

Polysaccharide-based natural polymer for an eco-friendly food packaging material

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Abstract—Polysaccharide, one of the most abundant polymers in nature, is utilized in diverse industrial fields, ranging from food to medicine, owing to its unique functional features and biological activity. The increased global interest in current environmental issues, particularly in the food industry, has provoked the need for bio-based polymers as alternatives to synthetic polymers. As raw materials for food packaging, polysaccharide-based polymers have significant merits, including biodegradability, antioxidant or antimicrobial activity, flexibility, and barrier properties (ultraviolet (UV), oxygen, moisture, and carbon dioxide). Molecular modifications to overcome the difficulties in physicochemical properties and incorporate nanoparticles, plasticizers, or other natural extracts for synergetic improvement of functionality are necessary to develop the packaging technology. Recently, increasing innovations in eco-friendly packaging technologies have facilitated polysaccharides to achieve favorable characteristics replacing conventional packaging materials. This paper focuses on six polysaccharides used most widely in food packaging and describes their desirable barrier and mechanical properties, advantages/disadvantages, and strategies to surmount the intrinsic limitations of each candidate. Recent studies on functionality are also discussed.

Keywords: Polysaccharide, Natural Polymer, Food Packaging, Film, Coating

INTRODUCTION

Polysaccharides are one of the most abundant polymers in nature. They consist of mono- or disaccharide repeating units linked by glycosidic bonds up to tens to thousands of daltons [1-3]. The abundant hydroxyl groups of polysaccharides are responsible for hydrogen bonding, which promotes water absorbance and solubility [1]. These hydroxyl groups have also been manipulated as active sites for chemical modification [4]. In addition to hydroxyl groups, sulfuric groups are found in many polysaccharides, which act as antioxidants [5]. The many charged groups and long-chain network structures facilitate physical interactions and helical gelation [6,7]. Thus, the unique functional features and biological activities of polysaccharides have been utilized in diverse industrial applications, ranging from food and textiles to medicine [8,9].

In the food industry, petroleum-based polymers have been regarded as an excellent material in food packaging for decades owing to their excellent processability and mechanical stability [10]. The increasing awareness of critical environmental issues, such as pollution resulting from the production and persistence of waste from conventional synthetic polymers, has spurred a growing demand for biopolymers as environmentally friendly alternatives. Polysaccharide-based polymers, derived from sustainable and renewable natural resources, offer significant merits, including biodegradability, antioxidant or antimicrobial activity, flexibility, and excellent barrier properties against UV radiation, oxygen, moisture, and carbon

dioxide (Fig. 1). These attributes make them attractive candidates for addressing environmental concerns and promoting sustainability in various industries [10-14]. The biodegradable nature of polysaccharide-based polymers ensures that they undergo natural degradation processes, mitigating the long-term environmental impact posed by conventional polymers. Furthermore, certain polysaccharides exhibit valuable antioxidant or antimicrobial properties, which can enhance the preservation and safety of packaged products. The versatility and adjustable mechanical properties of these polymers enable their application in a wide array of contexts, ranging from rigid packaging to flexible films. Consequently, researchers and



Fig. 1. Requirements for eco-friendly food packaging material.

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industries are actively exploring the potential of polysaccharide-based polymers in diverse fields, such as food packaging, biomedical devices, and agricultural practices, with the aim of embracing more sustainable and ecologically responsible materials [11,15,16]. Those properties are requirements of food packaging materials now heading to eco-friendly packaging [17]. Moreover, according to the US Food and Drug Administration (FDA), several food-grade polysaccharides are known as ‘generally recognized as safe’ (GRAS). Thus, they have been widely exploited as food additives, such as plasticizers, texturizing reagents, emulsifiers, stabilizers, and thickeners, which are safe to eat and digest [18]. They have also shown great potential for utilization of edible packaging material, which is one of the most promising materials [11].

On the other hand, polysaccharide-based polymers have poor mechanical durability, limiting their practical material applications [19]. Various strategies such as molecular modification and incorporation of additives (plasticizers, metallic nanoparticles, plant extracts, organic acids, essential oils, etc.) aimed to improve mechan-

ical properties of polysaccharide-based packaging materials have been required [14,20].

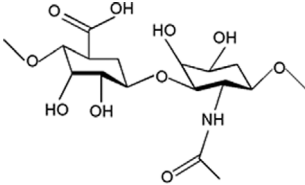
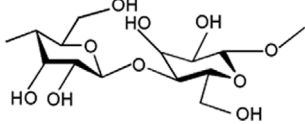
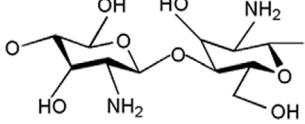
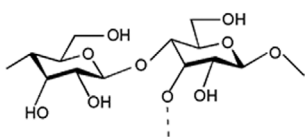
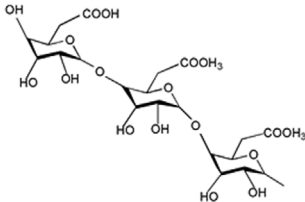
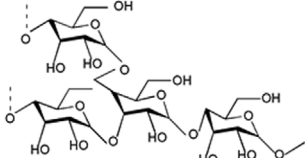
In this review, the most widely used polysaccharides (alginate, cellulose, chitosan, gums, pectin, and starch) in the food packaging area were chosen to review the previous studies. This review examines the structures, sources, characteristics, and advantages/disadvantages of each material for packaging utilization. In addition, molecular modifications to enhance the physicochemical properties or blend with other partner materials to overcome the intrinsic limitations are discussed. Understanding recent studies on the functionality of polysaccharides will provide useful information when applied to food packaging materials.

POLYSACCHARIDE-BASED FOOD PACKAGING MATERIALS

1. Alginate

Alginate (alginic acid or algin) is a linear anionic polysaccharide

Table 1. Structure, sources, and characteristics of polysaccharides

Materials	Structure	Sources	Functional property	Reference
Alginate		<ul style="list-style-type: none"> • Brown seaweed • Bacteria (<i>Azotobacter vinelandii</i> and <i>Pseudomonas</i> spp.) 	<ul style="list-style-type: none"> • Calcium-binding property • Gel forming property • Emulsification property • Oxygen permeation inhibition property 	[21-23,28-31,33]
Cellulose		<ul style="list-style-type: none"> • Cell walls • Envelopes of plants or bacteria (<i>rhizobium</i> or <i>agrobacterium</i>) 	<ul style="list-style-type: none"> • Gelling property • Alternation of the structure • Antibacterial property 	[62,63,71,72,78]
Chitosan		<ul style="list-style-type: none"> • Shell of crustaceans (shrimp and crab) • Cuticle insect fungi's cell membrane 	<ul style="list-style-type: none"> • Ionic interaction • Antiviral, antibacterial activity • Free radical stabilizer • Self-aggregation property 	[80,84-87]
Gums		<ul style="list-style-type: none"> • Plant • Microorganism 	<ul style="list-style-type: none"> • Viscosity-forming property • Antioxidant activity • Emulsification property • Ionic interaction property (gum arabic) • Alternation of the structure 	[98,103,104, 107,108,125,126]
Pectin		<ul style="list-style-type: none"> • Plants' cell wall • Homogalacturonan, rhamnogalacturonan I, II 	<ul style="list-style-type: none"> • Gelling property • High melting point • Emulsification property • Antioxidant property • Electrolyte leakage and cell death inducer 	[133,135,138,139,142]
Starch		<ul style="list-style-type: none"> • Granulated forms (e.g., corns, sweet potato, wheat, cassava, tapioca, rice, quinoa) 	<ul style="list-style-type: none"> • Transparency • Gelation ability • Hydrophobicity • High mechanical strength 	[167-169,175,189]

naturally derived from brown seaweed or bacteria (*Azotobacter vinelandii* and *Pseudomonas* spp.) [21-23]. The production yield was varied at extraction conditions and species, resulting maximum yield of 51.8% from brown seaweed [24] and 16.6 g/L using bacterium production [25]. Chemically, alginate is mainly organized by two subunits, β -D-mannuronic acid (M) and α -L-guluronic acid (G), varied by their natural sources (Table 1) [26,27]. The M/G combinations and their molecular weights can be tailored easily within bacteria, resulting in at least 200 different alginates with a range of physical and chemical properties [20,23].

The most distinct characteristic of alginate is its calcium-binding ability (formation of “egg-box” structure) [28,29], which allows it to transform into flexible fabricants and retain water. Hydrogels, films, beads, sponges, and fibers can be fabricated easily with this simple calcium-assisted physical crosslinking [30,31]. This crosslinking leads to additional enhancement in tensile strength by up to two times [32]. Crosslinking with calcium ions also promotes low water solubility correlated with the WVP by reducing the alginate chain mobility [33]. The addition of ethanol as a co-solvent into the CaCl_2 solution improves the Ca^{2+} crosslinking degree, visual appearance, surface homogeneity, and thickness, which is attributed to reduced moisture permeability of films [34,35]. Moreover, sucrose and monovalent cations (Na^+ and K^+) have also been utilized to form film materials as a crosslinking modifier for uniformity of film surface external gelation [34,36].

Since 1970, alginate has gained FDA approval as a GRAS substance, solidifying its position as a widely used ‘edible’ additive in the food industry. Its applications include serving as a gel-forming agent, emulsifier, thickener, and stabilizer [13,20,37-39]. Alginate’s tasteless and scentless properties further enhance its appeal as a food additive. It meets stringent purity standards for food additives, with specified limits for $\text{As} < 3 \text{ mg/kg}$, $\text{Pb} < 5 \text{ mg/kg}$, $\text{Hg} < 1 \text{ mg/kg}$, $\text{Cd} < 1 \text{ mg/kg}$ and formaldehyde $< 50 \text{ mg/kg}$ [40] (Table 2). Commercially available alginate, purified through a multi-step extraction process to meet these purity criteria, has shown no immunore-sponse when ingested or implanted into animals [21]. The sulfate groups of alginate hinder oxygen permeation, which also benefits

its application as a food packaging film [1]. The sustainability of alginate films was evaluated in terms of their degradation rate. The study revealed that alginate-based films with a thickness of 100 μm demonstrated nearly 100% weight loss after 72 hours at room temperature. It was observed that the degradation rate of these films could be influenced by factors such as film thickness, cross-linking density, incorporation of additives, and environmental conditions [41].

On the other hand, the relatively low mechanical stability and poor moisture barrier properties owing to its high hydrophilicity made alginate packaging intrinsically brittle and vulnerable to bacterial infections [13,42,43]. Alginate often requires additional cross-linkers or plasticizers (e.g., glycerol) to increase mechanical properties and overcome these deficiencies [44]. The plasticizer glycerol replaces the crystallinity in the alginate polymer chain with hydrogen bonds and increases Young’s moduli 3.19 times [45]. It also lowers water vapor permeability (WVP) by 5.18 fold compared to the non-crosslinked one [44]. Xylitol and mannitol were also utilized for plasticizers to crosslink film materials [46]. Both tensile strength and elongation at a break value were improved compared to uncrosslinked alginate films by 2.3-fold and 2-fold, respectively [47]. Sulfur nanoparticles also affect the mechanical strength and control of WVP. The incorporation of 2 wt% sulfur nanoparticles resulted in a 12% and 41% increase in tensile strength and water vapor resistance, respectively, compared to non-added films [48]. Blending cellulose nanocrystals is another approach to reinforce alginate for packaging applications [32,49,50].

Incorporating nanoparticles (sulfur, silver, zinc oxide, and titanium dioxide) sometimes enhances the antimicrobial properties and UV protection ability by promoting the colorimetric shield effect [51-53]. Sulfur nanoparticles decrease the transparency of films and improve UV protection [54]. Zinc oxide, graphene oxide, and sepiolite were blended with alginate film to provide electrical conductivity for packaged food sterilization under ohmic heating and an electric field [33]. Recently, essential oil and plant extracts have been utilized to develop active packaging films due to their retention, antioxidant and antimicrobial properties [55-57]. As additives in

Table 2. Industrial requirements for polysaccharide based-food packaging

Materials	Price range* (\$/100 g)	GRAS	Required level of purity	Sustainability (Degradation)	Reference
Alginate	10.7-22.2	FDA approval	As < 3 mg/kg Pb < 5 mg/kg Hg < 1 mg/kg Cd < 1 mg/kg Formaldehyde < 50 mg/kg	100%	[20,21,40,41]
Cellulose	17.4-17.5	FDA approval	NA**	>80%	[64,66]
Chitosan	16.7	FDA approval	NA**	>80%	[83,88]
Gums	17-140	FDA approval	NA**	>80%	[101,118]
Pectin	87.9-135.8	FDA approval	<65% AUA content	100%	[138,145,147]
Starch	8.9-65.1	FDA approval	NA**	>90%	[172]

*Price range is referred to Sigma Aldrich of each commercial product, **NA intended no value available, GRAS: Generally Recognized As Safe, FDA: Food and Drug Administration, AUA: anhydrouronic acid

film materials, silver nanoparticles and lemongrass essential oil act in a synergic way to preserve the softness of surface texture and the color of cheese against both Gram-negative and Gram-positive for up to 14 days [58]. Besides, guava leaf water extracts enhanced the antibacterial properties of films by 1.6-times higher than non-added films owing to their intrinsic phenolic compounds (gallic acid, ellagic acid, avicularin and quercetin) [59].

2. Cellulose

Cellulose is a linear D-glucose chain joined with β -1,4-glycosidic bonds [60], primarily in the cell walls or envelopes of plants (yield: 10-17%, varies depending on the extraction methods) or bacteria (*rhizobium* or *agrobacterium*, yield: 13-63%, varies depending on the culture condition) and it is sorted as GRAS by the FDA [61-64]. Cellulose, derived from sustainable plant-based sources, is abundantly produced with an estimated annual yield ranging from 10^{11} to 10^{12} tons. This biopolymer can be readily degraded into oligosaccharides or glucose through various processes, including heat treatment, soil decomposition, or enzymatic digestion [65]. When subjected to thermal treatment, cellulose exhibits a significant mass loss rate of up to 80% at 400 °C [66]. Notably, bacterial cellulose possesses a significantly higher level of purity compared to plant cellulose due to the absence of unnecessary chemical materials in its extraction and purification processes [67].

Cellulose is characterized by high strength by hydrogen bonds and van der Waals forces between the fibers and their bundles. The strong hydrogen bonding and van der Waals force tightly pack the cellulose fibers, reducing the solubility in an aqueous solution [68]. The tensile strength and Young's modulus of cellulose are 7,500 MPa and 140 GPa, respectively [69]. The abundant hydroxyl groups interact ionically with nanoparticles, which overcomes the limitation of adhesion between nanoparticles [70]. The silver nanoparticle-mixed cellulose coating prolongs the shelf life of strawberries to seven days [71].

Many cellulose derivatives have been reported, including carboxymethylcellulose (CMC), hydroxypropyl cellulose (HPC), hydroxyethyl cellulose (HEC), and cellulose acetate (CA) [71,72]. Because the physical and chemical properties vary according to the cellulose derivatives, it is possible to tune the properties as desired. Especially, CMC has a high solubility in water compared to other cellulose derivatives [73]. In the food packaging fields, carboxymethyl cellulose (CMC)-based films exhibit appropriate UV barrier activity, tensile strength, and thermal stability that helps keep vitamin C in red chilies for a week [74]. For cellulose acetate (CA), its pore size or its morphology, mechanical properties, and thermal stability are manageable by its concentration [75,76].

The cellulose from bacteria known as bacterial cellulose (BC) has high purity and consists of dense nanofibril [77]. Thus, it has a point such as physicochemical, mechanical, and biological properties. The BC is blended with CMC for producing films that have high soluble, mechanical properties and antibacterial activity [78]. These films indicate great water solubility, flexibility and antibacterial activity for gram-negative and positive bacteria [78]. The oranges and tomatoes coated in this film have good ability in maintenance until 42 days on 6 °C [78]. The edible food film that BC is blended with is whey protein (WP) [79]. It gives the film more crystallinity and synergy for the effect of antibacterial activity to film because

both materials have antibacterial activity [79]. The mechanical properties of the film improve from 2.5 MPa to 120 MPa [79].

3. Chitosan

Chitosan is a linear polysaccharide isolated from the shell of crustaceans (shrimp (yield: 30-40%) and crabs (yield: 15-30%)), insect cuticles (yield: 5-25%), and fungi cell membranes (yield: 10-25%) [80]. Chitosan is a long chain of D-glucosamine and N-acetylglucosamine, deacetylated from chitin [81]. Repurposing waste from the seafood industry to produce this biomaterial contributes to environmental sustainability. Chitosan exhibits a significant mass loss rate of up to 80% at 250 °C [82,83]. Its cationic acetyl amine effectively interacts with anionic partners [84], such as the surface of viruses or bacteria [85] or metal ions [86]. As for amino and carboxyl groups of chitosan, it stabilizes free radicals from oxidation caused by cell membrane damage or enzymic browning of fruit or vegetables [87].

Chitosan is classified as GRAS by the FDA [88], and its biodegradability has been verified from diverse experiments. In addition, it has been widely considered an antibacterial, antioxidant, and edible food packaging material [89]. In particular, its ease of fabrication has allowed chitosan to be formulated into diverse forms, such as gels, films, nanoparticles, coatings, and nanofibers. As of today, many commercial products are on the market, including chito plant (ChiPro GmbH, Germany), Oll-YS (Venture innovation, US), kaitoSol (Advanced green nanotechnology Sdn Bhd, UK), and chitosan antibacterial storage bags (Wells, Republic of Korea) [90].

Several attempts have been made to improve the desired properties of chitosan [82]. For example, sodium hydroxide was used as a cross-linker to reinforce chitosan-based film-generating hydrogen bonds. With sodium hydroxide, the NH_3^+ groups on the chitosan are deprotonated to amino groups (NH_2) [91]. Chitosan has self-aggregation properties due to -OH and - NH_2 groups [92]. Thus, the film is produced by blending with different molecular weights of chitosan, carboxymethyl cellulose and curcumin. This complex film improves the elongation of break value by rising the molecular weight of chitosan until 1,700 kDa [93]. The resulting effect of dense crosslinking is reducing the oxygen permeability and water vapor permeability. The dense structure and its resulting increased mechanical properties are exerted by combining chitosan and other material, such as gelatin. This prevents water loss and reduces the cell wall damage of vegetables or fruit [94]. Sometimes a small amount of essential oil promotes the flexibility and transparency of chitosan films. A chitosan film with rosemary essential oil exhibited a 1.5-fold increase in visible light transparency with 25% reduced UV light transmission [95]. The functional activity can be given to food packaging film. The chokeberry extraction that has antioxidant activity is combined with chitosan film, and the chitosan film that is added to the extraction increases the water vapor permeability and reduces oxygen permeability (0.17 mmol/100 g film to 0.56 mmol/100 g film) [96].

4. Gums

Gum is a natural polysaccharide derived from plants or microorganisms with excellent biodegradability, biocompatibility, non-toxicity, and odorlessness. The viscosity-forming ability of gums, which originates from the high number of hydrogen bonds, has

allowed them to be exploited as a food packaging material [97].

4-1. Gum Arabic

Among plant-derived gum, gum arabic is most often used in films for food preservation. Gum arabic is one of the exudates obtained from tree trunks of various acacia species, mainly *Acacia Senegal* and *Acacia Seyal* [98]. *Acacia Senegal* tree has the highest production per season, yielding several kilograms [99]. It is a heteropolysaccharide consisting of L-arabinose, L-rhamnose, and D-glucuronic acid with 1,3-linked β -D-galactopyranosyl units throughout the backbone [100]. In the case of gum arabic, it has been proven to be safe as an FDA-approved GRAS material and is known as a sustainable eco-friendly material. For instance, studies on alginate and gum arabic-based sponges demonstrated a weight loss of up to 80% after 48 hours, indicating significant biodegradability [101]. Similarly, gum arabic-based bioplastics designed for eco-friendly food packaging showed complete biodegradation within 15 days [102].

Gum arabic is negatively charged by the deprotonation of the carboxyl group attached to the glucuronic acid residue, which has a strong interaction with other biomolecules of positively charged materials [103]. In one study, positively charged chitosan and cinnamon essential oil were used with gum arabic to produce a film with higher antioxidant activity through the strong interaction between chitosan and gum arabic [104]. In addition, various methods have recently been studied to contain higher antioxidant and functional spices by encapsulating polyphenols and essential oils through complex coacervate formation between protein separation and gum arabic [105,106].

Gum arabic has been manipulated as a long-lasting microencapsulation material based on its amphiphilic behavior with antioxidant properties [107,108]. Various modification methods have been used to improve these characteristics. The modification of gum arabic using trimetaphosphate dramatically improved emulsification by increasing viscosity, swelling properties, and particle size distribution and showed efficient encapsulation of the *Cymbopogon citratus* essential oil [109]. Ultrasonic treatment does not require an organic solvent, and since it is a non-heat treatment technology, it can be used in the food industry. It has been shown that the antioxidant ability, antibacterial properties, and various physicochemical properties of polysaccharides can be improved by ultrasonic modification, and the encapsulation efficiency of polyphenols is improved by 74.2% through complex coacervate and ultrasonic treatment [110,111]. In addition, the deformation of gum arabic due to the Maillard reaction and ozone treatment improved emulsification properties and antioxidant ability [112-114].

4-2. Xanthan Gum

Xanthan gum is a bacterial exopolysaccharide obtained from *Xanthomonas campestris*, which can be obtained at a high yield of 14.744 g/L when glucose is used as a carbon source [115]. It has a D-glucose backbone linked by a 1 \rightarrow 4 glycoside bond with trisaccharide side chains (D-mannose, glucuronic acid, and D-mannose) [116]. The pyruvyl group attached to the terminal mannose residue promotes intermolecular interactions to improve the solution viscosity and storage modulus [117]. The negatively charged carboxyl groups (COO⁻) make xanthan gum anionic and dissolve well in water with high viscosity. Xanthan gum exhibits high bio-

degradability. When combined with polyacrylic acid blended hydrogel, it showed biodegradation rate of about 80% after 70 days [118]. The biodegradation of pure polyvinyl alcohol (PVA) films, starch, and chitosan blended PVA films took at least 12 days, while xanthan gum blended PVA food packaging films were all absorbed into the soil and biodegradable in just 12 hours, indicating very high biodegradability [119]. The FDA mandates that the residual concentration of isopropyl alcohol used in the extraction process must not exceed 750 ppm. For xanthan gum to be recognized as a safe GRAS material, it must pass both the Locust bean gum gel test and pyruvic acid test, meeting the stringent safety standards set by the FDA. This makes xanthan gum a valuable component for thickening, emulsifying, and stabilizing various food products [120].

Xanthan gum can change its properties by causing a variety of chemical and physical modifications. The low-temperature plasma treatment may be applied in the food industry by removing pollutants, improving oil retention capacity, and reducing hydroxyl groups [121]. The lysozyme-xanthan gum combined through the Maillard reaction has antioxidant properties, and the mixed film with natamycin has proven its performance as a cheese preservation film [122]. In addition, carboxymethylation, thiol derivatization, and alkylation can increase the utilization of xanthan gum by modifying various rheological properties, such as improving solubility or improving emulsion properties [123-125]. Methacrylic acid is grafted with various polysaccharides to provide antibacterial and moisture stability, and in the case of xanthan gum, methacrylic acid can be grafted through a Fe²⁺/H₂O₂ redox initiator [126]. Even without the use of such modified xanthan gum, xanthan gum is being studied as an eco-friendly coating in combination with lipids [127, 128], proteins [129], and polysaccharides [130,131], and by-product-based natural materials for cost reduction are also considered to be mixed with xanthan gum [132].

5. Pectin

Pectin is one of the main hetero-polysaccharides in the cell walls of higher terrestrial plants (e.g., up to 4.0% of the total fresh weight of plants), allowing cell extension and plant growth [133]. Due to its abundance, the yield of pectin isolated from mango peels, for instance, ranged between 14.6-28.42% (based on a dry weight) varied by extraction conditions [134]. Homogalacturonan (HGA), rhamnogalacturonan I (RG-I), and rhamnogalacturonan II (RG-II) are three main domains in the complex structure of pectin [135]. Among them, approximately 70% of the entire length is from HGA, which constitutes α -D-galacturonic acid monomers linked via glycosidic α -(1 \rightarrow 4) bonds [136]. It has a wide range of degrees of methyl-acetyl esterification [137]. Methyl-esterification modified the carboxyl group of the C-6 carbon and acetylation occurs at the O-2 or O-3 position [136]. Depending on the degrees of methyl-acetyl esterification, pectin can be classified into high-methoxyl (>50%) and low-methoxyl (<50%) types, which determines the viscoelastic functionality [138]. This eventually impacts the gelation process and film formation [139,140]. Generally, in the presence of calcium ions, low methoxyl pectin (LMP) shows egg-box structures stabilized by van der Waals interactions and hydrogen bonds between the free carboxyl groups and methylated groups, resulting in a physically crosslinked network [135]. While for high methoxyl

pectin (HMP), esterified carboxyl groups reduce the hydration of hydrophobic interactions and electrostatic repulsion between molecules, leading to aggregation of pectin chains [141]. In addition to methyl-acetyl esterification, botanical origin, and extraction methods also alter pectin's chemical or physical properties of pectin [135,142]. Pectin can be readily extractable by chemical (enzymes) or physical (pressure, ultrasound waves, or microwaves) methods, unlike other conventional polysaccharides requiring multiple hydrolysis processes [142].

The purity of pectin is gauged by its anhydrouronic acid (AUA) content, which is determined based on the degree of hydrolysis of neutral sugars under various extraction conditions such as pH and temperature [143]. At higher strength of acidic condition, the percentage of galacturonic acid is high, implying high purity [144]. According to the Food and Agriculture Organization (FAO) and the Food Chemical Codex (FCC), pectin with less than 65% of AUA content can be commercially marketed with ensured purity, meeting the legislative requirements for its application in food [145].

Pectin is a molecular-modified material that exhibits rapid gelation in a few minutes [146]. In addition, it has a higher melting temperature and gas/moisture barrier properties [133]. Modified pectin has a high potential for use in flavor materials encapsulation and degradable bioplastic materials instead of synthetic polymers for food packaging [146]. Notably, pectin films stand out as a compelling substitute for plastic packaging materials, as they can thoroughly degrade within 30 days when incubated in both seawater and soil environments [147]. It has also been used as an additive agent for stabilizing, gelling, texturizing, emulsifying, and thickening products, such as jellies, ice cream, jams, and yogurt drinks [148]. Pectin is also listed as GRAS by the FDA [138].

LMP is suitable for edible coatings owing to the calcium ion-assisted fast gelation [149]. In contrast, HMP is used for rigid films (20 ± 7 MPa of tensile strength) by increasing the surface density, thermal stability, and gas-moisture barriers, such as water, oxygen, or carbon dioxide [135,139]. Moreover, pectin scavenges undesirable elements that occur in the oxidation process, such as radical oxidative species, oxygen, or acidic compounds [138]. It eventually helps prolong the shelf-life of packaged food: up to five days for persimmon and apples [150,151], eight days for strawberries [152], nine days for chicken thighs [153], and over thirty days for peanuts [154].

As a similar stream, diverse functional elements have been incorporated into pectin to exert antimicrobial activity. Examples include phenolic compounds, free fatty acids, nanoparticles, and other natural bioactive compounds [155-157]. Once the functionalized pectin penetrates through a microbial membrane, it induces electrolyte leakage and cell death [142]. For greater antioxidant activity and oxygen barrier properties, diverse antioxidants naturally present in plants (e.g., olive, cocoa bean shell, and mango peels) have been used for as additives [158,159]. Especially, for example, pectin-based films added with olive extracts and beeswax reduced lipid oxidation of packaged meat by 100% during 7 days [160].

Blending other polysaccharides (e.g., chitosan and gums) or proteins (e.g., gelatin and sodium caseinate) also improves the thermal (from around 97.8°C to 102.1°C) and mechanical properties (tensile strength of up to 58.51 MPa) [161-164]. Recently, various

pectin/natural polymeric compound-based bioactive films functionalized with reinforcements were developed in intelligent packaging which capable of monitoring freshness or chilling tolerance [165,166].

6. Starch

Starch, the main ingredient in most cereals, is composed of amylose (a linear polymer of $(1 \rightarrow 4)$ - α -linolen) and amylopectin (a branched polymer of $(1 \rightarrow 6)$ -linolen), obtained from a granulated form of various sources, such as corn, sweet potatoes, wheat, cassava, tapioca, barley, rice, and quinoa [167-169]. It can be obtained in a high yield of up to 89% from various barley varieties [170], and in the case of corn, it has a starch content of more than 80%, and can be obtained in a yield of more than 50% [171]. Starch is a GRAS material that has been approved by the FDA as a food additive for various modifications such as acid reforming, esterification, and etherification. In addition, starch has been manipulated actively into films or gas barrier membranes based on its biodegradability, transparency, and gelation ability. In particular, starch films extracted from cassava, sweet potatoes, and potatoes demonstrated more than 90% total weight reduction after 31 days, of which cassava starch films exhibit an impressive 99% weight reduction, showcasing their exceptional biodegradability [172]. Its colorless, tasteless, and odorless merits are particularly beneficial for edible films and materials [173].

Despite its excellent ability as a film and coating material, the branch configuration of amylopectin deters strong hydrogen bonds between the hydroxyl groups [174,175]. Currently, many reports have overcome this limitation by the selective extraction of amylopectin from 50°C to 70°C , or amylose conversion to amylopectin by ultrasonic-assisted extraction [172,176,177]. Glucoamylase can increase the amylose content through hydrolysis [178]. Thus, increasing the relative content of amylose over amylopectin provides more hydrogen bonding sites and enhances the hydrophobicity and mechanical strength to be exploited as gas barrier membranes [175,179].

Another approach is the chemical modification of starch. A large number of active hydroxyl groups are valuable sites to conjugate guest groups [180-182], such as polyols (glycerol, sorbitol, and xylitol), which increase hydrophobicity and reduce brittleness [183, 184]. Acetylation of starch is another effective method of lowering hygroscopicity [185,186], and succinate is improved by substituting hydroxy groups to reduce polarity, thereby improving moisture-blocking properties [187,188]. In addition, moisture stability may be improved through grafting methacrylic acid of starch [189] and crosslinking of citric acid [190].

Starch nanocrystals (SNCs), through acid hydrolysis, are supplemented with thermoplastic starch to improve mechanical properties and moisture barrier properties. However, the addition of a high concentration of SNC resulted in a significant reduction in tensile strength due to the cohesion effect between SNCs [191]. To prevent such an agglomeration effect, SNC may be cross-linked and deformed using sodium hexametaphosphate or glutaraldehyde to reduce the agglomeration of SNC and improve dispersion [192].

The physical modification method of starch includes treating plasma, ultraviolet rays, heat treatment, etc. Sulfur hexafluoride

(SF6) plasma treatment increased the hydrophobicity of starch [193], and crosslinking through ultraviolet treatment improved mechanical strength, moisture resistance, with surface hydrophobicity characteristics [194,195]. Denaturation through microwave heat treatment increased the amylose content of starch [196].

Recently, the characteristics of starch-based films have been improved at low costs through natural materials obtained from various by-products. Various properties such as moisture barrier properties, mechanical properties, and transparency could be improved in the case of mixed films with lignocellulose nanofibers extracted from Casaba bagasse [197], succinic-modified starch films containing nut by-product extracts [198], and acetylated sugar cane bagasse fiber and acetylated starch mixed film [186].

CONCLUSION

Consumer interest in health and the environment has raised environmental concern regarding synthetic polymers, prompting the search for sustainable and eco-friendly alternatives to replace current plastic and synthetic materials used in food packaging. Among these alternatives, polysaccharides have been proven to have excellent important properties such as barrier properties, biocompatibility, biodegradability, and transparency, and they are attracting considerable attention as the next packaging material because they are very inexpensive and advantageous for commercialization. However, polysaccharides have problems with poor mechanical strength and moisture-blocking properties, making it difficult to apply them to packaging materials. Currently, many studies are underway on modification or mixed use with other materials to solve these problems, but these strategies will improve the production cost of products. In order to commercialize polysaccharide packaging in the future, many studies on cost-effective strategies to solve problems should be continued.

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CONFLICT OF INTEREST

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

ETHICAL STATEMENTS

Neither ethical approval nor informed consent was required for this study.

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