating food-environment interactions [2, 3]. Environmental concerns and consumer demands for high-quality eco-friendly products that are similar to those found in nature (natural products), has prompted the development of technologies for novel packaging materials, such as the production of biodegradable films from renewable polymers [1, 3, 4]. As a result, consumer demand for packaging materials has switched to safe and environment friendly biodegradable materials, particularly from renewable agriculture by-products and food processing industry wastes. Polysaccharides including starch, cellulose, sodium alginate, pectin, chitosan, and gums, as well as proteins like whey, soy, gluten, and gelatin, are among the most commonly used biopolymers in the manufacture of biodegradable films [5]. Because of their abundance in nature, biodegradability, and edibility, these natural biopolymers are widely employed. Casting, pressing, and extrusion, followed by blowing, are some of the procedures utilized in the production of these films [6]. Plant-derived bioactive substances, such as essential oils, vitamins, minerals, polyphenols, and carotenoids, are extensively distributed in nature in addition to biopolymers. Because of their biological nature, different parts of plants, such as leaves, flowers, seeds, and roots, can possibly be employed in the manufacture of environment friendly films with functional features [7]. Some bioactive substances have antioxidant and antibacterial properties [8–10]. Bioactive films with new and/or improved properties, such as antioxidant [8, 9] and antimicrobial [10] effects, innovative colors [11, 12], and customized barrier and mechanical properties, have been developed using biopolymers and natural bioactive compounds [8, 11, 13]. Some of the techniques used for their production include the use of inherently bioactive biopolymer-based materials [14, 15], as well as the direct or sprinkling incorporation of free or encapsulated bioactive compounds into the film-forming solutions [8, 12].

Some polymers generated from renewable agro-waste sources are edible and have played important roles in food throughout history as well as in the food, pharmaceutical, and other industries. Biopolymers can be used alone or in combination with other biopolymers to produce an edible coating or film material [16, 17]. In comparison to non-edible polymeric packaging, edible coatings and films offer a number of advantages. They can simplify food packaging and, even if they are not consumed with the packaged product, they can assist to environmental pollution reduction due to their biodegradable nature. Material fragmentation and subsequent mineralization are the mechanisms through which polymers degrade in a bioactive environment. Outer temperature and moisture, as well as the enzyme activity of microorganisms degrade polymer, resulting in fragmented polymer residues. These polymer fragments are only considered biodegradable if they are consumed as food and for energy by microorganisms and converted into carbon dioxide (CO₂), water (H₂O), and biomass under aerobic conditions and hydrocarbons, methane, and biomass under anaerobic conditions at the end of the degradation process [18].

2. Agro-waste based renewable sources used in development of edible coatings and films

Bio-packaging films are made of materials derived from renewable resources that degrade completely. These can be made directly by biological systems (for example, plants, animals, algae, and microbes) or by polymerizing bio-based monomers (e.g.,

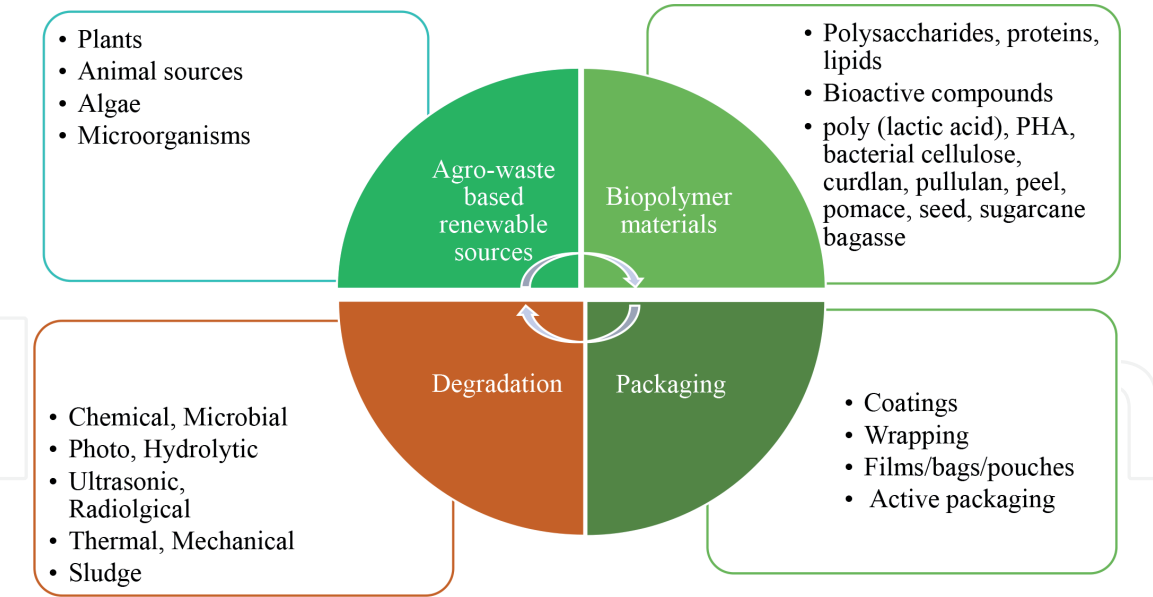


Figure 1.
Life cycle of agro-waste based renewable sources used in the development of edible coatings or films with modifications. (Adopted from Giosafatto et al. [19].)

polylactic acid). Classification and life cycle of various agro-waste based renewable sources used in the development of edible coatings or films has been depicted in **Figure 1**. These bio-polymer materials have been classified into four groups based on their origin and manufacturing method [20]. Among the biopolymers utilized in the packaging business include natural polysaccharides, proteins, and their derivatives [21, 22]. Polysaccharides (e.g., cellulose, pectin, gum, starch, chitosan) and proteins (e.g., collagen, casein, whey protein, egg protein, gluten) extracted from biomass, polymers synthesized from bio-derived monomers (e.g., polylactic acid (PLA)), and those produced directly by microorganisms (e.g., polyhydroxyalkanoates (PHA), pullulan, curdlan, bacterial cellulose) are examples of such materials based on renewable resources that are commonly used for food packaging applications [21]. These bio-based materials have good barrier properties and can be mass-produced on a large industrial scale for moderately low costs, making them a viable alternative to petroleum-based plastics. However, due to considerable divergence in respect to plastics, such as weak tensile strength, brittleness, thermal instability, and water sensitivity, commercialization of polymers produced from biomass is still limited [23–26]. As a result, various reinforcing materials and chemicals, such as plasticizers (e.g., glycerol, glycol, sorbitol), are combined with edible films and coatings to enhance their quality [27–31]).

In most circumstances, one of the above-mentioned biomaterials can be used alone or in combination with other biopolymers to create an edible coating or film material [16, 17].

3. Preparation of edible coatings and films

Edible coatings and films can be liquid, semi-solid or solid matrix that is wrapped around the surface of a food product and can be used as main packaging without providing any sensory or nutritional benefits. These are intended to be tasteless, colorless, non-toxic and unaffected by the sensory properties of the food product [32]. Trinetta [33] reported that when edible coatings and films are applied to cold or hot beverages, edible film dissolves and releases its contents,

giving customers comfort portion control, and the elimination of solid waste. Recently, consumer awareness of edible, biodegradable, and environment friendly packaging materials has grown; edible films and coatings are increasingly being employed in the food processing industry for a wide range of food products. A comprehensive list of biopolymers used, their properties, functions and processing methods employed for production of edible coatings and films for various food products has been presented in **Table 1**. The coating method chosen has an impact not only on the preservation effect of the coating generated on the food products, but also on the cost of manufacturing and process efficiency. There are two types of edible packagings: (i) edible coatings applied directly to the food products and (ii) premade films wrapped around the food products. Two processes can be used to create edible coatings [54]. Dry-process methods, such as thermoplastic extrusion, rely on the thermoplastic characteristics of polymers when plasticized and heated above their glass-transition temperature in low-water-content circumstances. Extruded films have the drawback of not being able to cover uneven surfaces. On a commercial scale, extrusion and spraying are the predominant procedures for film creation and coating deposition, respectively. On the other hand, at a lab scale, the casting method for film creation and dipping methods for coating deposition, are simple to use and preferred methods.

Bio-polymers	Properties	Functions in edible coatings and films	Food product	Processing methods	References
Starch Cellulose Pectin Gums Chitosan Agar Alginate Dextran	Thickeners Gellants Stabilizers Coatings	They form base structure of a solid polymer matrix. They control physical changes, microbial growth, nutritional qualities and shelf-life.	Mango, Apple, Tomato, Strawberries, Green chilies, Sausage, Water melon, Plums, Bell pepper, Brinjal, Potatoes, Taro corms	Extrusion Solvent casting, co-extrusion, Dipping	[34–40]
Gelatin Pea protein isolate Casein Collagen Blood protein Fish protein Whey protein	Gellants Thickeners Stabilizers Emulsifiers Foaming	They help in transport of antimicrobials and antioxidants. They control transport of gases (mainly O ₂)	Soybean oil Cheese slice, Sausage, Meat slice, Soluble coffee, Walnut kernels, Apple, Blood hake, Beef tenderloins, Pork loins, Salmon fillets, Chicken breasts, Rice crisp balls	Solvent casting, Extrusion, Panning, Spraying, Dipping, Compression, Injection Molding, Electrospinning, 3D-printing	[5, 41–48]
Waxes Pullulan esters Chocolates Milk butter Oils (Olive oil and sunflower oil) Paraffin Glycerides	Protectors Coatings	They help to avoid drying or dehydration of the edible films and provide flexibility. They show anti-aging effects.	Strawberry, Fresh-cut apples	Solvent casting, Spreading, Dipping	[49, 50]

Bio-polymers	Properties	Functions in edible coatings and films	Food product	Processing methods	References
Additives (Glycerol, Resins, Polyglycerol, Polyricinoleate, Lecithin, Ascorbic acid, Bioactive compounds)	Viscosity resistance Flexibility Antioxidants Stabilizers Anti-fungal Herbicides Fertilizers Antimicrobial Anti-inflammatory	They decrease the intermolecular force, melting temperature in the mixture and modify viscosity and rheological properties. They increase the solubility of polymers in water and work as stabilizers as well as protection for the products.	Pear, Mango, Quail eggs, Fresh-cut apples	Solvent casting, Spreading, Dipping	[49, 51–53]

Table 1.
List of biopolymers used, their properties, functions and processing methods employed for production of edible coatings and films for various food products.

4. Classification of edible coatings and films

Edible coatings and edible films are not the same; edible coatings can be applied directly to the surface of fruits, vegetables, and other food products in liquid form, usually by immersing the product in an edible material solution. Whilst edible films are molded as solid sheets and then utilized to wrap and package the food products [55]. The edible coating and film components are biodegradable and non-toxic. Biopolymer matrixes such as polysaccharides, proteins, lipids, and composite materials are used to create edible materials (**Table 1**). These coatings and films are thin layers created as a coating on a food surface or put (pre-made) between food components. Their goal is to enhance the shelf life of the food product while simultaneously acting as a safety barrier. They can retard moisture migration and the loss of volatile chemicals, as well as inhibit respiration and delay textural changes. In addition, as compared to typical synthetic films, they are good fat and oil barriers and have a high selective gas permeability ratio CO₂/O₂ [56]. They can also serve as carriers for food additives like antioxidants [57] and/or antimicrobial agents [10], as well as improve the product’s mechanical integrity and handling properties. For some applications, stand-alone edible films with strong mechanical qualities could replace synthetic packaging films. Composition of biopolymers, their concentration, drainage time, viscosity, and other factors influence the mechanical and barrier properties of edible films and coatings [58].

5. Incorporation of bioactive compounds into edible coatings and films

Bioactive chemicals are generally secondary metabolites of plants that have both nutritional value and other functions in their metabolism, such as growth stimulant and protection against biotic and abiotic stress [59]. They are widely distributed in

nature. Fruits and vegetables [11], leaves, blossoms [2], grains, seeds [60], rhizomes and roots [61], of different sorts of plants are important sources of bioactive components including phenols, proteins, essential oils, terpenoids and flavonoids. Plant-determined bioactive compounds are being viewed as fascinating elements for the creation of biodegradable and bioactive films because of their usefulness and natural origin [7]. Plant extracts and fruit pulps as sources of bioactive compounds or isolated bioactive compounds in film-forming solutions have been demonstrated to have antioxidant and antibacterial effects on the subsequent films, prolonging their utility in bioactive and biodegradable films or packaging [2, 3, 24, 62]. Plant derived naturally bioactive compounds are incorporated directly into agro-based polymers or the encapsulated plant-derived bioactive chemicals are integrated into the biopolymers by spraying during the production process [63]. Some edible coatings obtained from plant-derived bioactive compounds along with their methods of incorporation into the coatings, method of development of the edible coatings and films from these phytochemicals and the functional properties of these coatings and films are enlisted in **Table 2**.

Plant-derived bioactive compounds	Methods for incorporation	Methods of development of edible coatings and films	Functional properties	References
Blackberry pulp	Directly by sprinkling into the film-forming solution	Casting	Increased water vapor permeability and solubility in water; Reduced tensile strength; Antioxidant properties	[8, 12]
Curcumin	Directly into the film forming solution	Casting	Antioxidant and antimicrobial activity	[64]
Cranberry extract	Directly into the film forming solution	Casting	Antioxidant	[65]
Vitamin E (α -tocopherol encapsulated in carboxy methyl cellulose)	Directly into the film forming solution	Solution casting	Antioxidant; Decreased water vapor permeability and tensile strength	[66]
Tea Polyphenols	Directly into the film forming solution	Casting	Antioxidant and antimicrobial properties; Improved water barrier properties and tensile strength	[67, 68]
Babassu	Producing the film using inherently bioactive biopolymeric materials from agricultural by-products	Casting	Antioxidant	[15]
Essential oils	Directly into the film-forming solution	Casting	Improved barrier properties	[2]

Table 2.
List of some edible coatings obtained from plant-derived bioactive compounds, their methods of incorporation, method of development of the edible coatings and films and their functional properties.

6. Properties of edible coatings and films from agro-waste based polymers

In the food processing industry, edible coating/film provides a consistent quality for food items with market safety, nutritional value, and low manufacturing costs [69]. Control of mass transfers, mechanical protection, and sensory appeal are the most significant functions of an edible film or coating. Preventing desiccation of foods, regulating microenvironments of gases around foods, and controlling migration of ingredients and additives in food systems are all part of mass transfer control. Edible coatings on fresh foods can reduce quality changes and quantity losses by modifying and controlling the internal atmosphere of particular foods, which is an alternative to modified atmosphere storage. Even while penetration of oxygen may degrade food quality due to oxidation of the fragrance components in the food, modification of the internal atmosphere by the application of edible coatings can aggravate disorders associated with high carbon dioxide or low oxygen concentration. For fresh items, edible films with high water vapor permeability is also desired to extend the shelf life, while extremely high water vapor permeability is not, as it might cause significant moisture loss in the fruits during storage. The mechanical strength of an edible film must be sufficient to safeguard the packaging's integrity during distribution. The sensory qualities of an edible coating or film are critical aspects in final product approval.

The selection of ingredients is one of the most crucial aspects of making edible films. Polysaccharide-based edible coatings and films, a type of natural macromolecule with a high bioactivity, are often generated from agricultural feedstock or crustacean shell wastes. Polysaccharides that may form gels in water are found all over the plant kingdom. Some of them have been thoroughly explored, such as pectins in higher plants, carrageenans and agarose in algae, algal and bacterial alginates, and xanthans. Mucilages are heteropolysaccharides derived from plant stems, such as cactus stems. Food, cosmetics, pharmaceuticals, and other businesses may benefit from cactus mucilage [70]. The complex polysaccharide is a type of dietary fiber that can absorb adequate water before dissolving and dispersing and generating viscous or gelatinous colloids. The low cost of cactus mucilage as a coating is an important desirable consideration.

On the other hand, proteins such as casein, whey proteins, and maize zein, have been employed as a moisture barrier in edible coatings since they are numerous, abundant, inexpensive, and readily available. Corn zein, soy protein, wheat proteins (gluten, gliadin), peanut protein, gelatin, casein, and milk whey proteins have all been used in the production of protein-based films [5]. Food protein may act as natural vehicles, adapted to carry vital micronutrients (e.g. calcium and phosphate), building blocks (e.g. amino acids), as well as immune system components (e.g. immunoglobulins and lactoferrin) [71]. Furthermore, food proteins can be employed in coating formulations to create environment friendly packagings that are easily degradable and can be applied to a variety of foods such as vegetables, fruits, poultry, and fish items [72]. Protein-based edible films are appealing because, when compared to lipid- and polysaccharide-based edible films, they have superior gas barrier properties. Protein films' poor water vapor resistance and lower mechanical strength when compared to synthetic polymers, however, limit their use in food packaging.

Further, despite multifunctional potential of polysaccharides and proteins, the hydrophilic nature of these biopolymers limits their capacity to offer the desired edible film capabilities. Incorporation of hydrophobic chemicals, adjustment of

polymer interaction, and production of cross-links are some of the ways to increase the water barrier and mechanical properties of these films. Lipid molecules used in edible coatings include neutral lipids of glycerides, which are esters of glycerol and fatty acids, and waxes, which are esters of long-chain monohydric alcohols and fatty acids. They are used to give hydrophobicity to food coatings [73]. Although protein films have good oxygen barrier and mechanical properties at low and intermediate relative humidity due to their large number of polar groups and extensive polymer inter-chain, the hydrophilic nature of proteins prevents edible protein films from acting as an effective water vapor barrier. However, lipid films have limited water vapor permeability due to their hydrophobic nature, but they are extremely brittle because of their monomeric structure. Furthermore, lipids generate opaque films or coatings and are susceptible to oxidation. These characteristics may affect the organoleptic characteristics of food and reduce their marketability. Natural antioxidants and antibacterial agents have also been added to the edible film to help prevent autoxidation of high-fat foods and boost oil resistance in fried foods [74, 75]. During storage, edible materials act as barrier against moisture and gases from fresh produce, slowing enzymatic oxidation and protecting the food from browning and texture softening. These may also have the capacity to preserve natural volatile flavor compounds and prevent color components from discoloration [76]. Edible coatings and films aid to preserve phytochemical (phenolic, antioxidants, color) and physicochemical (total soluble solids, weight loss, pH, and respiration rate) attributes in fresh and minimally processed fruits and vegetables over time [77].

7. Physicochemical and morphological characterization of edible coatings and films

The main attributes and techniques for characterization of edible coatings and films are given below:

7.1 Physicochemical characterization

- Mechanical properties
- Solubility
- Color and transparency
- Thermal properties
- Microscopy
- Barrier properties

7.2 Performance evaluation

- Moisture loss, color, film thickness, microbial test
- Sensory properties
- Barrier properties (O_2 permeability, CO_2 permeability, water vapor permeability)

7.3 Morphological characterization

- Atomic force microscopy
- Transmission electron microscopy
- Scanning electron microscopy
- Universal tensile machine
- Fourier transform infrared spectroscopy
- Thermal methods
- Differential scanning calorimetry
- Thermogravimetric analysis
- Differential thermal analysis
- Dynamic mechanical analysis
- X-Ray diffraction
- Nuclear magnetic resonance spectroscopy analysis
- Dynamic light scattering
- Rheological analysis
- Zeta potential analysis

8. Application of edible coatings and films

Edible coatings and films produced from a variety of biopolymers can effectively preserve the nutritional and organoleptic qualities of various foods (**Figure 2**). Edible coatings and films are known as eco-friendly packaging materials, as they replace synthetic or plastic packaging materials and lower the post-harvest losses of fruits and vegetables [78–81]. The edible coating extends shelf life [76, 82–84], prevent microbiological contamination [85], minimizes lipid oxidation [86], and lowers their degradation effect [87].

Biopolymers-based edible coatings operate as barrier layers against gas diffusion, fragrance alterations, water migration, and various volatile exchange [88, 89]. Because of their great selective permeability to oxygen and carbon dioxide, polysaccharides have mostly been employed for food wrapping. The majority of these low-cost films are made from cellulose and its derivatives, such as ethers and esters, starch, pectins, and gums, which are used in food preservation. Fresh fruit products such as tomatoes, cherries, fresh beans, strawberries, mangoes, and bananas have all been coated with cellulose-based edible coatings to prevent quality loss. Chitosan is a polysaccharide that is commonly used to prevent post-harvest deterioration in fresh fruits and vegetables. Chitosan is made up of chitin, which is found in nature just next to cellulose in quantity [90]. Tahir et al. [91] investigated the efficiency of

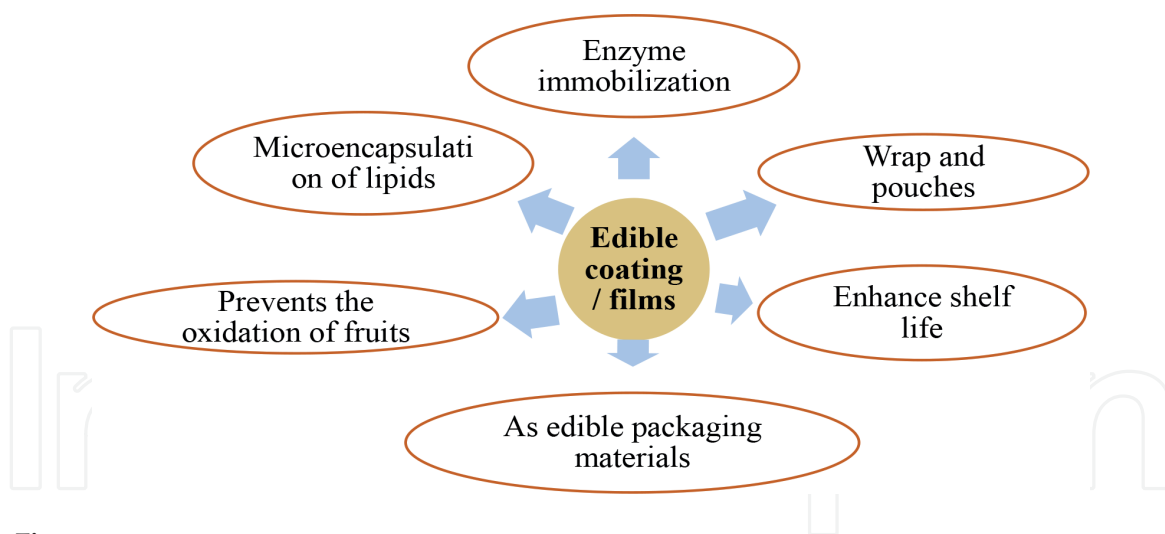


Figure 2.
Application of edible coating and films.

a gum arabic edible coating for increasing total antioxidant content in strawberry fruits during cold storage, with an increase in anthocyanin and phenolic contents. Furthermore, edible coatings containing chitosan and essential oils of oregano or thyme can inhibit the growth of spoilage and pathogen microorganisms while also improving the sensory quality of peeled shrimp [92]. Edible coatings are good transporter of functional ingredients and additives such color, flavor, minerals, vitamins, and antioxidant agents to improve the nutritional value, durability, and functionality of foods [77]. Ebrahimi and Rastegar [93] reported that a guar-based edible coating coated with *A. vera* and *Spirulina platensis* was effective in preserving the ascorbic acid content, total phenol, and antioxidant activity of mango maintained at room temperature. In addition, the coating extended the shelf life of mango fruit by reducing respiration and weight loss. Active films offer promising approach for slowly delivering the functional additives to the food surface, which could help to prevent food spoilage. Active packaging – a novel offshoot of the family of edible films - is quite encouraging as it can be carrier for a wide range of food additives, such as vitamins, antioxidants, minerals, colorants, fragrances, and antibacterial agents for the packaged food products [94].

9. Conclusions and future prospects

Starch, pectin, collagen, sodium alginate, gelatin, chitin, whey protein, chitosan, soy protein, gluten proteins and lipids are all examples of agro-industrial leftovers based biopolymers that have been widely used in the manufacturing of environment friendly food coatings and films. However, limited mechanical strengths and moisture barrier properties of most biopolymers-based edible coatings and films are the notable drawbacks. Combining agro- industrial leftovers based biopolymers with plant-derived bioactive substances (vitamins, carotenoids, phenolic compounds and phytochemicals, among others) permit the formation of bioactive films with antioxidants, antibacterial action. It is feasible to improve the mechanical and moisture barrier and physical properties of films by combining proteins (e.g., milk proteins, soy protein, collagen, and gelatin) with polysaccharides (e.g., starches, alginates, cellulose, and chitosan) or other polymers and hydrophobic compounds (lipids). Crosslinking procedures, on the other hand, could be a fascinating process that take into consideration chemical, enzymatic, and physical processes to produce biodegradable packaging materials with improved qualities from agro-industrial wastes.

Conflict of interest

The authors declare no conflict of interest.

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