Biodegradable Packaging Materials for Foods Preservation: Sources, Advantages, Limitations, and Future Perspectives

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Abstract: Biodegradable packaging materials generally comprise a solution to the environmental problem caused by the consecutive use of conventional packaging materials (petroleum-based materials) even though these have a high cost. The monomers resulting from the slow degradation of petroleum-based materials contribute to the pollution of the environment. Biodegradable packaging materials distinguished by high biodegradability and biocompatibility can successfully replace the aforementioned packaging materials and thus solve the environmental problems caused by their use or deposition. Although several of the biodegradable packaging materials present defective properties, mainly mechanical and barrier properties, these are reduced or even eliminated by the addition of various improving additives and by blending them with other biopolymers. Various natural preservatives such as essential oils or other phytochemical extracts can also be incorporated into the biopolymer network to increase its efficacy. This treatment is particularly beneficial since it contributes to the increasing of the shelf life and storability of packaged foods such as fruits, vegetables, dairy products, meat and its products, poultry, and fish. For all the above reasons, the preferences of consumers about the production of healthier foods with high nutritional value [4]. However, the increased demands of consumers about the production of healthier foods with high nutritional value and the solution of the usage of plastic material in food packaging (because of its negative effect to the environment) have activated efforts for the establishment of biodegradable packaging materials for food packaging [5].

Keywords: biodegradable packaging; food applications; advantages; limitations; storability; shelf life; future perspectives

1. Introduction

The quality and safety of food products has always been a concern in the food industry. There are reports that millions of people get sick on account of the consumption of contaminated foods [1,2]. The main factor that causes the degradation of foods is microbial growth [3]. Packaging is a solution that reduces physical damages and the deterioration of sensory characteristics and nutritional value [4]. However, the increased demands of consumers about the production of healthier foods with high nutritional value and the solution of the usage of plastic material in food packaging (because of its negative effect to the environment) have activated efforts for the establishment of biodegradable packaging materials for food packaging [5].

Traditional packaging materials produced by petroleum and the byproducts of petroleum have been used for many years by the food packaging sector. Some of these are high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE) as well as polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). It is estimated that the total volume of these traditional plastic material corresponds to an amount exceeding 90% of the total volume of plastics used industrially, and about 50%–70% of the total plastics waste
comes from them [6–8]. It is also estimated that the global production of bio-plastics was 2.11 million tons in 2020 [8] (Figure 1).

![Figure 1](image_url)

**Figure 1.** Global production of bioplastics in 2020 [8].

The traditional plastic materials have some advantages, such as high processability, flexibility, stability at extreme thermal conditions, excellent physicochemical characteristics, and low cost [9]. The main disadvantage of these materials is their very long-time decomposition [6]. A small amount of them (21%) is recycled and incinerated, but a large amount (79%) is rejected, harming nature [10,11]. The collected plastics in landfills and seas can pollute the environment. The products of their decomposition can be introduced to the food marine chain [12,13]. This environmental pollution can threaten humans’ and animals’ health, causing various problems such as lack of essential nutrients [13], brain damage and behavioral disorders [14], along with cancer after long exposure [15,16]. The environmental problems caused by plastic materials have also been found by other studies [17,18]. Therefore, one of the most effective solutions to this problem is their substitution with biodegradable packaging materials [19]. Biodegradable packaging materials have advantages such as biodegradability and nontoxicity [19]. However, these present some disadvantages, such as the insufficient mechanical and barrier properties [5] and the high cost [1] compared to the conventional plastic packaging materials.

Indeed, bio-based edible films and coatings have been indicated to be suitable for packaging fruits, vegetables, dairy, and meat-based products at a commercial level [20]. Even though the bio-based polymers are promising based on the recent literature, the production cost is a potential limitation for its practical use. One of the main strategies to reduce the costs would likely be the mass production and increasing consumer awareness of biopolymer-based packaging. In addition, extra attention may be required for the water-insoluble bio-based polymers, so the latter can be properly disposed of [20].

On the other hand, microorganisms take part in the decomposition of biodegradable packaging during the enzymatic process [21]. Biodegradable polymers are divided into three categories (Table 1). The first category includes synthetic biodegradable polymers that include polymers derived from chemicals using renewable biobased monomers such as polyactic acid (PLA) and biodegradables that are based on fossil resources such as polybutylene adipate terephthalate (PBAT), poly(butylene succinate-co-butylene adipate)
(PBSA), polyvinyl alcohol (PVA), polyglycolic acid (PGA), and polycaprolactone (PCL). The second category includes natural biopolymers extracted from biomass, such as polysaccharides (starch, cellulose, chitosan, or chitin) and proteins (collagen, gelatin, casein, whey, soy protein, zein, wheat gluten, etc.). The last category includes polymers produced by microorganisms or genetically modified bacteria, such as the polyhydroxyalkanoates (PHAs); polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV), poly(3-Polyhydroxybutyrate-co-3-hydroxyvalerate (PHBV), and bacterial cellulose are the most representative. The second category is the most important one, as it is used in the production of food packaging [22]. The materials of this category have useful characteristics such as their biodegradability, renewability, and abundance in nature. However, properties such as mechanical, heat transfer, and barrier properties need improvement [22]. In this context, the aim of the present review article was dual: (i) to provide the most recent and collective knowledge on the use (including advantages and limitations) of biodegradable packaging materials applied for the storability and shelf-life extension of foods such as fruits and vegetables [21], dairy products [23], meat [23], poultry [24], and fish [25] and (ii) to give future directions on this topic. In addition, the review article provides critical thinking on the scarce data regarding lipid-based biodegradable packaging materials. We conclude that future work is needed, for further support and flourishing of the relevant literature/research on this topic.

Table 1. Classification of biodegradable polymers based on their source [5].

<table>
<thead>
<tr>
<th>Bio-Based Polymers</th>
<th>Synthetic Biodegradable Polymers</th>
<th>Natural Biopolymers Extracted from Biomass</th>
<th>Polymers Produced by Microorganisms</th>
</tr>
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<tbody>
<tr>
<td>From Biomass</td>
<td>From Petrochemicals</td>
<td>Polysaccharides</td>
<td>Lipids</td>
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<tr>
<td>PLA</td>
<td>PLA</td>
<td>Starch, Cellulose, Alginate, Carrageenan,</td>
<td>Glycerides Waxes</td>
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<td></td>
<td>PCL</td>
<td>Chitosan</td>
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<td></td>
<td>PVA</td>
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2. Synthetic from Biomass Biodegradable Polymers

PLA

Lactic acid monomers are used for the PLA production. These lactic acid monomers are produced by starch or any other carbohydrate-rich product (wheat, corn, sugarcane, kitchen waste, etc.) that undergoes fermentation. The most common method of synthesis of PLA is the polymerization of lactic acid produced by lactide monomers [26,27]. PLA has various important advantages, such as high mechanical resistance, nontoxicity, biodegradability, renewability, high sealability at low temperatures, its action as a barrier of flavor and odor for foodstuffs, its low level of energy consumption and emission of carbon, and the low amounts of waste during its production. The incorporation of various nanoparticles (sophorolipids, lysozyme, and cellulose nanocrystals) into PLA surface coatings has shown a preventive effect against various pathogens microorganisms, such as Staphylococcus aureus, Listeria monocytogenes, Micrococcus lysodeikticus, Escherichia coli, and Salmonella spp. [28].

The factors that limit the use of PLA in food packaging are its high brittleness, weak gas barrier, low heat-resistance capacity, and high cost [29,30]. The blending of PLA with cellulose can improve its heat resistance [31]. Furthermore, the improvement of PLA’s physical and chemical properties can be also achieved by the addition of nanofillers such as talk, silica, plasticizers, nanoclays, carbon nanotubes, nano-additives, and starch alone.
or combined with other bio-based and or biodegradable polymers such as PHAs [32–34]. The ratio of lactic acid isomers that take part in the synthesis of PLA determines its properties as a packaging material. PLA has a high melting point and crystallinity when it consists of 100% L-monomer, and when a ratio of 90/10% D/L monomers synthesizes the PLA, an improvement in the processing production of PLA is achieved, and the PLA fulfills the requirements of bulk packaging [29]. Indeed, packaging of fresh rainbow trout with PLA-based packaging materials with incorporated essential oils (thyme, rosemary, and oregano) increased its shelf life from 4 to 6 days [25].

3. Natural Biopolymers Extracted from Biomass

3.1. Polysaccharides

3.1.1. Starch

Starch is one of the main constituents of human diet, belonging to the general category of biomolecules called polysaccharides, and it is contained in foods such as potato, rice, maize, corn, and wheat [35–37]. Starch consists of two biopolymers, namely the linear amylose and the amorphous amylpectin. The chemical structure of amylose consists of molecules of α-D-glucose connected with α-(1-4) glycoside bond, while amylpectin has the same chemical structure with the presence of branches.

Starch is used in food packaging as both film packaging and coating. As film packaging, starch presents advantages such as excellent barrier properties in gases, high biodegradability, biocompatibility, availability, and edibility as well as low cost, abundance, harmlessness, and its ability to be modulated easily to films due to the presence of hydroxyl groups [38]. On account of these properties, starch is considered a good choice for food packaging. Its high barrier properties to gases permit the use of starch in the packaging of fruits and vegetables with high respiratory activity and that are sensitive to oxidation [39, 40]. Strawberries coated with starch from corn solution retained their firmness, clarity, and color and had a lower weight loss. Moreover, the addition of essential oils to starch coatings better controlled the growth of pathogens and increased the shelf life of strawberries and vegetables [41].

Despite these advantages, the use of starch in food packaging has also some disadvantages, such as its brittleness and its susceptibility to water. These drawbacks can be solved by the addition of plasticizers such as glycerol and polyglycerol [42, 43] and various additives such as cellulose, gelatin, chitosan, and citric acid [38]. The properties of starch can be also improved by using a deep eutectic solvent and formulation under reactive extrusion conditions (high pressure and temperature and low moisture content) [44]. Blending starch with many synthetic biodegradable polymers such as polylactic acid (PLA), polyvinyl alcohol (PVA), polycaprolactone (PCL), polybutyl succinic acid-butyl adipate (PBSA), and polyadipate butylene terephthalate (PBAT) improves the mechanical properties, the processability, the biodegradability, and the poor resistance to moisture of starch-based biodegradable packaging materials [45, 46].

Starch-based films can be used in monolayer or laminated forms with other films as a result of the upgradation of barrier properties. Furthermore, when these films are combined with flexible polyesters (PBAT), they become more flexible, while blending with PLA upgrades their rigidity and thermoforming properties [47]. Moreover, the use of nanomolecules such as nanoclay or zinc in starch-based films upgrades their mechanical properties [48–51]. Moreover, the starch-based films have the advantage of shape memory [41]. The materials with shape-memory characteristics can transform from the temporary phase to permanent phase when exposed to specific conditions of temperature, humidity, pH, etc.

The antimicrobial effect of various incorporated antimicrobial factors on starch-based films has been investigated by several authors. Bakery products packaged with Manioka starch-based films presented higher resistance to fungi attack and higher shelf life after the addition of essential oils into the films [49, 52]. The incorporation of citric pectin and
flour from Feijoa peel into starch-based films was used in apple packaging [53]. Furthermore, maqui berry extract incorporated into cowpea starch-based films was used for salmon packaging [54]. Another study reported that yam-starch-based films fortified with eugenol were used in pork packaging [55]. In addition, a bilayer film consisted of PLA and pea starch was used for cherry tomato packaging [56]. Similarly, rey-starch-based films containing rosehip extract were used for chicken breast packaging [57] and a mixture of acetylated cassava starch and green tea with linear low-density polyethylene films for sliced bacon packaging [58]. From these references, it is evidenced that starch-based films are the most appropriate packaging films for the substitution of conventional film packaging materials.

3.1.2. Cellulose and Hemicellulose

Cellulose is a biopolymer that is a part of the polysaccharides group. It is crystalline, strong, and resistant to hydrolysis. Chemically, cellulose consists of plenty of β-D-glucose molecules linked together with β-(1-4) glycoside bonds. Cellulose is the most abundant component of plants [59], and it is found in the cellular walls of plants, peels of fruits and vegetables, wood, agricultural residues, factory and food waste, food leftovers, cereal brans and husks, sugarcane bagasse, corn kernels, and many forms of algae along with different types of grass and even oomycetes [60,61].

The use of cellulose in food packaging exhibits many advantages that can be recognized as follows: (i) high mechanical and physical properties and (ii) high thermal resistance. However, its use has some limitations, such as its high water absorbability and the insufficient interfacial adhesion. One effort to overcome the limitation of the high water capacity of cellulose is its incorporation with other films, resulting in higher tensile strength, higher lipid resistance, and improved barrier properties to water [62,63]. Some of the most usable derivatives of cellulose are cellulose acetate, nitrate, sulfate, carboxymethyl, methyl, and ethyl nano-cellulose [64]. These have many advantages, such as edibility, biodegradability, bioavailability, non-toxicity, light weight, and pleasant organoleptic characteristics (color appearance, taste, aroma, and flavor), and they can be easily found at a low cost. In addition, cellulose can be incorporated and encapsulated with various active molecules of antimicrobials and antioxidants [65,66]. Cellulose derived from bacteria has extraordinary properties in comparison to other polysaccharide-based polymers. In the food industry, derivatives of cellulose are used as thickening and gelling agents, stabilizers, water-binding additives, and food packaging materials [67].

Hemicellulose (also known as polyose) is a polysaccharide often related to cellulose but with a distinguishable composition and structure. Hemicellulose is biosynthesized of diverse monosaccharides and can contain xylose and arabinose, glucose, mannose, galactose, and rhamnose. Hemicellulose includes most of the D-pentose monosaccharides and occasionally small amounts of L-monosaccharides as well. Xylose is, in most cases, the monosaccharide monomer that is found in the highest quantity, although in softwoods, mannose can be the most abundant monosaccharide. It is worth mentioning that acidified forms of regular monosaccharides can be found in hemicellulose, including glucuronic acid and galacturonic acid [68].

Given its branched and amorphous structure, unmodified hemicellulose films do not have advanced mechanical properties. Casting and drying methods have been used for the hemicellulose-based film production [69]. Moreover, the presence of a hydroxyl group makes it more susceptible to moisture absorption. The improvement of the mechanical and barrier properties of hemicellulose films can be achieved by physical and chemical modifications [70]. The addition of plasticizers such as sorbitol and glycerin in composite films (hemicelluloses–chitosan) resulted in improved barrier properties and elongation at break but reduced tensile strength. However, we must stress that the additions of plasticizers may result in increased moisture absorption due to the hydrophilic nature of plasticizers. To eliminate water absorption and increased hydrophobic nature, researchers
have adopted etherification with galactoglucomannan (GGM) given that the butyl glycidyl ether provides better thermal and mechanical properties [71].

3.1.3. Chitosan

Chitosan is a linear polysaccharide that consists of D-glucosamine and N-acetyl-D-glucosamine linked with a β-(1→4) glycoside bond. Chitosan is produced by chitin after alkaline treatment with sodium hydroxide. Chitin is a polysaccharide found in the exoskeleton of arthropods, the cell wall of some fungi, the glut Desmond mollusks, cephalopods beaks, radulae, and in some nematodes and diatoms. The presence of amino and hydroxyl groups in the molecular structure of chitosan enhances its ability to inhibit the growth of Gram-positive and Gram-negative bacteria.

Chitosan can be used in agriculture as a seed treatment and biopesticide. In winemaking, it can be used as a refinement agent. In the coating industry, it can be used in a self-healing polyurethane paint coating. In medicine, it is used as bandages and as an antibacterial agent. Chitosan can also contribute to the delivery of medicines through leather. Films made from chitosan possess high antimicrobial and antioxidant properties and are widely used in food packaging. The main mechanisms of the antimicrobial action of chitosan are the following:

1. The change of the bacterial cell wall charges are because of the interactions of its constituents with the amino groups of chitosan, resulting in the transfer of intracellular fluid to the environment, finally leading to the death of cells [72];
2. The formation of thin cellophane films on food surfaces is a result of the prevention of microbial attack and the exclusion of oxygen, resulting in the inhibition of aerobic microorganisms [73];
3. Chitosan can bind essential trace metals that take part in the microbial metabolic pathway [74];
4. Chitosan stimulates the synthesis of the chitinase enzyme that disrupts the fungal cell wall [75].

Films made from chitosan have high biodegradability and biocompatibility but also present disadvantages such as the low water barrier properties. This drawback can be limited by using mixtures of chitosan with bio-proteins. Except for the barrier properties, compatibility and thermal stability are also improved [73]. The blend of chitosan with other biomaterials, nanometals, and active compounds also increases the moisture barrier and mechanical properties [76]. Studies have shown that the incorporation of various essential oils in packaging materials based on chitosan/gelatin causes an increase in mechanical resistance by 30% and a reduction in its flexibility [77]. No significant changes were exhibited in water barrier properties [77–79]. Furthermore, no significant changes were presented in thermal stability [77,80,81]. It is worthy of note that ε-polylysine blended with chitosan contributed to the shelf-life extension of beef fillets and the increase in its storability under refrigeration [82].

3.1.4. Alginate

Alginites are the sodium, potassium, or calcium salts of alginic acid. Alginic acid, i.e., algin, is an edible polysaccharide that is found in brown algae. It has a high hydropathicility and is capable of entrapping water molecules in its three-dimensional net, resulting in the formation of a viscous gum. Alginic acid’s color ranges from white to yellowish-brown, and it is sold in filamentous and granular forms. It is worth noting that algin is an important constituent of the biofilms produced by the bacterium Pseudomonas aeruginosa, which is found in the lungs of some people who suffer from cystic fibrosis [83–85].

Alginate is a linear copolymer that consists of (1→4)-linked β-D-mannuronate and α-L-guluronate residues. The refinement of alginites is performed using brown seaweeds. The most commonly used alginate is the sodium alginate that is used widely in the food industries as a thickener and stabilizer and as animal food as well as for
fertilizers, textile printing, cosmetics, and pharmaceuticals [83,86–88]. The most popular seaweed that is used for the refinement of alginates is the giant kelp *Macrocystis pyrifera*, whose length can reach 20–40 m. There are also seaweeds of smaller length that are used for the isolation of alginates, such as *Ascophyllum nodosum* and types of *Laminaria*.

Due to the film-forming properties of alginates, such as their hydrophilicity and biocompatibility, they are extensively used in the preparation of edible coatings [89,90]. However, alginates have also some drawbacks that have limited their usage in food preservation, such as low resistance to UV radiation, water barrier properties, and high sensitivity to microbial growth. Some studies have been performed to determine the limitations of these disadvantages. The addition of aloe vera and frankincense oil in the film made from alginate produced better mechanical and moisture barrier properties, thermal stability, antimicrobial activity, and higher UV shielding [91]. The moisture-barrier properties of alginate and starch-based films can also be increased by the incorporation of microcrystalline cellulose [92]. Mechanical and antibacterial properties have also been improved by the incorporation of silver nanoparticles and lemongrass essential oil [93].

The application of alginate-based film with added aloe vera and frankincense oil to the packaging of green capsicum retarded their senescence and decreased their weight loss. In addition, the packaging of apple slices with alginate-based films incorporated with phenolic compounds such as thymol caused a significant inhibition to the growth of *Staphylococcus aureus* and *Escherichia coli*, decreased weight loss, increased the retention of nutrients, and maintained the surface color of apple slices [94].

3.1.5. Carrageenan

Carrageenans are a group of natural linear sulfated polysaccharides that are refined from red edible seaweeds such as *Chondrus crispus*, which are the most popular red edible seaweeds used to produce carrageenan. Carrageenans are widely used in the food industry because of their high gelling, thickening, stabilizing abilities, protective coating, and fat substitution capabilities [95]. These are also used successfully in dairy and meat products due to their strong binding to food proteins.

Chemically, carrageenans consist of sulfated polysaccharides. Carrageenan molecules have high flexibility and form curling helical structures. There are three main groups:

1. Kappa-carrageenan has one sulfate group per two repeating units and forms strong, rigid gels along with potassium ions and reacts with dairy proteins. It is obtained mainly from *Kappaphycus alvarezi* [96];
2. Iota-carrageenan has two sulfate groups per two repeating units and forms fewer rigid gels along with calcium ions. It is obtained mainly from *Eucheuma denticulatum* [96];
3. Lambda-carrageenan has three sulfate group per two repeating units and does not form gel, whereas it is used to thicken dairy products such as skim milk, cream cheese, yogurt, and sour cream.

Carrageenan is nontoxic and has high biocompatibility and biodegradability. Carrageenan offers higher stability of capsules, higher electronegativity, and better protection of encapsulated materials in comparison with other encapsulation matrices [97]. The difference in the structure of carrageenan compared to other polysaccharides gives the latter different biological activities, such as antioxidant, antitumor, immunomodulatory, anti-inflammatory, anticoagulant, antiviral, antibacterial, antifungal, and anti-hyperglycemic properties [5]. Many researchers have developed pH-sensitive and antioxidant-packaging carrageenan-based films that have been used in the encapsulation of fish oil and enriched nuggets, thus exhibiting positive results in lipid and protein oxidation [98,99].
4. Proteins

4.1. Soy Protein

Soy proteins are synthesized of globulin proteins 7S (β-conglycinin) and 11S (glycinin), which differ in structure as well as functional and molecular properties. These two components are associated with the functional properties of soy products [100]. Soy proteins are obtained from various soy sources such as soy milk, soy flour, or crude soybean.

Soy proteins are used as adhesives, composites, plastics, etc., in various industries, including the food industry. Soy proteins have high biodegradability and exceptional film-forming properties. In addition, the incorporation of antimicrobial compounds into soy protein films has led to the preparation of films of high effectiveness [101]. Nevertheless, soy protein films present some drawbacks, such as low mechanical and thermal resistance, poor processability, and water sensitivity, which can effectively be improved through laminating, coating with other polymers, plasticizing, nanoparticle reinforcing, or blending methods [101]. The coating of soy protein isolate-based films with polylactic acid produces better mechanical and water barrier properties [101].

Furthermore, the incorporation of cellulose nanocrystals into soy protein films improved film forming, tensile strength, barrier properties, and water resistance. This film was tested for the packaging of pork and strawberries and exhibited smaller total mesophilic counts and total volatile basic nitrogen of the stored pork meat and increased the shelf life of strawberries [102]. The addition of stearic acid to soy-based film reduced the water vapor permeability and the water absorption capacity. The incorporation of cysteine in the solution increased the tensile strength of the soy film by forming disulfide bonds [103].

4.2. Wheat Gluten

Wheat gluten consists of mainly two types of proteins: the glutenins and the gliadins [104,105], which can be classified into low molecular glutenins (30,000 to 80,000 Da) and high molecular (80,000 to several million Da) α/β, γ, and Ω gliadins. The functional properties of wheat gluten depend on the functional and structural characteristics of the glutenins and gliadins [104,105]. Glutenin-based films exhibited higher barrier properties compared to gliadins-based films or whole gluten [64]. The viscoelastic, lower solubility, biodegradability, and low oxygen barrier properties of wheat gluten give the opportunity of its usage in food packaging. However, it also has low moisture barrier properties, which could be improved by the addition of plasticizers, coatings, and blending with hydrophobic polymers. The coating of wheat-gluten-based films with silica hybrid coating film decreased the moisture sensitivity of this protein by four times [106]. Furthermore, the blend of three thermoplastic wheat-gluten-based films and polycaprolactone (PCL), both with and without chrome octanoate, provided some food packaging materials with potential shape-memory benefits [107].

4.3. Casein and Whey Proteins

Milk proteins consist mainly of two types of proteins: casein and whey proteins. Caseins are phosphoproteins (αS1, αS2, β, and κ), which account for 80% of the protein fraction in cow milk and between 20% and 60% of the protein fraction in human milk. Whey proteins are obtained from whey, the liquid phase created after cheese production. These proteins contain α-lactalbumin, β-lactoglobulin, serum albumin and immunoglobulins, protease peptones, and other minor proteins [108]. The caseins micelles are linked together by calcium–phosphate bridging and hydrophobic interactions. Caseins exhibit many advantages such as high nutritional value, high biodegradability and biocompatibility, gelation, emulsification, foaming and water-binding ability, and very good stability [109]. These properties result in the potential use of caseins for the so-called casein-based film production [110,111]. On the contrary, caseins have some considerable
disadvantages, such as low mechanical properties, and poor barrier properties, especially to moisture, gases, and volatile compounds [5]. These drawbacks can be eliminated by blending with other biodegradable materials. For example, the addition of genipin, wax, polysaccharides, lipids, and glutaraldehyde has been documented to limit the water absorption and incorporation of synthetic plasticizers [112–114]. Finally, milk proteins possess antimicrobial properties. The most common antimicrobials are lactoferrin and some peptides that are produced from the lysis of casein [115].

4.4. Corn Zein

Zein is a protein that is located in the endosperm of maize, and it consists of α-zein, β-zein, and γ-zein [116]. Zein is a byproduct of the starch production process and has high solubility in ethanol and high insolubility in water. On account of these properties, the zein-based films exhibit good barrier properties to moisture and are used for the packaging of foods that are sensitive to moisture, such as nuts and confectioneries [4].

Zein-based films are produced by the casting solution method, thermoplastic processing, and blown extrusion [5]. The applied processing method is associated with the specific mechanical and thermal properties of the developed films [116]. The water barrier properties of zein-based films can be improved by the incorporation of fatty acids due to the formation of a strong hydrophobic net, while the mechanical properties can be improved by lamination with other biopolymers and the addition of plasticizers [117,118].

4.5. Gelatin

Gelatin is a peptide that is produced by the partial hydrolysis of collagen. The sources used to produce gelatin the bovine and porcine bones and skin and the connective tissue of poultry and fish. The predominant physicochemical property of gelatin is its capacity to forms gels. Furthermore, gelatin has high elastic abilities, and it acts as a stabilizer, emulsifier, and foaming and micro-encapsulating agent [119].

Gelatin-based films have high mechanical and functional properties. The only disadvantage of gelatin-based films is the poor water barrier properties that could be limited by the addition of plasticizers, addition of agents enabling the formation of cross-links, and blending with other biopolymers such as soy protein isolate, oils, fatty acids, and specific polysaccharides [119]. It is also worth noting that the addition of antioxidant and antimicrobial agents to the gelatin-based films enhances the antioxidant and antimicrobial capacity of the films and improves their UV protection, water vapor barrier, and mechanical properties [120]. The antioxidant and antimicrobial capacity of gelatin-based films can be also increased by the incorporation of various types of functional nanoparticles, such as quercetin, lactoferrin, and chitosan nanofibers [121]. The packaging of chicken breast meat into gelatin–nanochitosan-based films containing Zataria multiflora essential oils caused a reduction in microflora and increased the shelf life of the meat [25].

5. Lipids

Glycerides and Waxes

Glycerides and waxes are two special categories of organic substances that are included in the general category of lipids and are used for biodegradable film production. The predominant characteristics of these components are their high insolubility to polar solvents and their high solubility to non-polar solvents. Lipids-based films are used as coatings in biodegradable films that have high hydrophilicity, including films made by proteins and polysaccharides [110,122].

Lipids-based films have a glossy surface and decrease the cost of packaging films. Lipids can also carry and deliver various bioactive compound in foods [123,124]. Apart from their use as coatings, lipids are also incorporated into biodegradable hydrophilic films. Despite the increase of the moisture barrier properties of hydrophilic films, this
incorporation can also improve the thermal stability, UV–vis barrier, and mechanical properties [125,126].

6. Polymers Produced by Microorganisms

**PHAs**

Polyhydroxyalkanoates are products that are produced from bacterial fermentation. Polyhydroxyalkanoates include PHB, PHV, PHBV, polyhydroxyhexanoate (PHH) and polyhydroxyoctanoate (PHO). PHB has many similarities with conventional plastics, and it is used more often compared to the other derivatives of PHAs [127]. Short-chain-length PHAs have poor flexibility and elasticity compared to medium-chain-length PHAs, but they have lower mechanical properties and crystallinity [128].

Food waste materials such as fats, domestic waste, frying oil, crude glycerol, starch, fructose, maltose, and xylose can be used to produce PHAs. PHAs possesses high biodegradability and similar properties as the conventional plastics such as PE and PP [129–132]. Their high levels of biodegradability give PHAs the advantage of usage in the packaging of perishable foods. PHAs are also used for the construction of medical implant devices, screws, or bone plates because of their high compatibility with human tissues. There are three categories of PHAs according to the total number of carbon atoms of repeating units. These categories include short-chain-length PHAs (sCL-PHAs), in which the repeating units include four to six carbon atoms; medium-chain-length PHAs (mCL-PHAs), with more than six carbons; and long-chain-length PHAs (lCL-PHAs), with more than 14 carbon atoms [127].

Regarding the biochemical synthesis of PHAs, an excessive amount of carbon and a limited amount of nitrogen sources in the substrate are required for PHA production [133]. When the levels of oxygen and nutrients are low, the reproduction of bacterial cells is decreased, and as a result, the synthesis of hydroxyalkyl-CoA (HA-CoA) and PHA production is achieved by polymerization through the action of enzyme PHA synthase. The intermediate product, i.e., acetyl-CoA, is produced through metabolic pathways such as the Krebs cycle, de novo synthesis of fatty acids, and the glycolysis cycle. The quantity of nutrients in the medium determines the metabolic conversion from acetyl CoA to PHAs. If the amount of nutrients is high, then acetyl CoA inhibits 3-ketothiolase synthesis because of the suppression of PHA production.

Despite the advantage of their high biodegradability, PHAs also have disadvantages such as high brittleness, high thermosensitivity, limited malleability, and high permeability to gases [134,135]. The performance of PHAs can be upgraded by their incorporation with carbon nanotubes, nanoclays, cellulose, metal oxides, and bioactive glasses [134–136]. Poly (3-hydroxybutyrate) is most commonly used in lieu of PHAs as a food packaging material and film and for medicinal purposes [137].

7. Executive Summary Regarding the Use of Biodegradable Packaging Materials for Foods Preservation

Table 2 summarizes the biodegradable packaging materials used for the preservation of foods of animal and plant origin, by indicating their sources, advantages, and limitations [24,25,49–52,54–58,61,70,82,94,98,99,102,127–170].

**Table 2. Biodegradable packaging materials for foods preservation: sources, advantages, and limitations.**

<table>
<thead>
<tr>
<th>Biodegradable Packaging Materials</th>
<th>Sources</th>
<th>Advantages</th>
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low oxygen barrier properties.

Casein and whey proteins | Milk. | High nutritional value, high biodegradability and biocompatibility, gelation, emulsification, foaming and water-binding ability, and very good stability. | Low mechanical properties and poor barrier properties, especially to moisture, gases, and volatile compounds. | Fresh cut pears, fresh spinach, poultry meat chicken breast filet, and apple and potato slices. | [138, 145–148]

Corn zein | Endosperm of maize. | Good barrier properties to moisture. | Poor mechanical properties. | Cheese and mashed potato balls. | [144]

Gelatin | Bones and skin of bovine and porcine and the connective tissue of poultry and fish. | High mechanical and functional properties. | Poor water barrier properties. | Chicken breast, meat. | [24]

PHAs | Fats, domestic waste, frying oil, crude glycerol, and starch, fructose, maltose, and xylose. | High biodegradability. | High brittleness, high thermosensitivity, limited malleability, and high permeability to gases. | Perishable foods. | [127–137]

8. Conclusions and Future Perspectives

Scientifically, it is known and accepted that in addition to the applied thermal processing and the storage temperature of food, a suitable packaging material can also contribute to the preservation of foods. The main criteria that must be considered are the following: (a) the barrier properties to gases, moisture, volatile compounds, and UV radiation; (b) the mechanical properties; (c) the thermal stability; and (d) the decomposition effects of the packaging materials on the environment. Although many of the petroleum-based packaging materials exhibit very good barrier, mechanical, and thermal properties, along with a low cost of production, these are capable of transferring contaminants to the environment during their decomposition. This transfer of contaminants leads to harmful effects on the food chain, as the contaminants can reach the digestive system of humans through consumption of contaminated food.

This drawback can be eliminated by the substitution of conventional packaging materials with biopolymer-based packaging materials that exhibit high biodegradability and biocompatibility. Furthermore, the barrier properties, the mechanical properties, and the thermal stability of biodegradable packaging materials can be improved by the incorporation of micro-molecular components into the net of the biopolymer and the blending of two or more different biopolymers for the production of co-composite packaging materials. At the same time, the evolution of nanotechnology in packaging films leads us to suggest the study of blends of various biopolymer-based films and the incorporation of natural antioxidant compounds at the macro- and nano level, aiming to enhance the antioxidant and antimicrobial activity of the food and the barrier and mechanical properties of the packaging materials. Additionally, given the limited available data on lipid-based biodegradable packaging materials, future work is needed, as is evidenced from the scarce data provided in the present review. In this context, the present review comprises a collective study and supports the literature that assesses the sources, potential use, advantages, and limitations of biodegradable packaging materials for the preservation of...
different foods, considering the most recent literature and offering some solid future perspectives.


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