coatings

MDPI

Review

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

Andreas Panou [1] and Ioannis Konstantinos Karabagias [2,*]

[1] Independent Researcher, 16451 Athens, Greece; andr_panou@yahoo.gr
[2] Department of Food Science & Technology, School of Agricultural Sciences, University of Patras, 30100 Agrinio, Greece
* Correspondence: ikaraba@upatras.gr; Tel.: +30-6978286866

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 and the critical thinking/decisions of the food product manufacturing industries in favor of the potential use of biodegradable packaging materials in foods are increasing more and more. In this context, the present review article addresses the most recently used biodegradable packaging materials for foods preservation by presenting their sources, advantages, limitations, and future perspectives.

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

Citation: Panou, A.; Karabagias, I.K. Biodegradable Packaging Materials for Foods Preservation: Sources, Advantages, Limitations, and Future Perspectives. *Coatings* **2023**, *13*, 1176. https://doi.org/10.3390/coatings13071176

Academic Editors: Siti Hajar Othman, Intan Syafinaz Mohamed Amin Tawakkal and Stefano Farris

Received: 6 May 2023
Revised: 23 June 2023
Accepted: 27 June 2023
Published: 29 June 2023

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).

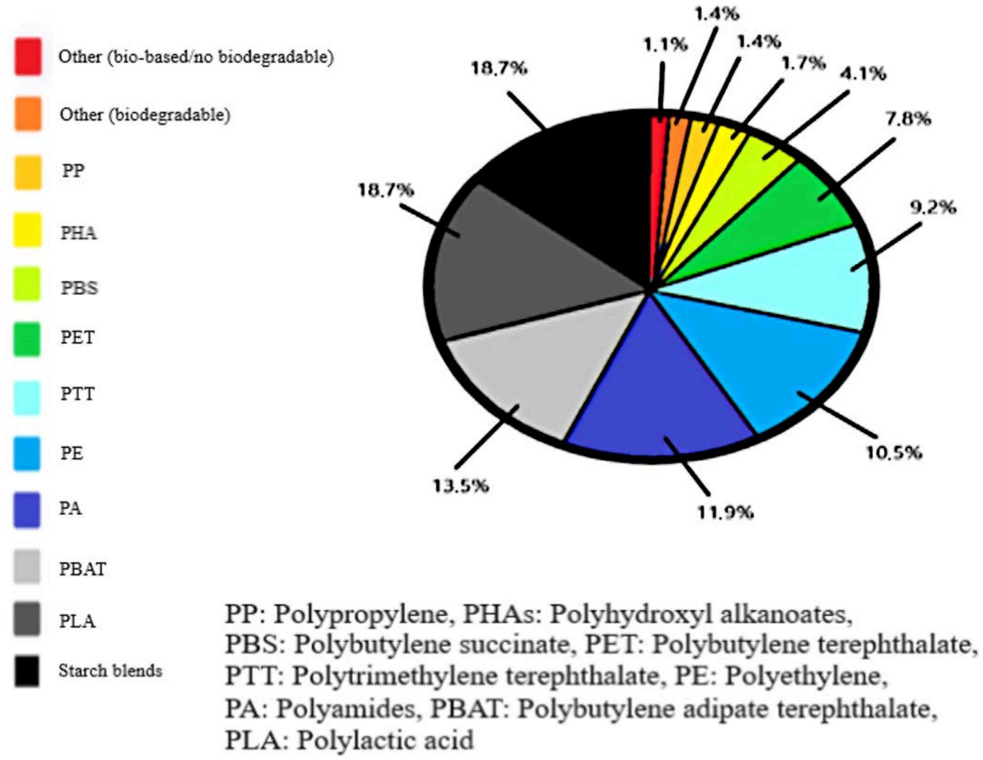

Figure 1. Global production of bioplastics in 2020 [8].

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 polylactic 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 polyhydroxyalkonoates (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 and flexibility 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].

Bio-Based Polymers					
Synthetic Biodegradable Polymers			Natural Biopolymers Extracted from Biomass		Polymers Produced by Microorganisms
From Biomass	From Petrochemicals	Polysaccharides	Lipids	Proteins	Microbial
PLA	PCL PVA PGA	Starch, Cellulose, Alginate, Carrageenan, Chitosan	Glycerides Waxes	Gelatin, Casein, Whey protein, Soy protein, Zein, Wheat gluten	Bacterial cellulose PHAs PHB PHV PHBV

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 fulfils 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 amylopectin. The chemical structure of amylose consists of molecules of a-D-glucose connected with a-(1-4) glycoside bond, while amylopectin 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 de 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 gladii of 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 wine-making, 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

Alginates 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 hydrophilicity 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].

Alginic acid is a linear copolymer that consists of (1→4)-linked β-D-mannuronate and α-L-guluronate residues. The refinement of alginates 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 alvarezii* [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, aS2, 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 fuctional 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

Polyhydroxyalkonoates are products that are produced from bacterial fermentation. Polyhydroxyalkonoates include PHB, PHV, PHBV, polyhydroxyhexanoate (PHH)l 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.

Biodegradable Packaging Materials	Sources	Advantages	Limitations	Foods	References
PLA	Wheat, corn, sugarcane, and kitchen waste.	High mechanical resistance, nontoxicity, biodegradability, renewability, high sealability at low temperatures, and acts as barrier of flavor and odor for foodstuffs.	High brittleness, weak gas barrier, low heat resistance capacity, and high cost.	Fresh rainbow trout, fresh-cut cherry tomatoes, mango, fresh red meat, sliced salami, bread, and fruits and vegetables.	[25,149–154]
Starch	Potato, rice, maize, corn, and wheat.	Excellent barrier properties in gases, high biodegradability, biocompatibility, availability and edibility, low cost, abundance, and harmlessness.	Brittleness and susceptibility to water.	Bakery products, apple, salmon, pork, cherry tomatoes, chicken breast, and sliced bacon.	[49,52,54–58]

Table 2. *Cont.*

Biodegradable Packaging Materials	Sources	Advantages	Limitations	Foods	References
Cellulose and hemicellulose	Cell wall of plants, peels of fruits and vegetables, wood, agricultural residues, factory and food waste, food leftovers, cereal brans and husks, sugarcane bagasse, and corn kernels.	High mechanical and physical properties and high thermal resistance.	High water absorbability and insufficient interfacial adhesion.	Strawberries, mangoes, cherries, blueberries apples, tomatoes, and bananas.	[61,70,139–141]
Chitosan	Exoskeleton of arthropods, the cell wall of some fungi, gladii of mollusks, cephalopods beaks, radulae, and in some nematodes and diatoms.	High biodegradability and biocompatibility.	Low water barrier properties.	Beef fillets, poultry meat, bread slices, cashew nuts, fresh cut melons, mushrooms, and *Ginkgo biloba* seeds	[82,155–160]
Alginate	Brown algae, brown seaweeds, giant kelp *Macrocystis pyrifera*, *Ascophyllum nodosum*, and types of *Laminaria*.	Biocompatibility.	Low resistance to UV radiation, water barrier properties, and high sensitivity to microbial growth.	Green capsicum, apple slices, cheese, apples and pears, and fresh-cut papaya.	[94,161–163]
Carrageenan	Edible red seaweeds.	Nontoxic, high biocompatibility and biodegradability.	-	Fish oil, enriched nuggets, cherry tomatoes, mangoes, strawberry, mushrooms, beef, chicken, and shrimp.	[98,99,164–170]
Soy protein	Soy milk, soy flour, and crude soybean.	High biodegradability and exceptional film-forming properties.	Low mechanical and thermal resistance, poor processability, and water sensitivity.	Pork and strawberries.	[102]
Wheat gluten	Wheat.	Viscoelastic properties, lower solubility, biodegradability, and low oxygen barrier properties.	Low moisture barrier Properties.	Bananas, grapes, persimmons, cherry, litchi, waxberry, and cheese.	[142,143]
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]

Table 2. *Cont.*

Biodegradable Packaging Materials	Sources	Advantages	Limitations	Foods	References
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.

Author Contributions: Conceptualization, I.K.K.; methodology, A.P. and I.K.K.; software, A.P. and I.K.K.; validation, I.K.K.; formal analysis, A.P.; investigation, A.P. and I.K.K.; resources, A.P. and I.K.K.; data curation, A.P. and I.K.K.; writing—original draft preparation, A.P.; writing—review and editing, I.K.K.; visualization, I.K.K.; supervision, I.K.K.; project administration, I.K.K.; funding acquisition, A.P. and I.K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Agarwal, A.; Shaida, B.; Rastogi, M.; Singh, N.B. Food Packaging Materials with Special Reference to Biopolymers-Properties and Applications. *Chem. Afr.* **2022**, *6*, 117–144. [CrossRef]
2. Bahrami, A.; Delshadi, R.; Assadpour, E.; Jafari, S.M.; Williams, L. Antimicrobial-loaded nanocarriers for food packaging applications. *Adv. Colloid Interface Sci.* **2020**, *278*, 102140. [CrossRef]
3. Chawla, R.; Sivakumar, S.; Kaur, H. Antimicrobial edible films in food packaging: Current scenario and recent nanotechnological advancements—A review. *Carbohydr. Polym. Technol. Appl.* **2021**, *2*, 100024. [CrossRef]
4. Ibarra, G.V.; Sendón, R.; Rodríguez-Bernaldo de Quirós, A. Antimicrobial Food Packaging Based on Biodegradable Materials. In *Antimicrobial Food Packaging*; Barros-Velázquez, J., Ed.; Academic Press: San Diego, CA, USA, 2016; pp. 363–384. [CrossRef]
5. Baghi, F.; Gharsallaoui, A.; Dumas, E.; Ghnimi, S. Advancements in Biodegradable Active Films for Food Packaging: Effects of Nano/Microcapsule Incorporation. *Foods* **2022**, *11*, 760. [CrossRef]
6. Kunwar, B.; Cheng, H.N.; Chandrashekaran, S.R.; Sharma, B.K. Plastics to fuel: A review. Renew. Sustain. *Energy Rev.* **2016**, *54*, 421–428. [CrossRef]
7. Alojaly, H.; Benyounis, K.Y. Packaging with Plastics and Polymeric Materials. In *Encyclopedia of Materials: Plastics and Polymers*; Hashmi, M.S.J., Ed.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 485–501. [CrossRef]
8. Zhang, W.; Zhang, Y.; Cao, J.; Jiang, W. Improving the performance of edible food packaging films by using nanocellulose as an additive. *Int. J. Biol. Macromol.* **2021**, *166*, 288–296. [CrossRef]
9. Ahmed, J.; Hiremath, N.; Jacob, H. Antimicrobial efficacies of essential oils/nanoparticles incorporated polylactide films against *L. monocytogenes* and *S. typhimurium* on contaminated cheese. *Int. J. Food Prop.* **2017**, *20*, 53–67. [CrossRef]
10. Geyer, R.; Jambeck, J.R.; Law, K.L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **2017**, *3*, e1700782. [CrossRef]
11. Pereira, J.M.; Rodríguez, Y.; Blasco-Monleon, S.; Porter, A.; Lewis, C.; Pham, C.K. Microplastic in the stomachs of open-ocean and deep-sea fishes of the North-East Atlantic. *Environ. Pollut.* **2020**, *265*, 115060. [CrossRef]
12. Roman, L.; Kastury, F.; Petit, S.; Aleman, R.; Wilcox, C.; Hardesty, B.D.; Hindell, M.A. Plastic, nutrition and pollution; relationships between ingested plastic and metal concentrations in the livers of two Pachyptila seabirds. *Sci. Rep.* **2020**, *10*, 18023. [CrossRef]
13. Mattsson, K.; Johnson, E.V.; Malmendal, A.; Linse, S.; Hansson, L.-A.; Cedervall, T. Brain damage and behavioral disorders in fish induced by plastic nanoparticles delivered through the food chain. *Sci. Rep.* **2017**, *7*, 11452. [CrossRef]
14. Ali, S.S.; Elsamahy, T.; Al-Tohamy, R.; Zhu, D.; Mahmoud, Y.A.-G.; Koutra, E.; Metwally, M.A.; Kornaros, M.; Sun, J. Plastic wastes biodegradation: Mechanisms, challenges and future prospects. *Sci. Total Environ.* **2021**, *780*, 146590. [CrossRef]
15. Kershaw, P. *Sources, Fate and Effects of Microplastics in the Marine Environment: A Global Assessment*; Technical Report; International Maritime Organization: London, UK, 2015; Available online: http://localhost:8080/xmlui/handle/123456789/735 (accessed on 12 December 2022).
16. Mangaraj, S.; Yadav, A.; Bal, L.M.; Dash, S.K.; Mahanti, N.K. Application of biodegradable polymers in food packaging industry: A comprehensive review. *J. Packag. Technol. Res.* **2019**, *3*, 77. [CrossRef]
17. Haward, M. Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. *Nat. Commun.* **2018**, *9*, 667. [CrossRef]
18. Charis, M.G.; Myrto, R.; Turki, M.S.A.; lknur, U.; Neil, J.R. Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era. *Trends Food Sci. Technol.* **2021**, *110*, 193–200. [CrossRef]
19. Rai, P.; Mehrotra, S.; Priya, S.; Gnansounou, E.; Sharma, S.K. Recent advances in the sustainable design and applications of biodegradable polymers. *Bioresour. Technol.* **2021**, *325*, 124739. [CrossRef]
20. Gupta, V.; Biswas, D.; Roy, S. A Comprehensive Review of Biodegradable Polymer-Based Films and Coatings and Their Food Packaging Applications. *Materials* **2022**, *15*, 5899. [CrossRef]
21. Zhong, Y.; Godwin, P.; Jin, Y.; Xiao, H. Biodegradable polymers and green-based antimicrobial packaging materials: A mini-review. *Adv. Ind. Eng. Polym. Res.* **2020**, *3*, 27–35. [CrossRef]
22. Jeevahan, J.; Chandrasekaran, M. Nanoedible films for food packaging: A review. *J. Mater. Sci.* **2019**, *54*, 12290–12318. [CrossRef]
23. Jeya, J.; Chandrasekaran, M.; Venkatesan, S.P.; Sriram, V.; Britto, J.G.; Mageshwaran, G.; Durairaj, R.B. Scaling up Difficulties and Commercial Aspects of Edible Films for Food Packaging: A Review. *Trends Food Sci. Technol.* **2020**, *100*, 210–222. [CrossRef]
24. Hematizad, I.; Khanjari, A.; Basti, A.A.; Karabagias, I.K.; Noori, N.; Ghadami, F.; Gholami, F.; Teimourifard, R. In vitro antibacterial activity of gelatin-nanochitosan films incorporated with *Zataria multiflora* Boiss essential oil and its influence on microbial, chemical, and sensorial properties of chicken breast meat during refrigerated storage. *Food Packag. Shelf Life* **2021**, *30*, 100751. [CrossRef]
25. Zeid, A.; Karabagias, I.K.; Nassif, M.; Kontominas, M.G. Preparation and evaluation of antioxidant packaging films made of polylactic acid containing thyme, rosemary, and oregano essential oils. *J. Food Process. Preserv.* **2019**, *43*, e14102. [CrossRef]
26. Thakur, S.; Chaudhary, J.; Singh, P.; Alsanie, W.F.; Grammatikos, S.A.; Thakur, V.K. Synthesis of Bio-based monomers and polymers using microbes for a sustainable bioeconomy. *Biores. Technol.* **2022**, *344*, 126156. [CrossRef]
27. Modi, S.J. Assessing the Feasibility of Poly-(3-,hydroxybutyrate-co-3-valerate) (PHBV) and Poly-(lactic acid) for Potential Food Packaging Applications. Ph.D. Thesis, Ohio State University, Columbus, OH, USA, 2010.
28. Silveira, V.A.I.; Marim, B.M.; Hipolito, A.; Gonçalves, M.C.; Mali, S.; Kobayashi, R.K.T.; Celligoi, M.A.P.C. Characterization and antimicrobial properties of bioactive packaging films based on polylactic acid-sophorolipid for the control of foodborne pathogens. *Food Packag. Shelf Life* **2020**, *26*, 100591. [CrossRef]

29. Jabeen, N.; Majid, I.; Nayik, G.A. Bioplastics and food packaging: A review. *Cogent Food Agric.* **2015**, *1*, 1–6. [CrossRef]
30. Byun, Y.; Kim, Y.T. Bioplastics for food packaging: Chemistry and physics. In *Innovations in Food Packaging*; Han, J.H., Ed.; Academic Press: Cambridge, MA, USA, 2014; pp. 349–366. [CrossRef]
31. Balla, E.; Daniilidis, V.; Karlioti, G.; Kalamas, T.; Stefanidou, M.; Bikiaris, N.D.; Vlachopoulos, A.; Koumentakou, I.; Bikiaris, D.N. Poly (lactic Acid): A versatile biobased polymer for the future with multifunctional properties—From monomer synthesis, polymerization techniques and molecular weight increase to PLA applications. *Polymers* **2021**, *13*, 1822. [CrossRef]
32. Loh, G.H.; Nor, Y.Y.; Engku, Z.; Engku, Z. Review of bioplastics as food packaging materials. *AIMS Mater. Sci.* **2021**, *8*, 166–184. [CrossRef]
33. Van Den Oever, M.; Molenveld, K.; Van Der Zee, M.; Harriëtte, B. *Bio-Based and Biodegradable Plastics—Facts and Figures: Focus on Food Packaging*; Wageningen Food & Biobased Research: Wageningen, The Netherlands, 2017; pp. 3–53. [CrossRef]
34. Voznyak, Y.; Morawiec, J.; Galeski, A. Ductility of polylactide composites reinforced with polyhydroxyalkanoates nanofibers. *Compos. Part A Appl. Sci. Manufactur.* **2016**, *90*, 218–224. [CrossRef]
35. Shevkani, K.; Singh, N.; Bajaj, R.; Kaur, A. Wheat starch production, structure, functionality and applications—A review. *Int. J. Food Sci. Technol.* **2017**, *52*, 38–58. [CrossRef]
36. Deng, N.; Deng, Z.; Tang, C.; Liu, C.; Luo, S.; Chen, T.; Hu, X. Formation, structure and properties of the starch-polyphenol inclusion complex: A review. *Trends Food Sci. Technol.* **2021**, *112*, 667–675. [CrossRef]
37. Oyeyinka, S.A.; Akintayo, O.A.; Adebo, O.A.; Kayitesi, E.; Njobeh, P.B. A review on the physicochemical properties of starches modified by microwave alone and in combination with other methods. *Int. J. Biol. Macromol.* **2021**, *176*, 87–95. [CrossRef]
38. Cheng, H.; Chen, L.; McClements, D.J.; Yang, T.; Zhang, Z.; Ren, F.; Miao, M.; Tian, Y.; Jin, Z. Starch-based biodegradable packaging materials: A review of their preparation, characterization and diverse applications in the food industry. *Trends Food Sci. Technol.* **2021**, *114*, 70–82. [CrossRef]
39. Thakur, R.; Pristijono, P.; Golding, J.B.; Stathopoulos, C.E.; Scarlett, C.J.; Bowyer, M.; Vuong, Q.V. Development and application of rice starch based edible coating to improve the postharvest storage potential and quality of plum fruit (*Prunus salicina*). *Sci. Hortic.* **2018**, *237*, 59–66. [CrossRef]
40. Naz, M.Y.; Sulaiman, S.A. Slow release coating remedy for nitrogen loss from conventional urea: A review. *J. Control. Release* **2016**, *225*, 109–120. [CrossRef]
41. Mironescu, M.; Lazea-Stoyanova, A.; Barbinta-Patrascu, M.E.; Virchea, L.I.; Rexhepi, D.; Mathe, E.; Georgescu, C. Green design of novel starch-based packaging materials sustaining human and environmental health. *Polymers* **2021**, *13*, 1190. [CrossRef]
42. Nawab, A.; Alam, F.; Haq, M.A.; Lutfi, Z.; Hasnain, A. Mango kernel starch-gum composite films: Physical, mechanical and barrier properties. *Int. J. Biol. Macromol.* **2017**, *98*, 869–876. [CrossRef]
43. Nordin, N.; Othman, S.H.; Rashid, S.A.; Basha, R.K. Effects of glycerol and thymol on physical, mechanical, and thermal properties of corn starch films. *Food Hydrocoll.* **2020**, *106*, 105884. [CrossRef]
44. Adamus, J.; Spychaj, T.; Zdanowicz, M.; Jędrzejewski, R. Thermoplastic starch with deep eutectic solvents and montmorillonite as a base for composite materials. *Ind. Crops Prod.* **2018**, *123*, 278–284. [CrossRef]
45. Thirmizir, M.Z.A.; Ishak, Z.A.M.; Salim, M.S. Compatibilization and Crosslinking in Biodegradable Thermoplastic Polyester Blends. In *Reactive and Functional Polymers, 2: Modification Reactions, Compatibility and Blends*; Gutiérrez, T.J., Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 23–89.
46. Ortega-Toro, R.; Muñoz, A.; Talens, P.; Chiralt, A. Improvement of properties of glycerol plasticized starch films by blending with a low ratio of polycaprolactone and/or polyethylene glycol. *Food Hydrocoll.* **2016**, *56*, 9–19. [CrossRef]
47. Ratnawati, R.; Wulandari, R.; Kumoro, A.C.; Hadiyanto, H. Response surface methodology for formulating PVA/starch/lignin biodegradable plastic. *Emerg. Sci. J.* **2022**, *6*, 238–255. [CrossRef]
48. Ni, S.; Zhang, H.; Godwin, P.M.; Dai, H.; Xiao, H. ZnO nanoparticles enhanced hydrophobicity for starch film and paper. *Mater. Lett.* **2018**, *230*, 207–210. [CrossRef]
49. Nafchi, A.M.; Alias, A.K.; Mahmud, S.; Robal, M. Antimicrobial, rheological, and physicochemical properties of sago starch films filled with nanorod-rich zinc oxide. *J. Food Eng.* **2012**, *113*, 511–519. [CrossRef]
50. Vaezi, K.; Asadpour, G.; Sharifi, H. Effect of ZnO nanoparticles on the mechanical, barrier and optical properties of thermoplastic cationic starch/montmorillonite biodegradable films. *Int. J. Biol. Macromol.* **2019**, *124*, 519–529. [CrossRef]
51. Ali, A.; Xie, F.; Yu, L.; Liu, H.; Meng, L.; Khalid, S.; Chen, L. Preparation and characterization of starch-based composite films reinforced by polysaccharide-based crystals. *Compos. Part B Eng.* **2018**, *133*, 122–128. [CrossRef]
52. Souza, A.C.; Goto, G.E.O.; Mainardi, J.A.; Coelho, A.C.V.; Tadini, C.C. Cassava starch composite films incorporated with cinnamon essential oil: Antimicrobial activity, microstructure, mechanical and barrier properties. *LWT—Food Sci. Technol.* **2013**, *54*, 346–352. [CrossRef]
53. Sganzerla, W.G.; Rosa, G.B.; Ferreira, A.L.A.; da Rosa, C.G.; Beling, P.C.; Xavier, L.O.; Hansen, C.M.; Ferrareze, J.P.; Nunes, M.R.; Barreto, P.L.M.; et al. Bioactive food packaging based on starch, citric pectin and functionalized with Acca sellowiana waste by-product: Characterization and application in the postharvest conservation of apple. *Int. J. Biol. Macromol.* **2020**, *147*, 295–303. [CrossRef]
54. Baek, S.-K.; Kim, S.; Song, K.B. Cowpea starch films containing maqui berry extract and their application in salmon packaging. *Food Packag. Shelf Life* **2019**, *22*, 100394. [CrossRef]

55. Cheng, J.; Wang, H.; Kang, S.; Xia, L.; Jiang, S.; Chen, M.; Jiang, S. An active packaging film based on yam starch with eugenol and its application for pork preservation. *Food Hydrocoll.* **2019**, *96*, 546–554. [CrossRef]
56. Zhou, X.; Yang, R.; Wang, B.; Chen, K. Development and characterization of bilayer films based on pea starch/polylactic acid and use in the cherry tomatoes packaging. *Carbohydr. Polym.* **2019**, *222*, 114912. [CrossRef]
57. Hassan, M.; Dave, K.; Chandrawati, R.; Dehghani, F.; Gomes, V.G. 3D printing of biopolymer nanocomposites for tissue engineering: Nanomaterials, processing and structure-function relation. *Eur. Polym. J.* **2019**, *121*, 109340. [CrossRef]
58. Panrong, T.; Karbowiak, T.; Harnkarnsujarit, N. Thermoplastic starch and green tea blends with LLDPE films for active packaging of meat and oil-based products. *Food Packag. Shelf Life* **2019**, *21*, 100331. [CrossRef]
59. Hu, L.; Du, H.; Liu, C.; Zhang, Y.; Yu, G.; Zhang, X.; Si, C.; Li, B.; Peng, H. Comparative Evaluation of the Efficient Conversion of Corn Husk Filament and Corn Husk Powder to Valuable Materials via a Sustainable and Clean Biorefinery Process. *ACS Sustain. Chem. Eng.* **2019**, *7*, 1327–1336. [CrossRef]
60. Liu, W.; Du, H.; Liu, H.; Xie, H.; Xu, T.; Zhao, X.; Liu, Y.; Zhang, X.; Si, C. Highly Efficient and Sustainable Preparation of Carboxylic and Thermostable Cellulose Nanocrystals via FeCl3-Catalyzed Innocuous Citric Acid Hydrolysis. *ACS Sustain. Chem. Eng.* **2020**, *8*, 16691–16700. [CrossRef]
61. Zhao, G.; Du, J.; Chen, W.; Pan, M.; Chen, D. Preparation and thermostability of cellulose nanocrystals and nanofibrils from two sources of biomass: Rice straw and poplar wood. *Cellulose* **2019**, *26*, 8625–8643. [CrossRef]
62. Wang, W.; Gu, F.; Deng, Z.; Zhu, Y.; Zhu, J.; Guo, T.; Song, J.; Xiao, H. Multilayer surface construction for enhancing barrier properties of cellulose-based packaging. *Carbohydr. Polym.* **2021**, *255*, 117431. [CrossRef]
63. Azmin, S.N.H.M.; Hayat, N.A.b.M.; Nor, M.S.M. Development and characterization of food packaging bioplastic film from cocoa pod husk cellulose incorporated with sugarcane bagasse fibre. *J. Bioresour. Bioprod.* **2020**, *5*, 248–255. [CrossRef]
64. Liu, Y.; Ahmed, S.; Sameen, D.E.; Wang, Y.; Lu, R.; Dai, J.; Li, S.; Qin, W. A review of cellulose and its derivatives in biopolymer-based for food packaging application. *Trends Food Sci. Technol.* **2021**, *112*, 532–546. [CrossRef]
65. Pooresmaeil, M.; Behzadi Nia, S.; Namazi, H. Green encapsulation of LDH (Zn/Al)-5-Fu with carboxymethyl cellulose biopolymer; new nanovehicle for oral colorectal cancer treatment. *Int. J. Biol. Macromol.* **2019**, *139*, 994–1001. [CrossRef]
66. Guzman-Puyol, S.; Hierrezuelo, J.; Benítez, J.J.; Tedeschi, G.; Porras-Vázquez, J.M.; Heredia, A.; Athanassiou, A.; Romero, D.; Heredia-Guerrero, J.A. Transparent, UV-blocking, and high barrier cellulose-based bioplastics with naringin as active food packaging materials. *Int. J. Biol. Macromol.* **2022**, *209*, 1985–1994. [CrossRef]
67. Cazón, P.; Vázquez, M. Bacterial cellulose as a biodegradable food packaging material: A review. *Food Hydrocoll.* **2021**, *113*, 106530. [CrossRef]
68. Smith, P.J.; Curry, T.M.; Yang, J.-Y.; Barnes, W.J.; Ziegler, S.J.; Mittal, A.; Moremen, K.W.; York, W.S.; Bomble, Y.J.; Peña, M.J.; et al. Enzymatic Synthesis of Xylan Microparticles with Tunable Morphologies. *ACS Mater. Au.* **2022**, *2*, 440–452. [CrossRef] [PubMed]
69. Patil, P.H.; Pardeshi, C.V.; Mahajan, H.S.; Surana, S.J. Hemicellulose-based delivery systems: Focus on pharmaceutical and biomedical applications. In *Hemicellulose Biorefinery: A Sustainable Solution for Value Addition to Bio-Based Products and Bioenergy*; Springer: Singapore, 2022; pp. 467–507.
70. Zhao, Y.; Sun, H.; Yang, B.; Fan, B.; Zhang, H.; Weng, Y. Enhancement of mechanical and barrier property of hemicellulose film via crosslinking with sodium trimetaphosphate. *Polymers* **2021**, *13*, 927. [CrossRef] [PubMed]
71. Härdelin, L.; Bernin, D.; Börjesson, M.; Ström, A.; Larsson, A. Altered thermal and mechanical properties of spruce galactoglucomannan films modified with an etherification reaction. *Biomacromolecules* **2020**, *21*, 1832–1840. [CrossRef] [PubMed]
72. Wang, H.; Qian, J.; Ding, F. Emerging chitosan-based films for food packaging applications. *J. Agric. Food Chem.* **2018**, *66*, 395–413. [CrossRef] [PubMed]
73. Priyadarshi, R.; Rhim, J.-W. Chitosan-based biodegradable functional films for food packaging applications. *Innov. Food Sci. Emerg. Technol.* **2020**, *62*, 102346. [CrossRef]
74. Hafsa, J.; Ali, S.M.; Khedher, M.R.B.; Charfeddine, B.; Limem, K.; Majdoub, H.; Rouatbi, S. Physical, antioxidant and antimicrobial properties of chitosan films containing Eucalyptus globulus essential oil. *LWT—Food Sci. Technol.* **2016**, *68*, 356–364. [CrossRef]
75. Carlos, E.O.-V.; José, Á.G.-B. Postharvest quality of peeled prickly pear fruit treated with acetic acid and chitosan. *Postharvest Biol. Technol.* **2014**, *92*, 139–145. [CrossRef]
76. Wang, H.; Ding, F.; Ma, L.; Zhang, Y. Edible films from chitosan-gelatin: Physical properties and food packaging application. *Food Biosci.* **2021**, *40*, 100871. [CrossRef]
77. Roy, S.; Min, S.-J.; Rhim, J.-W. Essential Oil-Added Chitosan/Gelatin-Based Active Packaging Film: A Comparative Study. *J. Compos. Sci.* **2023**, *7*, 126. [CrossRef]
78. Roy, S.; Rhim, J.-W. Genipin-Crosslinked Gelatin/Chitosan-Based Functional Films Incorporated with Rosemary Essential Oil and Quercetin. *Materials* **2022**, *15*, 3769. [CrossRef]
79. Kumar, S.; Shukla, A.; Baul, P.P.; Mitra, A.; Halder, D. Biodegradable Hybrid Nanocomposites of Chitosan/Gelatin and Silver Nanoparticles for Active Food Packaging Applications. *Food Packag. Shelf Life* **2018**, *16*, 178–184. [CrossRef]
80. Roy, S.; Rhim, J.-W. Fabrication of Bioactive Binary Composite Film Based on Gelatin/Chitosan Incorporated with Cinnamon Essential Oil and Rutin. *Colloids Surf. B Biointerfaces* **2021**, *204*, 111830. [CrossRef] [PubMed]
81. Hosseini, S.F.; Rezaei, M.; Zandi, M.; Farahmandghavi, F. Development of Bioactive Fish Gelatin/Chitosan Nanoparticles Composite Films with Antimicrobial Properties. *Food Chem.* **2016**, *194*, 1266–1274. [CrossRef] [PubMed]

82. Alirezalu, K.; Pirouzi, S.; Yaghoubi, M.; Karimi-Dehkordi, M.; Jafarzadeh, S.; Mousavi Khaneghah, A. Packaging of beef fillet with active chitosan film incorporated with ε-polylysine: An assessment of quality indices and shelf life. *Meat Sci.* **2021**, *176*, 108475. [CrossRef] [PubMed]
83. Xu, M.; Qin, M.; Cheng, Y.; Niu, X.; Kong, J.; Zhang, X.; Huang, D.; Wang, H. Alginate microgels as delivery vehicles for cell-based therapies in tissue engineering and regenerative medicine. *Carbohydr. Polym.* **2021**, *266*, 118128. [CrossRef] [PubMed]
84. Blanco-Cabra, N.; Paetzold, B.; Ferrar, T.; Mazzolini, R.; Torrents, E.; Serrano, L.; LLuch-Senar, M. Characterization of different alginate lyases for dissolving Pseudomonas aeruginosa biofilms. *Sci. Rep.* **2020**, *10*, 9390. [CrossRef]
85. Günter, E.A.; Popeyko, O.V.; Belozerov, V.S.; Martinson, E.A.; Litvinets, S.G. Physicochemical and swelling properties of composite gel microparticles based on alginate and callus cultures pectins with low and high degrees of methylesterification. *Int. J. Biol. Macromol.* **2020**, *164*, 863–870. [CrossRef]
86. Lee, K.Y.; Mooney, D.J. Alginate: Properties and biomedical applications. *Prog. Polym. Sci.* **2012**, *37*, 106–126. [CrossRef]
87. Parreidt, S.T.; Müller, K.; Schmid, M. Alginate-Based Edible Films and Coatings for Food Packaging Applications. *Foods* **2018**, *7*, 170. [CrossRef]
88. Zhang, H.; Zhang, F.; Yuan, R. Chapter 13—Applications of natural polymer-based hydrogels in the food industry. In *Hydrogels Based on Natural Polymers*; Chen, Y., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 357–410. [CrossRef]
89. Abdel Aziz, M.S.; Salama, H.E. Effect of vinyl montmorillonite on the physical, responsive and antimicrobial properties of the optimized polyacrylic acid/chitosan superabsorbent via Box-Behnken model. *Int. J. Biol. Macromol.* **2018**, *116*, 840–848. [CrossRef]
90. Aziz, M.S.A.; Salama, H.E.; Saad, G.R. Diglycidyl ether of bisphenol A/chitosan-graft-polyaniline composites with electromagnetic interference shielding properties: Synthesis, characterization, and curing kinetics. *Polym. Eng. Sci.* **2019**, *59*, 372–381. [CrossRef]
91. Salama, H.E.; Aziz, A.M.S. Development of active edible coating of alginate and aloe vera enriched with frankincense oil for retarding the senescence of green capsicums. *LWT* **2021**, *145*, 111341. [CrossRef]
92. Salama, H.; Aziz, M.; Saad, G.; Elsoholy, M.G. Optimization of the water vapor permeability of starch/alginate edible system reinforced with microcrystalline cellulose for the shelf-life extension of green capsicums. *Egypt J. Chem.* **2021**, *64*, 4625–4633. [CrossRef]
93. Motelica, L.; Ficai, D.; Oprea, O.-C.; Ficai, A.; Ene, V.-L.; Vasile, B.-S.; Andronescu, E.; Holban, A.-M. Antibacterial biodegradable films based on alginate with silver nanoparticles and lemongrass essential oil–Innovative packaging for cheese. *Nanomaterials* **2021**, *11*, 2377. [CrossRef]
94. Chen, J.; Wu, A.; Yang, M.; Ge, Y.; Pristijono, P.; Li, J.; Xu, B.; Mi, H. Characterization of sodium alginate-based films incorporated with thymol for fresh-cut apple packaging. *Food Control* **2021**, *126*, 108063. [CrossRef]
95. Zia, K.M.; Tabasum, S.; Nasif, M.; Sultan, N.; Aslam, N.; Noreen, A.; Zuber, M. A review on synthesis, properties and applications of natural polymer based carrageenan blends and composites. *Int. J. Biol. Macromol.* **2017**, *96*, 282–301. [CrossRef]
96. Dong, Y.; Wei, Z.; Xue, C. Recent advances in carrageenan-based delivery systems for bioactive ingredients: A review. *Trends Food Sci. Technol.* **2021**, *112*, 348–361. [CrossRef]
97. Khotimchenko, M.; Tiasto, V.; Kalitnik, A.; Begun, M.; Khotimchenko, R.; Leonteva, E.; Bryukhovetskiy, I.; Khotimchenko, Y. Antitumor potential of carrageenans from marine red algae. *Carbohydr. Polym.* **2020**, *246*, 116568. [CrossRef]
98. Liu, Y.; Qin, Y.; Bai, R.; Zhang, X.; Yuan, L.; Liu, J. Preparation of pH-sensitive and antioxidant packaging films based on κ-carrageenan and mulberry polyphenolic extract. *Int. J. Biol. Macromol.* **2019**, *134*, 993–1001. [CrossRef]
99. Pourashouri, P.; Shabanpour, B.; Heydari, S.; Raeisi, S. Encapsulation of fish oil by carrageenan and gum tragacanth as wall materials and its application to the enrichment of chicken nuggets. *LWT* **2021**, *137*, 110334. [CrossRef]
100. Ciannamea, E.M.; Stefani, P.M.; Ruseckaite, R.A. Properties and antioxidant activity of soy protein concentrate films incorporated with red grape extract processed by casting and compression molding. *LWT* **2016**, *74*, 353–362. [CrossRef]
101. Tian, H.; Guo, G.; Fu, X.; Yao, Y.; Yuan, L.; Xiang, A. Fabrication, properties and applications of soy-protein-based materials: A review. *Int. J. Biol. Macromol.* **2018**, *120*, 475–490. [CrossRef] [PubMed]
102. Xiao, Y.; Liu, Y.; Kang, S.; Xu, H. Insight into the formation mechanism of soy protein isolate films improved by cellulose nanocrystals. *Food Chem.* **2021**, *359*, 129971. [CrossRef] [PubMed]
103. Ye, Q.; Han, Y.; Zhang, J.; Zhang, W.; Xia, C.; Li, J. Bio-based films with improved water resistance derived from soy protein isolate and stearic acid via bioconjugation. *J. Clean Prod.* **2019**, *214*, 125–131. [CrossRef]
104. Payne, P.I. Endosperm Proteins. In *A Genetic Approach to Plant Biochemistry*; Blonstein, A.D., King, P.J., Eds.; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; p. 210.
105. Zhao, H.; Shen, C.; Wu, Z.; Zhang, Z.; Xu, C. Comparison of wheat, soybean, rice, and pea protein properties for effective applications in food products. *J. Food Biochem.* **2020**, *44*, e13157. [CrossRef]
106. Rovera, C.; Türe, H.; Hedenqvist, M.S.; Farris, S. Water vapor barrier properties of wheat gluten/silica hybrid coatings on paperboard for food packaging applications. *Food Packag. Shelf Life* **2020**, *26*, 100561. [CrossRef]
107. Gutiérrez, T.J.; Mendieta, J.R.; Ortega-Toro, R. In-depth study from gluten/PCL-based food packaging films obtained under reactive extrusion conditions using chrome octanoate as a potential food grade catalyst. *Food Hydrocoll.* **2021**, *111*, 106255. [CrossRef]
108. Horne, D.S. Chapter 6—Casein micelle structure and stability. In *Milk Proteins*, 3rd ed.; Boland, M., Singh, H., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 213–250.

109. Martins, J.T.; Bourbon, A.I.; Pinheiro, A.C.; Fasolin, L.H.; Vicente, A.A. Protein-Based Structures for Food Applications: From Macro to Nanoscale. *Front. Sustain. Food Syst.* **2018**, *2*, 77. [CrossRef]
110. Mohamed, S.A.A.; El-Sakhawy, M.; El-Sakhawy, M.A.-M. Polysaccharides, Protein and Lipid -Based Natural Edible Films in Food Packaging: A Review. *Carbohydr. Polym.* **2020**, *238*, 116178. [CrossRef]
111. Moughan, P.J. Chapter 17—Milk proteins: A rich source of bioactives for developing functional foods. In *Milk Proteins*, 3rd ed.; Boland, M., Singh, H., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 633–649.
112. Daniloski, D.; Petkoska, A.T.; Lee, N.A.; Bekhit, A.E.-D.; Carne, A.; Vaskoska, R.; Vasiljevic, T. Active edible packaging based on milk proteins: A route to carry and deliver nutraceuticals. *Trends Food Sci. Technol.* **2021**, *111*, 688–705. [CrossRef]
113. Tkaczewska, J. Peptides and protein hydrolysates as food preservatives and bioactive components of edible films and coatings—A review. *Trends Food Sci. Technol.* **2020**, *106*, 298–311. [CrossRef]
114. Chhikara, S.; Kumar, D. Edible coating and edible film as food packaging material: A review. *J. Packag. Technol. Res.* **2021**, *6*, 1–10. [CrossRef]
115. Zhao, Q.; Shi, Y.; Wang, X.; Huang, A. Characterization of a novel antimicrobial peptide from buffalo casein hydrolysate based on live bacteria adsorption. *J. Dairy Sci.* **2020**, *103*, 11116–11128. [CrossRef] [PubMed]
116. Zhang, X.; Dong, C.; Hu, Y.; Gao, M.; Luan, G. Zein as a structural protein in gluten-free systems: An overview. *Food Sci. Hum. Wellness* **2021**, *10*, 270–277. [CrossRef]
117. Huo, W.; Wei, D.; Zhu, W.; Li, Z.; Jiang, Y. High-elongation zein films for flexible packaging by synergistic plasticization: Preparation, structure and properties. *J. Cereal Sci.* **2018**, *79*, 354–361. [CrossRef]
118. Kashiri, M.; López-Carballo, G.; Hernández-Muñoz, P.; Gavara, R. Antimicrobial packaging based on a LAE containing zein coating to control foodborne pathogens in chicken soup. *Int. J. Food Microbiol.* **2019**, *306*, 108272. [CrossRef]
119. Suderman, N.; Isa, M.I.N.; Sarbon, N.M. The effect of plasticizers on the functional properties of biodegradable gelatin-based film: A review. *Food Biosci.* **2018**, *24*, 111–119. [CrossRef]
120. Roy, S.; Rhim, J.-W. Preparation of antimicrobial and antioxidant gelatin/curcumin composite films for active food packaging application. *Colloids Surf. B Biointerfaces* **2020**, *188*, 110761. [CrossRef]
121. Tavassoli, M.; Sani, M.A.; Khezerlou, A.; Ehsani, A.; McClements, D.J. Multifunctional nanocomposite active packaging materials: Immobilization of quercetin, lactoferrin, and chitosan nanofiber particles in gelatin films. *Food Hydrocoll.* **2021**, *118*, 106747. [CrossRef]
122. Akoh, C.C. *Food Lipids: Chemistry, Nutrition, and Biotechnology*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2017; ISBN 978-1-4987-4487-4.
123. Azar, N.F.A.; Pezeshki, A.; Ghanbarzadeh, B.; Hamishehkar, H.; Mohammadi, M. Nanostructured lipid carriers: Promising delivery systems for encapsulation of food ingredients. *J. Agric. Food Res.* **2020**, *2*, 100084. [CrossRef]
124. Costa-Fernandez, S.; Mattos, J.K.R.; Scheunemann, G.S.; Salata, G.C.; Chorilli, M.; Watanabe, I.-S.; de Araujo, G.L.B.; Santos, M.F.; Ishida, K.; Lopes, L.B. Nanostructured lipid carriers containing chitosan or sodium alginate for co-encapsulation of antioxidants and an antimicrobial agent for potential application in wound healing. *Int. J. Biol. Macromol.* **2021**, *183*, 668–680. [CrossRef] [PubMed]
125. Syahida, N.S.; Ismail-Fitry, M.R.; Ainun, Z.M.A.; Nur Hanani, Z.A. Effects of palm wax on the physical, mechanical and water barrier properties of fish gelatin films for food packaging application. *Food Packag. Shelf Life* **2020**, *23*, 100437. [CrossRef]
126. De Oliveira Filho, J.G.; Bezerra, C.C.D.O.N.; Albiero, B.R.; Oldoni, F.C.A.; Miranda, M.; Egea, M.B.; de Azeredo, H.M.C.; Ferreira, M.D. New approach in the development of edible films: The use of carnauba wax micro- or nanoemulsions in arrowroot starch-based films. *Food Packag. Shelf Life* **2020**, *26*, 100589. [CrossRef]
127. Sathya, A.B.; Sivasubramanian, V.; Santhiagu, A.; Sebastian, C.; Sivashankar, R. Production of polyhydroxyalkanoates from renewable sources using bacteria. *J. Polym. Environ.* **2018**, *26*, 3995–4012. [CrossRef]
128. Li, Z.; Yang, J.; Loh, X.J. Polyhydroxyalkanoates: Opening doors for a sustainable future. *NPG Asia Mater.* **2016**, *8*, e265. [CrossRef]
129. Asgher, M.; Qamar, S.A.; Bilal, M.; Iqbal, H.M. Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Res. Int.* **2020**, *137*, 109625. [CrossRef]
130. Mannina, G.; Presti, D.; Montiel-Jarillo, G.; Suarez-Ojeda, M.E. Bioplastic recovery from wastewater: A new protocol for polyhydroxyalkanoates (PHA) extraction from mixed microbial cultures. *Bioresour. Technol.* **2019**, *282*, 361–369. [CrossRef] [PubMed]
131. Luyt, A.S.; Malik, S.S. Can biodegradable plastics solve plastic solid waste accumulation? In *Plastics to Energy: Fuel, Chemicals, and Sustainability Implications*; Al-Salem, S.M., Ed.; William Andrew Publishing: New York, NY, USA, 2019; pp. 403–423.
132. Vandi, L.; Chan, C.M.; Werker, A.; Richardson, D.; Laycock, B.; Pratt, S. Wood-PHA composites: Mapping opportunities. *Polymers* **2018**, *10*, 751. [CrossRef] [PubMed]
133. Costa, S.S.; Miranda, A.L.; de Morais, M.G.; Costa, J.A.V.; Druzian, J.I. Microalgae as source of polyhydroxyalkanoates (PHAs)—A review. *Int. J. Biol. Macromol.* **2019**, *131*, 536–547. [CrossRef]
134. Gumel, A.M.; Annuar, M.S.M. Nanocomposites of polyhydroxyalkanoates (PHAs). In *Polyhydroxyalkanoate (PHA) Based Blends, Composites and Nanocomposites, RSC*; Roy, I., Visakh, P.M., Eds.; The Royal Society of Chemistry: London, UK, 2014; pp. 98–118. [CrossRef]
135. Valentini, F.; Dorigato, A.; Rigotti, A.; Pegoretti, A. Polyhydroxyalkanoates/fibrillated nanocellulose composites for additive manufacturing. *J. Polym. Environ.* **2019**, *27*, 1333–1341. [CrossRef]

136. Keskin, G.; Kızıl, G.; Bechelany, M.; Pochat-Bohatier, C.; Oner, M. Potential of polyhydroxyalkanoate (PHA) polymers family as substitutes of petroleum based polymers for packaging applications and solutions brought by their composites to form barrier materials. *Pure Appl. Chem.* **2017**, *28*, 1841–1848. [CrossRef]
137. Niaounakis, M. Definitions of terms and types of biopolymers. In *Biopolymers: Applications and Trends*; William Andrew Publishing: Oxford, UK, 2015; pp. 1–90.
138. Noori, N.; Khanjari, A.; Rezaeigolestani, M.; Karabagias, I.K.; Mokhtari, S. Development of Antibacterial Biocomposites Based on Poly(lactic acid) with Spice Essential Oil (*Pimpinella anisum*) for Food Applications. *Polymers* **2021**, *13*, 3791. [CrossRef] [PubMed]
139. Bandyopadhyay, S.; Saha, N.; Brodnjak, U.V.; Sáha, P. Bacterial cellulose and guar gum based modified PVP-CMC hydrogel films: Characterized for packaging fresh berries. *Food Packag. Shelf Life* **2019**, *22*, 100402. [CrossRef]
140. Pirsa, S. Nanocomposite base on carboxymethylcellulose hydrogel: Simultaneous absorbent of ethylene and humidity to increase the shelf life of banana fruit. *Int. J. Biol. Macromol.* **2021**, *193*, 300–310. [CrossRef]
141. Zhao, Y.; Zhou, S.; Xia, X.; Tan, M.; Lv, Y.; Cheng, Y.; Tao, Y.; Lu, J.; Du, J.; Wang, H. High-performance carboxymethyl cellulose-based hydrogel film for food packaging and preservation system. *Int. J. Biol. Macromol.* **2022**, *223*, 1126–1137. [CrossRef] [PubMed]
142. Özkök, G.K.; Caba, Z.T. Investigation of biodegradable coatings produced from three different protein sources for white cheese packaging. *Harran Tarim Ve Gida Bilim. Derg.* **2019**, *23*, 1–12. [CrossRef]
143. Chen, Y.; Li, Y.; Qin, S.; Han, S.; Qi, H. Antimicrobial, UV blocking, water-resistant and degradable coatings and packaging films based on wheat gluten and lignocellulose for food preservation. *Compos. Part B* **2022**, *238*, 109868. [CrossRef]
144. Pena-Serna, C.; Penna, A.L.B.; LopesFilho, J.F. Zein-based blend coatings: Impact on the quality of a model cheese of short ripening period. *J. Food Eng.* **2015**, *171*, 208–213. [CrossRef]
145. Yousuf, B.; Qadri, O.S.; Srivastava, A.K. Recent developments in shelf-life extension of fresh-cut fruits and vegetables by application of different edible coatings: A review. *LWT* **2018**, *89*, 198–209. [CrossRef]
146. Abedi, A.; Lakzadeh, L.; Amouheydari, M. Effect of an edible coating composed of whey protein concentrate and rosemary essential oil on the shelf life of fresh spinach. *J. Food Process Preserv.* **2021**, *45*, 15284. [CrossRef]
147. Andrade, M.A.; Barbosa, C.H.; Souza, V.G.L.; Coelhoso, I.M.; Reboleira, J.; Bernardino, S.; Ganhão, R.; Mendes, S.; Fernando, A.L.; Vilarinho, F.; et al. Novel active food packaging films based on whey protein incorporated with seaweed extract: Development, characterization, and application in fresh poultry meat. *Coatings* **2021**, *11*, 229. [CrossRef]
148. Galus, S.; Mikus, M.; Ciurzyńska, A.; Domian, E.; Kowalska, J.; Marzec, A.; Kowalska, H. The effect of whey protein-based edible coatings incorporated with lemon and lemongrass essential oils on the quality attributes of fresh-cut pears during storage. *Coatings* **2021**, *11*, 745. [CrossRef]
149. Ramos, Ó.L.; Pereira, R.N.; Cerqueira, M.A.; Martins, J.R.; Teixeira, J.A.; Malcata, F.X.; Vicente, A.A. Chapter 8—Bio-Based Nanocomposites for Food Packaging and Their Effect in Food Quality and Safety. In *Food Packaging and Preservation*; Grumezescu, A.M., Holban, A.M., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 271–306. [CrossRef]
150. Rapisarda, M.; Patanè, C.; Pellegrino, A.; Malvuccio, A.; Rizzo, V.; Muratore, G.; Rizzarelli, P. Compostable polylactide and cellulose based packaging for fresh-cut cherry tomatoes: Performance evaluation and influence of sterilization treatment. *Materials* **2020**, *13*, 3432. [CrossRef] [PubMed]
151. Kamthai, S.; Magaraphan, R. Development of an active polylactic acid (PLA) packaging film by adding bleached bagasse carboxymethyl cellulose (CMCB) for mango storage life extension. *Packag. Technol. Sci.* **2019**, *32*, 103–116. [CrossRef]
152. Vilarinho, F.; Sanches Silva, A.; Vaz, M.F.; Farinha, J.P. Nanocellulose in green food packaging. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 1526–1537. [CrossRef]
153. Suwanamornlert, P.; Kerddonfag, N.; Sane, A.; Chinsirikul, W.; Zhou, W.; Chonhenchob, V. Poly(lactic acid)/poly(butylene-succinate-co-adipate) (PLA/PBSA) blend films containing thymol as alternative to synthetic preservatives for active packaging of bread. *Food Packag. Shelf Life* **2020**, *25*, 100515. [CrossRef]
154. Panseri, S.; Martino, P.A.; Cagnardi, P.; Celano, G.; Tedesco, D.; Castrica, M.; Balzaretti, C.; Chiesa, L.M. Feasibility of biodegradable based packaging used for red meat storage during shelf-life: A pilot study. *Food Chem.* **2018**, *249*, 22–29. [CrossRef] [PubMed]
155. Priyadarshi, R.; Sauraj, S.; Kumar, B.; Deeba, F.; Kulshreshtha, A.; Negi, Y.S. Chitosan films incorporated with apricot (*Prunus armeniaca*) kernel essential oil as active food packaging material. *Food Hydrocoll.* **2018**, *85*, 158–166. [CrossRef]
156. Rambabu, K.; Bharath, G.; Banat, F.; Show, P.L.; Cocoletzi, H.H. Mango leaf extract incorporated chitosan antioxidant film for active food packaging. *Int. J. Biol. Macromol.* **2019**, *126*, 1234–1243. [CrossRef]
157. Ortiz-Duarte, G.; Pérez-Cabrera, L.E.; Artés-Hernández, F.; Martínez-Hernández, G.B. Ag-chitosan nanocomposites in edible coatings affect the quality of fresh-cut melon. *Postharvest Biol. Technol.* **2019**, *147*, 174–184. [CrossRef]
158. Huang, Q.; Qian, X.; Jiang, T.; Zheng, X. Effect of chitosan and guar gum based composite edible coating on quality of mushroom (*Lentinus edodes*) during postharvest storage. *Sci. Hortic.* **2019**, *253*, 382–389. [CrossRef]
159. Tian, F.; Chen, W.; Wu, C.; Kou, X.; Fan, G.; Li, T.; Wu, Z. Preservation of *Ginkgo biloba* seeds by coating with chitosan/nano-TiO_2 and chitosan/nano-SiO_2 films. *Int. J. Biol. Macromol.* **2019**, *126*, 917–925. [CrossRef] [PubMed]
160. Souza, V.G.L.; Pires, J.R.A.; Vieira, É.T.; Coelhoso, I.M.; Duarte, M.P.; Fernando, A.L. Activity of chitosan-montmorillonite bionanocomposites incorporated with rosemary essential oil: From in vitro assays to application in fresh poultry meat. *Food Hydrocoll.* **2019**, *89*, 241–252. [CrossRef]

161. Ksoudaa, G.; Sellimia, S.; Merlierb, F.; Falcimaigne, A.; Thomassetb, B.; Nasria, M.; Hajjia, M. Composition, antibacterial and antioxidant activities of Pimpinella saxifrage essential oil and application to cheese preservation as coating additive. *Food Chem.* **2019**, *288*, 47–56. [CrossRef]
162. Kapetanakoua, A.; Nestoraa, S.; Evagelioub, V.; Skandamisa, P. Sodium alginate–cinnamon essential oil coated apples and pears: Variability of Aspergillus carbonarius growth and ochratoxin A production. *Food Res. Int.* **2019**, *119*, 876–885. [CrossRef] [PubMed]
163. Tabassum, N.; Khan, M.A. Modified atmosphere packaging of fresh-cut papaya using alginate based edible coating: Quality evaluation and shelf life study. *Sci. Hortic.* **2020**, *259*, 108853. [CrossRef]
164. Abdillah, A.A.; Charles, A.L. Characterization of a natural biodegradable edible film obtained from arrowroot starch and iota-carrageenan and application in food packaging. *Int. J. Biol. Macromol.* **2021**, *191*, 618–626. [CrossRef]
165. Meindrawan, B.; Suyatma, N.E.; Wardana, A.A.; Pamela, V.Y. Nanocomposite coating based on carrageenan and ZnO nanoparticles to maintain the storage quality of mango. *Food Packag. Shelf Life* **2018**, *18*, 140–146. [CrossRef]
166. Malik, A.R.; Ganaie, T.A.; Masoodi, F.A.; Gani, A.; Wani, S.M.; Gull, A.; Ahad, T. Effect of gum Arabic, xanthan and carrageenan coatings containing antimicrobial agent on postharvest quality of strawberry: Assessing the physicochemical, enzyme activity and bioactive properties. *Int. J. Biol. Macromol.* **2021**, *183*, 2100–2108. [CrossRef]
167. Li, F.; Liu, Y.; Cao, Y.; Zhang, Y.; Zhe, T.; Guo, Z.; Sun, X.; Wang, Q.; Wang, L. Copper sulfide nanoparticle-carrageenan films for packaging application. *Food Hydrocoll.* **2020**, *109*, 106094–106103. [CrossRef]
168. Zhou, X.; Zong, X.; Zhang, M.; Ge, Q.; Qi, J.; Liang, J.; Xu, X.; Xiong, G. Effect of konjac glucomannan/carrageenan-based edible emulsion coatings with camellia oil on quality and shelf-life of chicken meat. *Int. J. Biol. Macromol.* **2021**, *183*, 331–339. [CrossRef] [PubMed]
169. Liu, J.; Wang, H.; Wang, P.; Guo, M.; Jiang, S.; Li, X.; Jiang, S. Films based on κ-carrageenan incorporated with curcumin for freshness monitoring. *Food Hydrocoll.* **2018**, *83*, 134–142. [CrossRef]
170. Zhang, R.; Wang, X.; Li, L.; Cheng, M.; Zhang, L. Optimization of konjac glucomannan/carrageenan/nano-SiO_2 coatings for extending the shelf-life of *Agaricus bisporus*. *Int. J. Biol. Macromol.* **2019**, *122*, 857–865. [CrossRef] [PubMed]