Review

Edible food packaging- An overview

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Abstract: This review aims to describe an edible packaging system in food production. The growing global population, changes in climate and dietary patterns, as well as increasing need for environmental protection have created an increasing demand for waste-free food production. The need for durable and sustainable packaging materials has become significant to avoid food waste and environmental pollution. Edible packaging has emerged as a promising solution also to extend the shelf life of food products and reduce dependence on petroleum-based resources. In this review, the importance, composition, and functions of edible packaging materials, as well as their production methods, were described. The market value of edible packaging materials is expanding. It needs further research and development of edible packaging materials to increase sustainable, eco-friendly packaging practices significant for environmental protection and food safety.

Keywords: edible packaging; environmental pollution; food safety; sustainability

1. Introduction

Food packaging systems exhibit an important role in the global food business [1]. Effective packing reduces food waste and guarantees adequate quality during shelf life. Food packaging also serves as a means of attracting customers, informing them about the product, and keeping and protecting the contents [2]. Materials used for packaging can protect food from a variety of hazards, including breakage, evaporation, microbes, light, temperature, and spoilage [3].

Packaging materials used in the food industry are conventional types and consist of glass, cardboard, metal, or plastics. Plastics are the most commonly used materials for food packaging [4]. The food industry widely uses polyethylene, polypropylene, and polyethylene terephthalate in food packaging because they are not expensive, relatively simple to shape, and weigh less than glass or metal materials, although plastics are petroleum-based and not sustainable giving huge carbon print to the environment. Non-biodegradable packaging materials are not sustainable and provide package waste pollution to the environment [5]. With increasing concern about the environmental impact of packaging waste, consumers are demanding natural, high-quality, eco-friendly, and safer food packaging that is also convenient. This presents a significant challenge for the food industry to produce sustainable packages while minimizing environmental pollution. To meet these demands, the food industry is focusing on developing biodegradable, edible, and sustainable materials that can enhance food safety and quality, leading to increased research and industry attention on this issue [6].

In recent years, edible packaging research has undergone rapid expansion due to increased consumer interest in health, nutrition, food safety, as well as environmental protection from packaging waste[7]. Edible packaging is an important component of sustainable packaging. It significantly broadens the source of packaging materials, reduces the dependence on non-renewable petroleum resources, and efficiently decreases food losses and waste [8]. The growth of such packaging decreases carbon print in the environment. Edible packaging is also an emerging approach for food-quality optimization. One of the key benefits of using edible packaging systems is that they are an integral part of the food product. Consumers can eat it without unpacking and throwing it away. package away [9,10]. This review aims to describe an edible packaging system used in food production.

2. Edible packaging

Edible food packaging materials can be neutral, active, or intelligent packaging. Active packaging adds active components, such as antioxidants, vitamins, or antimicrobials, that are controlled in their release into the product and can increase food shelf life or improve other characteristics, such as sensory properties or product safety. Edible packaging can be in the form of a thin film and applied to the food surface or as a coating, which is a thin layer formed directly on the food surface. It should provide a barrier to moisture, oxygen, bacteria, and others to the food, and can be a carrier of protective compounds [10], such as antioxidant and/or antimicrobial agents [6]. This approach can incorporate starches, cellulose derivatives, chitosan, gums, animal or plant-based proteins, and lipids. The materials used to package food are made from compounds that humans can eat without posing any health risks. By simply altering their thicknesses with only a small intervention in the material composition and structure, they can convert these materials into various types of films and coatings. The thickness of edible films is a very important physical property for making edible films and it is better to be less than 0.3 mm [11]. Edible packaging has to be approved by food safety authorities. It is important that the packaging must not be absolutely water, gas, and ethylene barrier-proof, because fruit and vegetables have a certain degree of respiration [12].

Edible packages have the potential to be safe for consumption if it takes proper food safety measures during the time of processing, handling, and storage. A typical edible film should have good sensory qualities, microbial stability, good mechanical properties, be free of toxins, be safe for human health, be non-polluting and be low cost. Like other traditional packaging materials, edible packages also have to be tested for their respective quality parameters to ensure they are safe to consume. One critical factor to assess the safety of edible packaging is its microbiological quality.

3. History of Edible packaging

Edible packaging may seem like new but is an ancient old technology, used for centuries to protect food products and avoid the deterioration of their components. It waxed oranges and lemons in China in the 12th century to prevent water loss during transportation and storage [10]. The practice of preserving fresh fruits in wax or fats for later consumption was called "larding" [10]. Larding was a compromise for maintaining moisture content and losing various qualities, including optimal taste and texture. Boiling soy milk proteins in pans and further air drying created the first edible films, known as "Yuba" films, in Japan at the beginning of the 15th century [13]. During the 16th century, the larding of fruits, vegetables, meats, and fish was common in England to prevent moisture loss, similar to waxing. They granted the first gelatin film patent in the United States in the 19th century to safeguard several meat products. To limit gas transport through edible coatings, sucrose, and sugar derivatives were used as protective coatings on nuts to prevent oxidative rancidity [14]. In the 1930s, commercial waxing and lipid coatings were applied to fruits and vegetables, allowing for natural respiration and preventing dehydration during transport. This business has grown a lot in the last century. Its primary use was to keep water from leaking out of fruits and vegetables and to give them shine. There were many kinds of protein-based films, coatings, plastics, and textiles that could be purchased commercially before World War II [15]. Early in the 20th century, during World Wars I and II, there was a significant surge in the manufacture of commercialized protein-based

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wool substitutes due to the increasing demand for textile products made from agricultural commodities high in protein. In the first two decades of the 21st century, the development of edible films remained stagnant due to the emergence of plastic, a much more cost-effective packaging material [16]. Today's rising customer standards for quality, freshness, and healthful packaging choices drive the development of commercial edible films for a variety of food packaging systems. Moreover, growing environmental protection awareness requires the widespread introduction of non-polluting food packaging as edible packaging.

4. Production of edible film and coatings

Generally, edible materials are applied to food by coating, spraying, and immersion, or by being formed before a film and using it as a food wrap [17]. There are two processes for making edible films: wet and dry process.

4.1. Wet process

In the wet process, the film-forming components are mixed with a solvent, followed by drying to obtain a food film. This process is mainly represented by the casting method. The casting process is the common method of producing edible films and coatings on laboratory and pilot scales. This process involves three steps. Dissolving or dispersing the raw materials in water, alcohol, a mixture of the two, or a mixture of other solvents is typically the first method used to prepare films. Additives like plasticizers, antimicrobial agents, and coloring or flavoring agents [18] are incorporated into the matrix material to boost these materials' flexibility and durability [6]. Adjusting the pH or heating the solutions could be required to increase the solubility. The film-forming solution is then cast and dried at the proper temperature and relative humidity, which is the second and third step toward producing free-standing films [18]. In the casting step, the film-forming solution is poured into a predefined mold or Teflon-coated glass plate. The drying process allows the evaporation of solvent that makes a polymer film that adheres to the mold. Air drier such as hot air ovens, tray dryers, microwaves, and vacuum dryers are used for the casting of films for easy removal of solvents and peeling of the film [19]. Figure 1 shows the schematic representation of the casting process of edible film production.

4.2. Dry Process

In the dry processes, added components were converted into the film by utilizing the thermoplastic behavior at low moisture levels [20] . The wet processes consist of the formation of film by extrusion, compression molding, and injection molding [6].

The extrusion process is another method of producing edible films on a commercial scale which consists of three zones: feeding zone, kneading zone, and heating zone. This method alters structural properties and enhances the physiochemical characteristics of extruded substances [21]. The. In the feeding zone, the film components are mixed and air compression is used to reduce the moisture content of these components. This process is also known as a "dry process" because it functions best with a small amount of water or solvents. As the ingredients move through the kneading zone, the strain, temperature, and density of the mixture rise. Then they are heated above their glass transition temperature to convert into a melt form, which is extruded through a suitably- shaped nozzle by rotating forces of an extrusion screw. The resulting material is then subject to cooling to the formation of the film [22]. They used mechanical and thermal energy in this process to create the extruder-based film. Screw speed also has some impact on specific mechanical energy. Different screw speeds alter film properties, such as its homogeneity, shear rate, and stress, and control the residence time, which allows for the addition and removal of additives, including stabilizers. As screw speed is increasing, the torque value of the extrusion process to obtain films is decreasing. Other factors such as feed moisture content, screw speed, barrel temperature, die diameter, die pressure, energy input, etc are

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necessary for the extrusion process to affect the final products. This method has better mechanical and optical properties than the casting process, and also it requires less energy and takes less time to process the material. Extrusion processing is also a widely employed commercial technique in the food industry that offers high performance at a reasonable cost. Specific polymers, however, are constrained by the extrusion process's low moisture raw material blends and limited temperature tolerance. Figure 2 shows the schematic representation of the extrusion process of edible film production [19,20].

Compression molding is considered a sustainable process due to its rapid formation and less energy requirement. Here, the film-forming components are subjected to heating under high pressure in the mold until their solidification occurs. Processing time is also a critical parameter to determine film properties. This method is usually used with the extrusion method for preparing the film-forming material and then its thermoforming process. Krishna et al. (2012) [23] developed an edible film from fish gelatin with glycerol using extrusion and compression molding. The study revealed that film produced by the compression-mold technique will have high thicknesses and more flexibility than the solvent cast technique.

The injection molding method is mainly used for the production of plastic products, but it is also suitable for the mass production of edible films. This method consists of three stages: filling, packing, and cooling and its parameters are pre-injection pressure temperature, injection pressure, and molding temperature [24].

4.3. Production of edible coatings

Film-forming solutions can be applied directly to food surfaces as coatings in the form of a liquid suspension, emulsion, or powder. Dipping, spraying, brushing, fluidized bed processing, and the panning method are some of the methods for applying edible coatings to food products followed by drying. Figure 1 also shows the schematic representation of the production flow of edible coatings.

The dipping method is the most common and oldest commercial method for edible coatings on foods such as fruits, vegetables, and meat products [19]. This method can be a better choice for coating irregular food surfaces [21]. The density, viscosity, and surface tension of the coating solution are significant in estimating the film thickness. By directly dipping the product into the aqueous medium of coating formulations, removing it, and allowing it to air dry. It produces a thin membranous film over the product surface. Another method for coating formation is the foam application method. Emulsions are typically used in this method. The foam is breaking here through a lot of tumbling, so it can evenly distribute the coating solution over the product's surface [25].

The spraying method is preferred when only one surface needs to be coated and a thin layer of coating is necessary. Compared to pan or fluidized bed coating, it is a more precise form of coating application, where the solution is applied to the food surface using pressure [24]. However, after coating and drying the product's upper surface, spray coating mandates that the lower surface be covered with a different procedure. When applying the coating, the product needs to be spun to cover the lowest portion of the food. When it comes to items with large surfaces, spray coating is favored. In the coating process, the spray nozzle is crucial for design information including flow rate, droplet size, spray distance and angle, overlap speed, surface tension, temperature, viscosity, and pressure of the coating fluid [21,25].

Fluidized-bed processing is a process for applying a very thin layer to dry particles of extremely low density and/or size. This technique causes the powder to agglomerate in the system, increasing the coating material's solubility and dispersion. Hot air is used to fluidize the powder while a liquid binder is simultaneously sprayed. This process, makes the particles adhere, agglomerate and dry the agglomerates [21,25].

The pan-coating method is being used to cover hard, almost-spherical particles in thin or thick layers [19]. It enhances the flavor of the coated food and prevents the loss of moisture and lipids. The pharmaceutical and confectionery industries both use the pan-coating method to cover their products with the coating material. A pan is a large, rotating bowl in which the item to be coated is placed. The coating solution is added to the rotating pan using a ladle or spray. To disperse the coating solution over the food's surface, the product is rotated in the pan [25].

5. Barrier properties of edible packaging materials

The protective barrier function of an edible film helps to increase the shelf life of food products. However, because fruits and vegetables have some degree of respiration, it is crucial that the packaging not be completely water, gas, and ethylene barrier-proof. Edible packaging materials must meet several specific functional requirements and depend on the material type used, its formation, and its application.

5.1. Environmental barrier

The coatings and edible films act as an environmental barrier and regulate the mass transfer between the food and the surrounding environment. When choosing edible material for packaging, permeability is seen to be a crucial consideration. The impact of temperature and moisture on film reflects the circumstances of its intended use. Therefore, before employing it as a food packing material, the permeability must be measured under specified circumstances[26].

5.2. Moisture barrier

For a wide range of applications, edible films must have the right moisture barrier qualities. Reduce moisture exchange between compartments of heterogeneous foods such as pizza, quiche, cakes, or biscuits or between the constituent parts of mixtures such as apéritif mixes, breakfast mixes with dried fruit, and/or cereals with different water activity levels is crucial for maintaining the various crunchy and soft texture [27]. Variations in packaged food's water activity (aw) can lead to critical microbiological development, undesirable textural changes, and deteriorating chemical and enzymatic interactions [28].

Water activity (aw) is an important factor in determining the sensory quality and shelf life of food. Water vapor barrier properties are crucial for both fresh food products, such as vegetables, where it is important to prevent dehydration, and dry foods, such as bread, where it is critical to prevent moisture uptake from the environment [18]. Water vapor permeability (WVP) is the rate of water vapor transmission through a unit area, time, and pressure differences [18,29]. There are currently two ASTM (American Society for Testing and Materials) methods available to measure the water barrier properties of packaging materials. ASTM E96 or the Cup Method and ASTM F1249 or the Infrared detecting method [30]. The Cup method is widely used to measure the WVP of biodegradable films. According to this gravimetric method, the edible film sample seals the known area open the mouth of a cup. Inside the cup is filled with distilled water and, depending on the temperature, it produces certain vapor pressure. The sealed cup is stored at a constant temperature in an airtight chamber or desiccator filled with silica gel. Due to the different relative humidity levels, there is a partial pressure gradient on both sides of the film, which results in a driving force that helps water flow through the film. It decreased the weight of the cup by the flow of distilled water in the cup. The cup's weight loss will remain constant in dynamic equilibrium, and this weight loss will be used to determine the film's permeability at the specified temperature [18,29].

Cup weights are determined at specific intervals, and it achieved linear regression analysis of the increase in weight versus time. The water vapor transmission rate (WVTR) is calculated through the slope of the straight line (g/s) divided by the test area (m2) [31]:

$$WVTR = \frac{Slope}{film\ area} \tag{1}$$

WVP is estimated based on the below calculation:

$$WVP = \frac{WVTR \times thickness}{WVPP} \quad (2)$$

where WVTR is in gh−1 × m−2, the thickness is in millimeters, the partial pressure is in kilopascals, and WVPP is the water vapor partial pressure [29,32].

5.3. Oxygen barrier

Oxygen-sensitive foods can have their shelf life extended and their quality preserved by using edible packaging with low oxygen permeability (OP). Additionally, it contributes to a reduction in the use of certain pricey and luxurious, non-recyclable, oxygen-barrier plastics. Edible films have a wide range of OP values [28].

5.4. Oil barrier

Another way to address consumer preferences and health concerns is to reduce the fat content of fried food products with oil barrier coatings. It may develop oil barrier coatings into a viable substitute for reducing oil absorption during frying. The mechanical and barrier qualities of a coating, which are influenced by its composition and microstructure as well as by the parameters of the substrate, determine how effective it is [33]. It was shown that fluorinated oil repellents are potentially harmful to humans and the environment and are widely used in food packaging, especially for fast foods. Liu et al. (2022) [34] put forward a feasible and green approach to replacing fluorine-free oil repellent with microcrystalline wax emulsion as an oil repellent for paper.

5.5. Organoleptic properties

The organoleptic properties of edible films and coatings have to be as neutral as possible (clear, transparent, odorless, tasteless, etc.). So that they won't be noticed when eaten. Enhancements to the surface's appearance (like brilliance) and tactile properties (like decreased stickiness) might be needed. The ideal flavor, color, spiciness, acidity, sweetness, saltiness, and other qualities can also be preserved through the use of films and coatings [35].

6. Categories of edible packaging materials

Coatings and films, used to make edible packaging, must conform to two requirements. One is to be edible and the other is to be able to form a continuous layer [9]. Edible films and coatings can be categorized into proteins, polysaccharides, lipids, and composites (Fig. 3). Selecting edible films or coatings requires consideration of the substance from which it is made, the kind of food to apply, and how it will be applied. A plasticizer is frequently added to the solution to increase its flexibility and elasticity [28]. Depending on the final application, additional additives like antimicrobial agents, colors, and flavors can be added to the solution to produce specific film properties and functionality.

6.1. Polysaccharide–based packaging materials

A polysaccharide is a carbohydrate the most abundant natural macromolecule in nature [8], formed by long chains of repeating units linked together by glycosidic bonds, which are widely used in edible packaging. Polysaccharides can originate from many different sources: microbial (such as xanthan gum and pullulan), animal (such as chitin and chitosan), plant (such as cellulose, starch, and pectin), and marine (such as alginate). Films and coatings made of polysaccharides can be oil-free, tasteless, colorless, have better chemical stability, and have processing adaptability. It can reduce the dehydration, and darkening of surface oxidative rancidity and thereby can potentially apply to prolong the shelf life of fruits, vegetables, shellfish, or meat products [8,12]. Polysaccharide-based film coatings are effective barriers against oxygen and carbon dioxide at low and moderate

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relative humidity due to their intermolecular structure [12,44,45]. So that due to their selective permeabilities, they can use to extend the shelf life of fresh-cut fruits and vegetables by reducing the respiration rate and gas exchange [44]. But they provide a low barrier to moisture because of their hydrophilic nature [18]. In addition, they have a high sorption capacity, thus when consumed, they adsorb and remove metal ions, radionuclides, and other toxic chemicals from the body [45]. Table 1 groups edible packaging materials based on different polysaccharides.

6.1.1. Cellulose films

Cellulose is a linear homopolysaccharide in which anhydrous glucose rings are bound through β1-4 glycosidic bonds. It exhibits specific properties such as low densi-ty, high mechanical strength, low cost, durability, non-toxicity, renewability, biocom-patibility, biodegradability, good film-forming performance, chemical stability, and ease of making chemical derivatives [45]. Nevertheless, its inability to dissolve in wa-ter and most organic solvents limits cellulose's applicability in the production of edible films. solvents due to its structural complexity, high crystallinity, and tightly packed hydrogen bonds, and is thus unable to form stable gels [18,46]. One way to overcome this limitation is through derivatization like applying an alkali treatment followed by acidification using hydrophilic agents such as chloroacetic acid, methyl chloride, or propylene oxide to produce hydroplastic and thermoplastic cellulose derivatives. Var-ious cellulose derivatives that are commonly employed in the creation of edible food packaging include ethers such as methylcellulose, carboxymethylcellulose, hydroxy-propyl methylcellulose, and hydroxypropyl cellulose, as well as esters like cellulose ac-etate [12]. Hydroxypropyl cellulose and methylcellulose films are very efficient oxy-gen, carbon dioxide, and lipid barriers, but have a low resistance to water vapor trans-fer [47]. However, the water vapor barrier characteristics can be increased by includ-ing hydrophobic elements such as lipids in the film-forming solution. Methylcellulose and hydroxypropylmethylcellulose also generate thermally induced coatings that can be used to cover fried items [18,46]. Mallikarjunan et al. (1997) [48] showed that hy-droxypropyl methylcellulose and methyl cellulose edible coatings are efficient in the reduction of moisture loss and fat uptake of deep-fried starch products. The FDA ap-proved cellulose acetate as GRAS, prompting the food-packaging sector to develop and test new applications for this polymer. Cellulose acetate is mostly used to wrap fresh and baked items [46].

6.1.2. Chitosan films

Chitosan is a linear polysaccharide consisting of N-acetyl-glucosamine and N-glucosamine units. It derives from the alkaline N-deacetylation of chitin, the second most abundant natural polysaccharide after cellulose [46]. The primary sources of chitin are the exoskeletons of crustaceans and several insects and fungi [12]. Chitosan is non-toxic, biodegradable, and biocompatible [18]. Chitin is an insoluble polysaccharide in water or other common solvents. Under highly alkaline and warm conditions, they converted chitin to chitosan. After this treatment, produced chitosan become soluble in acidic mediums such as diluted hydrochloric, formic, and acetic acids [12,17].

Several studies reported the use of chitosan in food packaging because of its physicochemical properties. Chitosan has good film-forming properties with good mechanical properties and selective permeability to O2 and CO2 [46] and possesses antimicrobial and antioxidant properties also [49]. This film has a high sensitivity to water which reduces the barrier properties. So, the functional properties of chitosan films can be improved by using several methods which improve their hydrophobicity or blending with other compatible polymers which can result in an improved barrier and mechanical performance [46].

6.1.3. Starch films

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Starch has been extensively researched due to its abundance, low cost, biodegradability, and edible nature. Starch is a natural polysaccharide that consists of amylose and amylopectin. Amylose is responsible for the starch's film-forming abilities. The short-branched chains of amylopectin form the crystalline regions, while amylose and amylopectin branching points form the amorphous regions. Starch granules are not soluble in cold water, but when heated in water, the crystalline structure is disrupted and water molecules interact with the hydroxyl groups of amylose and amylopectin, resulting in partial solubilization. Gelatinization is necessary to obtain a homogeneous film-forming solution [18]. The tensile strength is relatively high but the elongation percentage is low resulting in poor mechanical properties. Starch films' poor mechanical properties, mainly the brittleness, are due to the amorphous regions formed by amylose. So it is necessary to add a plasticizer to overcome the film's brittleness, thereby improving flexibility and extensibility [50].

6.1.4. Alginate films

Alginate is a natural, edible hetero-polysaccharide extracted from marine brown seaweed (Phaeophyceae), where they occur in the form of sodium, calcium, and magnesium salts of alginic acid [51]. Alginate consists of a linear anionic polysaccharide polymer of β-(1-4)-D mannuronic (M-blocks) and α-L-guluronic acid (G-blocks). Due to the abundance of GM blocks and their interchain interactions, alginate exhibits gelling properties. They are non-toxic, biocompatible, biodegradable, biostable, and hydrophilic [52]. The U.S. Food and Drug Administration (FDA) listed sodium alginate as a Generally Recognized As Safe (GRAS) substance in Title 21 of the Code for Federal Regulations (CFR) [53] and it can form good films, good mechanical strength, moisture barrier and cohesiveness [54,55]. Alginate edible films are transparent, uniform, and highly water-soluble. To increase the water insolubility and stronger film, ionic interactions are induced by using divalent cations such as $Ca2+$ to cross-link alginate during film synthesis [56].

6.2. Protein-based packaging materials

Proteins are heteropolymers where amino acids are linked by covalent peptide bonds, which have a wide range of mechanical and physical characteristics, making them good for coating diverse food products. Proteins exist as fibrous (water-insoluble) or globular (water-soluble proteins. Gelatin, casein, whey protein, collagen, wheat glu-ten, soy protein, bean protein, and peanut protein are examples of common proteins in animal and plant sources, used for edible packaging [20]. Protein coatings have rela-tively higher mechanical properties and provide effective barriers to gases like $O2$, $CO2$ [72], aroma, and lipid [28], but have low water barrier properties [20]. Table 1 groups edible packaging materials based on different proteins.

6.2.1. Milk protein films

Milkproteinscomprise~80%caseinand20%wheyproteinhavingthepropertiesofmalleable,transparent,andtastelessfilms[40].Theseproteinsalsoserveasacarrierofadditiveslikeantioxidants,antimicrobials,andcolorants,therebyenhancingtheorganolepticpropertiesofthepackedproducts.Thetypeofbiopolymerandthetypeandconcentration-ofplasticizerem-ployedinfilmpreparationhadasignificantimpactonthefilmthickness,tensilestrength,andbarrierpropertiesofcaseinandwheyproteinfilms[64].

The casein-based films had the highest transparency among the protein-based films as well as they exhibit excellent firmness and elasticity, thermal persistence, moderate surface hydrophobicity, and low oxygen permeability. However, the main drawback of casein-based films, like most protein-based films, is low water vapor resistance [73], and it is better to combine with lipids to form composite films [74]. Picchio et al., (2018) [75] suggested the possibility of using tannic acid as a crosslinking agent for improving the

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physiochemical properties of casein-based films. Caseinate is the most common form of casein, which is highly water-soluble [36], but gets insoluble when subject to a buffer solution at pH 4.6 [76]. Sodium caseinate (NaCAs) and Calcium caseinate (CaCAs) are the most commercially available caseinates. Caseinates are made by precipitating casein by lowering the pH to 4.6, either by adding a microbial culture or diluting mineral acid. After that, the casein curd is washed with water and dissolved in an appropriate alkali to bring the pH up to approximately 7.0 before being spray-dried. When NaOH is used to change the pH, sodium caseinate is made, or if Ca(OH)2 is used, calcium caseinate is produced [77].

Whey proteins consist of whey protein isolates (WPI) and whey protein concentrates (WPC) and have differences in protein concentration. WPIs are the most prevalent protein-based materials utilized in films and coatings [78]. This whey protein film is gaining more attention than polysaccharides and other protein-based films because of its biodegradable, edible nature as well as its mechanical and barrier properties [79]. WP-based films and coatings are flexible, colorless, odorless, and transparent, with distinguishing features such as amphiphilic nature, conformation, denaturation, and electrostatic charges, which can be produced by methods like casting, dipping, extrusion, enrobing, fluidization, foaming, spraying. WP films can prevent microbial spoilage by limiting the amount of water vapor condensation in fruit and vegetable packaging [32].

6.2.2. Collagen films

Meat proteins are classified as sarcoplasmic, stromal, or myofibrillar. Sarcoplasmic proteins include enzymes, myoglobulins, and cytoplasmic proteins. Stromal proteins include collagen and elastin, whereas myofibrillar proteins include myosin, actin, tropomyosin, and troponins. Stromal and myofibrillar proteins are used in the production of edible films and coatings. Collagen is a fibrous, stromal protein extracted from connective tissue, tendons, skin, bones, and the vascular system, which are by-products of meat processing [35] and used as edible films for meat products. This type of coating has the advantage of preventing humidity loss and giving the product a uniform appearance, boosting its structural qualities [17].

6.2.3. Gelatin films

Gelatin is a water-soluble protein produced by hydrolysis of the fibrous protein collagen, which is tasteless, and transparent with faint yellow color [41]. Fish, pork, and bovine are the sources of collagen for gelatin production [40]. Depending on the synthesis method, gelatin can be classified as (I) Type A, derived from acid-treated collagen, and (II) Type B, obtained from alkali-treated collagen [46,80]. Gelatin is utilized to give gelling, adjustment, texturization, and emulsification for bakery, beverages, confectionary, and dairy items in the food industry. However, its limited mechanical and thermal stability has prevented it from being used in many applications [80]. The gelatin-based film shows low O2 permeability and good mechanical properties but is highly sensitive to moisture and permeable to water vapor due to its hygroscopic nature [46].

6.2.4. Zein films

Zein is a prolamin protein found in corn, which dissolves in 70-80% ethanol [81]. It has thermoplastic behavior and hydrophobic, antioxidant, and antibacterial properties. Zein-based films are smooth, thermally stable, has selective barriers to O2, CO2, and oils. Hence, it possesses excellent film-forming properties because of its hydrophobic nature and barrier properties. Despite that, they exhibit poor mechanical properties and fragility. However, the addition of plasticizers or combining it with other polymers as composite films can improve its structural properties [35,46]. Pavlátková et al. (2023) [82] developed zein/chitosan-based blend systems enriched with thymol, cinnamon, thyme, and oregano and studied physicochemical properties and antimicrobial efficiency with the potential for active packaging applications of fresh strawberries. The result showed that the zein/chitosan blend is suitable as a bioactive compound carrier to make barriers and prevent moisture loss, ensuring microbial food quality and prolonging the shelf life of fruits. These systems can serve as sustainable active food packaging.

6.3. Lipid-based packaging materials

Lipids are naturally hydrophobic polymers that come from plants, animals, or insects. Natural waxes, acetylated monoglycerides, and resins are the edible packaging lipids utilized most frequently. Lipids cannot form cohesive and independent films. Therefore, they are used for packaging or composite films. Lipids can make films and coat-ings that are good at keeping out moisture [38]. Wax coatings are considerably more impervious to water migration when compared with other lipid or non-lipid edible films. These can be used by themselves or with other ingredients [26]. Table 1 groups edible packaging materials based on different lipids.

Waxes are made by esters of a long-chain fatty acid and a long-chain alcohol, and they have a larger molecular weight. Waxes have animal and vegetal origins and serve as protective covering tissues. Due to their strong hydrophobicity, waxes made from esters aid in minimizing moisture permeability, which is why they are utilized in edible packaging [17,83]. Both natural and synthetic waxes have been used as protective coatings, alone or in combination with other ingredients [28]. Natural waxes include carnauba wax [84], candelilla wax [85], rice bran wax [86], and beeswax [87], and synthetic waxes include paraffin wax [88] and petroleum wax [89].

6.4. Composite films

Composite films are multi-component systems that combine several hydrophobic and hydrophilic compounds for improved functional qualities [20]. In these types of edible packaging, the combination of at least two constituents is used where the weak-ness of an individual substance is compensated by adding the other component. For example, the water vapor permeability of polysaccharides and proteins can be im-proved by adding lipids, forming an edible composite that possesses both hydrophilic and hydrophobic properties [6]. A study by Sanchez-Gonzalez et al., (2011) [90] de-veloped hydroxypropylmethylcellulose and chitosan-based edible coating with and without bergamot essential oil (EO) for cold storage of grapes. They suggested that HPMC coating containing bergamot EO was the most effective formulation in com-parison to chitosan alone with bergamot EO, in displaying effective antimicrobial ac-tion and maximum control over respiration rates with minimum weight losses during postharvest cold storage. The extension of ivy gourd (Coccinia indica) shelf life was studied with the blend of gum acacia/ pectin/ pullulan composite films using sorbitol and glycerol as a plasticizer. To evaluate the effectiveness of the coating solution, measurements of weight loss, titrable acidity (TA), total soluble solids (TSS), antioxi-dant, total phenolic content (TPC), and storage time were made. According to the re-sults, the ivy gourd's shelf life increased by 35% throughout the 23-day storage period. The anti-microbial test showed that the prepared film/coating is more resistant to Pseudomonas aeruginosa due to the presence of pullulan [91].

Composite edible films have been categorized as binary or ternary based on the number of biopolymers. Combining pectin and zeolite Y results in a classic example of a binary edible film [92]. Such systems allow for a variety of protein-protein, carbohydrate-carbohydrate, and protein-carbohydrate combinations. There is a lot of literature on composite films and coatings created by combining two hydrocolloids, however, edible films or coatings by combining three hydrocolloids are rare [93].

Significant advances have been made in the field of composites and it seems to be correlated with the evolution of nanotechnology. For improving the mechanical barrier properties of edible packaging materials, bio-nanocomposite materials are known for their promising properties [26].

7. Additives in edible films

Film additives are materials other than film formers that are added into films to improve structural, mechanical, and handling qualities or to perform active functionali-ties.

7.1. Plasticizers

The edible films made from polymers have poor mechanical qualities; they are fragile and prone to cracking when drying. These issues can be resolved by incorporating plasticizers into the film composition [78]. Plasticizers are small-molecular-weight hydrophilic agents that are added to film-forming preparations to improve film mechanical properties [28,91]. The council of the IUPAC (International Union of Pure and Applied Chemistry) defined plasticizer as a substance or material incorporated in a material to increase its flexibility, workability, or distensibility [94]. The films made from a variety of polysaccharides are often brittle in the absence of a plasticizer due to interactions between polymer chains. By reducing the intermolecular interactions between adjacent polymer chains, plasticizers decrease cohesion within the film network. Plasticizers alter or enhance the mechanical properties in this way [18,39,61]. Mono-, di-, or oligosaccharides (e.g., glucose, fructose-glucose syrups, and sucrose), polyols (e.g., glycerol, sorbitol, glyceryl derivatives, and polyethylene glycols) [78], and lipids and derivatives (e.g., phospholipids, monoglycerides, fatty acids, and surfactants) are common plasticizers used in edible packaging [18,28]. Glycerol has been frequently used to maintain moisture in starch-based products [95]. In the study conducted by [39,61], glycerol was used as a plasticizer to improve the mechanical properties of their polysaccharide-based film.

7.2. Emulsifiers

Emulsifiers are polar and nonpolar surface-active compounds capable of changing interfacial energy at the interface of immiscible systems, such as a water-lipid interface or a water-air surface. Emulsifiers are required to create and stabilize well-dispersed lipid particles in composite emulsion films, as well as to achieve sufficient surface wettability to ensure proper surface coverage and adhesion to the coated surface. Natural lecithins are important emulsifiers; others include acetylated monoglyceride, lecithin, glycerol monopalmitate, glycerol monostearate, polysorbate 60, polysorbate 65, polysorbate 80, sodium lauryl sulfate, sodium stearoyl lactylate, sorbitan monooleate, and sorbitan monostearate are some common emulsifiers [41]. Because of their amphiphilic nature, many proteins exhibit emulsifying capabilities [28].

7.3. Antimicrobials

Edible coatings can be used as carriers of antifungal and antibacterial agents to extend the shelf life of food products. They can be also used as carriers of nutrients to improve the nutritional content of finished processed food products. As an alternative for limiting the growth of bacteria, both natural and synthetic antimicrobial agents have been created and added to various edible packaging materials [9]. The most commonly used antimicrobial substances introduced in films are nisin, enzymes, chitosan, oils, plant extracts and preservatives, bacteriocins, ethylenediaminetetraacetic acid (EDTA), metal nanoparticles as well as various plant extracts and their essential oils [9,38]. The antibacterial action of chitosan is particularly efficient against yeasts and molds, followed by gram-positive and gram-negative bacteria [9]. Table 2. shows the effect of different antimicrobial agents on edible packaging materials.

7.4. Plant extracts

Plant essential oil extracts, such as grapefruit seed, cinnamon, allspice, clove, thyme, rosemary, onion, garlic, radish, mustard, horseradish, and oregano, are high in phe-nolic compounds such as flavonoids and phenolic acids, which have a variety of bio-logical effects such as antioxidant and antimicrobial activity [28]. Natural antimicro-bial agents can be added to foods without being labeled as antimicrobial agents or pre-servatives [99]. Asian medicinal plants and spices can be used as food preservatives and flavorings. Its addition can improve the antioxidant and antimicrobial properties of edible films. Kong et al. (2023) [100] incorporated various Asian plant extracts and essential oil in edible film, which improved the physiochemical and mechanical prop-erties of edible films. And also, it contributed antimicrobial and antioxidant activity to the edible film.

7.5. Antioxidants

Antioxidants are chemical compounds that can add to edible packaging materi-als to delay the start or slow the rate of oxidation reactions. Examples of antioxidants include tocopherols, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), propyl gallate, tertiary butylhydroquinone, ascorbic acid, citric acid, ascorbyl palmitate, tartaric acid, polyphenols, and carotenoids. Nogueira et al. (2019) [101] studied the antioxidant property of blackberry powder on arrowroot starch-based edi-ble film. The antioxidant property of blackberry and other plant extracts is related to polyphenols and anthocyanins content which is maintained when added to the edible film. Assis et al. (2018) [102] developed a cassava starch-based biodegradable film, encapsulated with β-carotene with antioxidant properties.

8. Regulations

The edible packaging is an integral part of the edible portion of the food product; so, it has to conform to food safety regulations. Food ingredients and additives permitted by Codex Alimentarius, US Food and Drug Administration, or EU regulations can be used to formulate films and coatings [35]. The edible packaging may be categorized as food contact materials, food packaging materials, food products, or food ingredients depending on its function. Ingredients used in the production of edible packaging films or coatings must either be approved by the Food and Drug Administration in the U.S. or EFSA (European Food Safety Authority) in the E.U. or other national food safety authorities. Currently, most non-plastic food contact materials are not regulated by European legislation and it covers only a few; directive 2007/42/EC on materials and articles made of regenerated cellulose film intended to come into contact with foods [103].

Several edible films and coatings contain ingredients that may trigger allergic reactions in some consumers. So, any coating that contains a recognized allergen must be properly labeled [35]. The use of organic solvents in the production of edible packaging materials is prohibited due to the potential contamination of food products and increased toxicology issues. Any edible packaging material must not harm human health and must be approved by official food safety institutions to ensure compliance with food safety regulations.

Overall, edible packaging materials have to be developed and used to comply with local and national food safety rules to ensure their safety. To attract customers, marketing strategies such as awareness programs, price discounts, and advertisements should be used. When making use of edible packaging materials and additives, it is necessary to follow good manufacturing practices (GMP) [26].

9. Market examples

The main problem for the food business is the loss of quality during storage, which ultimately increases waste. Edible packaging can improve food quality and shelf life by providing moisture and gas barrier properties. Various companies and start-ups are developing edible packaging materials on a commercial level, mostly in the U.S. The global edible packaging market was valued at USD 0.84 billion in 2021 and is expected to reach around USD 2.8 billion by 2030, recording a mean annual growth rate of 14.31% during the forecast period from 2022 to 2030 [104]. Market examples of edible packaging are shown in Table 3.

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10. Conclusion

The growing global population, changes in climate and dietary patterns, as well as increasing need for environmental protection have created an increasing demand for waste-free food production. The need for durable and sustainable packaging mate-rials has become significant to avoid food waste and environmental pollution. Edible packaging has emerged as a promising solution to extend the shelf life of food products and also reduce dependence on petroleum-based resources. This review has discussed the importance, composition, and functions of edible packaging materials, as well as their production methods. To ensure the acceptability of these materials, it is im-portant to consider factors such as appearance, organoleptic features, and labeling in-formation. The market value of edible packaging is expanding, which requires further research and development of these materials to increase sustainable, eco-friendly packaging practices enhancing environmental protection and food safety.

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