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Application of Polysaccharide-Based Materials in Food Packaging

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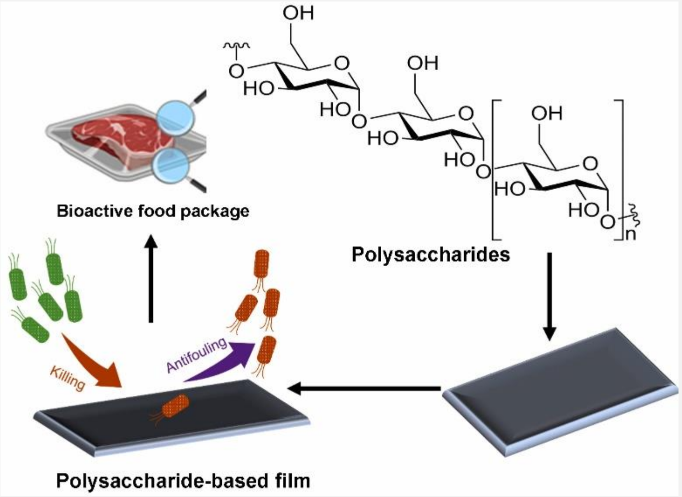
ABSTRACT

This short review provides an overview of the applications of polysaccharides in food packaging and their pivotal role in addressing sustainability and food preservation challenges. Polysaccharides such as chitosan, cellulose, and starch have emerged as eco-friendly alternatives to traditional synthetic packaging materials. They offer various advantages including biodegradability, renewability, and the ability to tailor their properties to meet specific packaging requirements. These polysaccharide-based materials serve as essential components in food packaging applications such as wraps, coatings, and sachets. They not only contribute to reducing the environmental footprint of the food packaging industry but also aid in preserving the freshness and safety of food products. Furthermore, polysaccharides can be modified to enhance their moisture resistance, barrier properties, or controlled-release capabilities making them adaptable to diverse packaging requirements. Overall, polysaccharide-based materials have gained significant attention and the growing importance of polysaccharide-based materials in food packaging is underscored by their versatile nature, biodegradability, eco-friendly attributes, and positive impact on sustainability. The adoption of polysaccharide-based materials represents a promising step towards sustainable and effective solutions in the dynamic field of food packaging.



Keywords: Polysaccharide-based materials, modification, food packaging, biocompatibility

1. Introduction

In recent years, the global food packaging industry has been undergoing a significant transformation driven by a growing awareness of the environmental impact of conventional packaging materials and an increasing demand for sustainable alternatives. With increasing concerns about plastic pollution, the carbon footprint of packaging materials, and the depletion of limited resources, there is a need to explore renewable and biodegradable alternatives. Polysaccharides, long-chain carbohydrates composed of multiple sugar molecules have emerged as a promising alternative to address these concerns while maintaining the functionality and safety of food packaging [1]. The use of polysaccharide-based materials is a big step forward in creating eco-friendly and effective packaging. The use of polysaccharides in food packaging is associated with the broader global movement towards sustainability. Polysaccharides which can be sourced from a variety of natural materials such as plants, algae, and even bacteria offer an attractive solution [2].

One of the key advantages of polysaccharides in food packaging is their biodegradability. Unlike traditional petroleum-based plastics which persist in the environment for centuries, polysaccharides can be naturally broken down by microorganisms returning to the earth without leaving harmful residues. This biodegradability minimizes the long-term ecological impact of packaging waste, reducing the burden on landfills, and marine ecosystems [3]. Moreover, polysaccharides are non-toxic with no harm to human health which makes them a safe choice for food packaging applications [4]. As consumers become increasingly concerned about the potential migration of harmful chemicals

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from packaging materials into their food, polysaccharides offer a supporting alternative. Beyond their environmental and health benefits, polysaccharides possess desirable functional properties for food packaging. They can be engineered to provide barrier properties against moisture, oxygen, and other external factors preserving the freshness and quality of food products.

Polysaccharides can also be tailored to create films, coatings, and containers with excellent mechanical strength and flexibility ensuring the protection and convenience that consumers expect [5]. Polysaccharides are abundant in nature and serve a multitude of critical functions in living organisms, as well as playing significant roles in various industrial and scientific applications. In nature, polysaccharides serve as essential energy storage compounds (e.g., glycogen in animals and starch in plants) and provide structural support to cells and organisms (e.g., cellulose in plant cell walls). They also function as signaling molecules and play critical roles in cell adhesion, immune responses, and various physiological processes. Beyond their biological significance, polysaccharides have found extensive utility in human attempts [6,7]. In the food industry, they serve as thickening agents, stabilizers, and emulsifiers. In pharmaceuticals, they are used as drug carriers and excipients [8]. In materials science, they contribute to the development of biodegradable plastics, films, and hydrogels. Furthermore, polysaccharides hold immense potential in emerging fields like tissue engineering, drug delivery, and renewable energy production [9].

In essence, the importance of the application of polysaccharide-based materials in food packaging extends beyond functional benefits. It represents a transformative step towards a more sustainable and environmentally conscious packaging industry. By integrating these materials into packaging solutions, the food industry not only addresses current environmental challenges but also anticipates and contributes to the evolving expectations of consumers who seek products aligned with responsible and eco-friendly practices [3,10]. The different applications of polysaccharide-based materials in food packaging showcase their adaptability and effectiveness in addressing various packaging applications and challenges, offering a range of functionalities that contribute to both the preservation of food quality and the promotion of sustainable packaging practices [3,11]. Several key applications highlight the versatility of polysaccharides in this context comprising edible films and coatings, biodegradable packaging, active packaging systems, barrier coatings, nanocomposites, biodegradable sachets and pouches, and modified atmosphere packaging (MAP) [1,12–14]. This short review explores the exciting developments and applications of polysaccharides in food packaging. It investigates briefly the diverse sources of polysaccharides, the modification techniques, the unique properties, and the safety concepts that make them suitable for food packaging applications.

2. Polysaccharides and their properties

Polysaccharides, long-chain carbohydrates composed of multiple sugar molecules have got increasing attention as a sustainable and multipurpose alternative with remarkable properties in the field of food packaging [1]. In a world increasingly concerned with plastic pollution and the long-lasting environmental impact of non-biodegradable materials, the biodegradability of polysaccharides is a notable advantage. While traditional petroleum-based plastics persist in the environment for centuries, polysaccharides are naturally degraded by microorganisms returning to the ecosystem as harmless compounds. This essential biodegradability improves the burden on landfills. Furthermore, the sustainability of polysaccharides is underscored by their renewable sources. By reducing the reliance on limited fossil fuel resources, polysaccharide-based materials align with the principles of a circular economy contributing to a more sustainable packaging landscape [3]. Additionally, in the context of food packaging, safety is dominant. In this regard, polysaccharides are generally recognized as safe for food contact. Their natural origin ensures that they do not release harmful chemicals into food products addressing concerns about potential health risks associated with packaging materials. This inherent safety makes polysaccharides a reliable choice for preserving the integrity and safety of packaged food items. Moisture resistance, oxygen barrier characteristics, heat sealability, flavor and nutrient encapsulation, and film-forming capabilities are the other unique properties of polysaccharides that make them suitable for specific packaging purposes [15,16].

One widely used polysaccharide in food packaging is chitosan which derives from chitin found in the shells of crustaceans like shrimp and crab [17]. Another prominent polysaccharide is cellulose sourced from plant materials such as wood pulp, cotton, and paper. Cellulose films can be used in various food packaging applications including wrapping, sachets, and edible coatings reducing the environmental impact associated with traditional plastic packaging [18,19]. Starch is yet another polysaccharide utilized in food packaging. Starch-based films are biodegradable and possess good mechanical strength. They are commonly employed in single-use packaging materials and bioplastics that offer a sustainable alternative for a range of food products [3,15].

Polysaccharides exhibit varying degrees of solubility in water which is influenced by factors such as the type of sugar units, branching, and the presence of functional groups [2]. Some, like cellulose, are insoluble in water and contribute to the structural integrity of plant cell walls while others such as starch and glycogen are highly soluble and serve as energy storage molecules [21]. Moreover, many polysaccharides, especially those with long linear chains have the property of high viscosity in aqueous solutions [22]. This makes them valuable in the food industry as thickening agents and stabilizers improving the texture and stability of various products from sauces to ice creams [23,24]. Polysaccharides are also typically biodegradable and break down by natural processes into simpler compounds. This property is especially important in the development of environmentally friendly materials such as biodegradable plastics and films as they reduce the burden of non-recyclable waste [3].

Additionally, the hydrophilicity of polysaccharides is noticeable which makes them hydrophilic (**Table 1**). This property allows them to retain moisture making them useful in various applications such as in skincare products and wound dressings where maintaining a moist environment is beneficial for healing [25]. Gelling and Thickening features of polysaccharides like agar and pectin give the ability to form gels when exposed to certain conditions such as heat or changes in pH. These gelling properties are exploited in food products like jams and jellies [21]. Other polysaccharides like xanthan gum act as efficient thickeners in both food and industrial applications [26,27]. Bioactivity, Renewability, and Compatibility are the other properties of polysaccharides [3,23,24]. Certain polysaccharides derived from natural sources such as seaweed-derived carrageenan and bacterial-produced hyaluronic acid exhibit bioactive properties. They have been used in pharmaceuticals and medical applications including wound healing and drug delivery systems [30,31]. Many polysaccharides are derived from renewable resources such as starch from corn or cellulose from wood making them attractive for sustainable materials and biofuel production to reduce the reliance on limited fossil resources. Also, polysaccharides often exhibit compatibility with other materials which is valuable in composite materials and pharmaceutical formulations. They can be blended or modified to enhance their properties and performance in various applications [3,16].

2.1.Modifications of polysaccharides for food packaging

Research findings indicate that the bioactivities of natural polysaccharides are intricately tied to their inherent characteristics including factors like the types of glycosidic bonds, solubility, relative molecular mass, main-chain configuration, and spatial configuration. Among these factors, the types of glycosidic bonds, modes of connection, and monosaccharide compositions stand out as the most essential as they serve as the primary determinants of whether polysaccharides exhibit bioactivity, while the others primarily influence the degree of bioactivity. The former attributes are inherent to polysaccharides and cannot be altered, whereas the latter can be modified through appropriate methods. Consequently, numerous studies have been concentrated on the alteration of polysaccharides and the synthesis of polysaccharides possessing optimal bioactivities [13].

Molecular modification has the potential to transform the dimensional structure, molecular weight, and the characteristics of substituent groups in polysaccharides, thereby affecting their bioactivities. Thus far, several molecular modification techniques have been developed which can generally be categorized as chemical, physical, and biological modifications, respectively. Chemical modification is a widely adopted approach that can alter the structure of polysaccharides by introducing substituent groups, thereby enhancing their innate bioactivities and generating novel functional properties encompassing sulfation, alkylation, carboxymethylation, phosphorylation, selenization, acetylation, and others [14,32]. On the other hand, physical modification methods aim to break down the original polysaccharide backbone to create lower molecular weight fragments. This method preserves the fundamental structure of the polysaccharides while causing limited conformational changes. Commonly utilized techniques include ultrasonic disruption, radiation-induced reactions, microwave exposure, etc., [33]. Biological modification of polysaccharides primarily is enzyme-driven which involves the degradation of polysaccharides catalyzed by enzymes [34]. In comparison to chemical modification, enzymatic modification boasts several advantages including high specificity, efficiency, and minimal side effects. Enzymatic degradation typically leads to relatively uniform molecular masses of polysaccharide products and has a limited impact on the primary structure of the polysaccharide. Enzymatic degradation primarily focuses on breaking down the polysaccharide backbone which reduces molecular weight and viscosity [12].

The chemical structure of polysaccharides used in food packaging is characterized by long chains of sugar molecules linked together. These sugar units are primarily glucose but they can also include other monosaccharides like fructose, galactose, and mannose depending on the specific type of polysaccharide. Polysaccharides used in food packaging such as starch, cellulose, chitosan, alginate, agar, and pectin consist of repeating sugar units joined by glycosidic bonds. The arrangement and bonding patterns within these structures can vary leading to differences in their physical and chemical properties [2]. In the matter of food packaging, polysaccharides can be subjected to various chemical modifications to optimize their mechanical properties for specific packaging requirements [14].

Tailoring the solubility of polysaccharides is another area of focus for modifications. Some polysaccharides like pullulan are water-soluble making them suitable for certain applications [35]. However, for applications requiring water resistance or controlled release, modifications can be applied to adjust the solubility. Modified polysaccharides are often used in the development of edible coatings for fruits and vegetables to create a protective barrier that maintains product quality. The chemical structure of modified pullulan may include various functional groups and changes to its native structure. For instance, pullulan can be modified through esterification and acetylation processes. These modifications introduce new chemical groups such as acetyl or hydrophobic groups into the pullulan structure. The resulting modified pullulan may have improved water resistance, barrier properties, or mechanical strength and it is better suited for food packaging applications. By tailoring the chemical structure of pullulan through these modifications, it becomes a versatile and customizable biopolymer for creating films, coatings, and edible packaging materials that help protect and extend the shelf life of food products while offering eco-friendly and sustainable packaging solutions [35–37].

Another important modification focus is on improving the water resistance of polysaccharide-based materials. Many polysaccharides are inherently hydrophilic which can be a limitation in applications where moisture barrier properties are crucial. By introducing hydrophobic groups through chemical modifications, polysaccharides can be made more water-resistant. Modified starches, for instance, are used in packaging applications where moisture resistance is essential for some products such as frozen food [38]. Chemical modifications can also be employed to fine-tune the barrier properties of polysaccharide-based materials. For example, polysaccharides can be chemically modified to enhance their oxygen barrier characteristics preserving the freshness of packaged food products. This is particularly relevant in applications where preventing oxidation is crucial such as packaging for fats and oils [36].

Moreover, polysaccharides can be blended with other biopolymers or nanoparticles to create hybrid materials that combine the desirable properties of both components such as improved barrier properties and flexibility [9]. For example, blending alginate with chitosan can result in a material with improved mechanical strength and enhanced barrier properties making it ideal for various food packaging applications [39,40]. Furthermore, enzymatic modifications of polysaccharides offer a more environmentally friendly approach. Enzymes can be used to modify the structure of polysaccharides without the use of harsh chemicals. Enzyme-modified starches, for instance, are used in eco-friendly food packaging as they maintain the biodegradability and sustainability of the material. Another example is maltodextrins made by enzymatic hydrolysis which are short chains of glucose molecules that are used as thickeners, stabilizers, coating, and bulking agents in various food products [41].

3. Applications of polysaccharide-based materials in food packaging

3.1. Cellulose

Cellulose is composed of linear chains of glucose molecules linked together by β-1,4 glycosidic bonds. These long and unbranched chains can consist of thousands of glucose units creating a robust and rigid structure. The arrangement of cellulose chains within plant cell walls forms crystalline microfibrils providing exceptional strength and resistance to degradation. Cellulose is also highly hydrophilic and can absorb and hold water which is essential for its role in plant cell walls. It is concerned for its exceptional mechanical strength and suitability in applications such as paperboard coatings and transparent films. For instance, the study presented a novel paper-based packaging material created by enhancing conventional paper with TEMPO-oxidized cellulose nanofibers (TOCN) and cationic guar gum (CGG) hydrogel film. Precisely, the paper was subjected to a layer-by-layer deposition process to incorporate the hydrogel film resulting in a significant enhancement of the paper's mechanical and barrier properties. To illustrate, the paper modified with a 4-layer hydrogel film exhibited a remarkable tensile strength of 34.03 MPa and a burst strength of 510 kPa. In contrast, the unmodified paper had a tensile strength of 26.78 MPa and a bursting strength of 388 kPa. The packaging capabilities of this TOCN/CGG hydrogel film-modified paper were demonstrated through a successful fresh mooncake packaging test. This hydrogel film not only rendered the paper oil-resistant but also preserved the mooncake's freshness. Consequently, this material represented a sustainable and environmentally friendly solution for food packaging (**Figure 1**) [42].

Cellulose is the most abundant organic compound on the earth found in the cell walls of plants and some algae. The process of extracting cellulose typically involves "Harvesting" from various plants such as wood, cotton, hemp, and other fibrous materials "Pulping" separates cellulose from lignin, hemicellulose, and other impurities. This process may use mechanical, chemical, or enzymatic methods and "Bleaching" that removes residual impurities and achieves the desired level of whiteness [13,14,32]. Cellulosic materials for packaging are divided into two distinct categories: regenerated and modified cellulose. Enhancing the thermoplastic behavior of cellulose typically involves chemical reactions such as etherification and esterification targeting the free hydroxyl groups. Various derivatives have found their way into commercial markets with cellulose acetate, cellulose esters (used in extrusion and molding), and regenerated cellulose for fibers being the primary choices for industrial purposes [11].

To improve the properties, methods like chemical modification, plasticizers, and blending with other polymers are employed [43]. Higher substitution degrees and greater molecular weights of hydroxypropylmethyl cellulose have been found to significantly enhance the mechanical properties and water vapor resistance of cellulose-based edible films. Additionally, edible coatings made from hydroxypropylmethyl cellulose and methyl cellulose have proven effective in reducing moisture loss and fat absorption in deep-fried starch products. To enhance the functionality of cellulose derivative-based edible films, various antioxidant and antimicrobial components have been incorporated. For instance, carboxymethyl cellulose films were improved by the addition of liposomes loaded with quercetin and rutin [44], α-tocopherol [45] spent coffee ground polysaccharides[46], and candelilla wax [46]. Methyl cellulose-based films containing murta fruit extract and native chilean berry extract displayed high antioxidant activity making them suitable for packaging fatty food products. Edible coatings with bacteriocin from *Bacillus methylotrophicus* BM47 were shown to extend the shelf life of fresh strawberries [47]. Films made from hydroxyethyl cellulose and cellulose acetate enriched with a resveratrol inclusion complex exhibited strong antimicrobial effects against *Campylobacter* [44]. In contrast, when nisin was incorporated into films composed of hydroxypropyl methylcellulose, it demonstrated notable antimicrobial activity against *Listeria*, *Enterococcus*, *Staphylococcus*, and various *Bacillus* spp. [48]. The capacity of these active bilayer cellulose films to impede the proliferation of foodborne pathogens renders them well-suited for the packaging of poultry meat [11]. Cellulose when combined with nanoparticles such as clay nanoparticles or graphene oxide, nanocellulose films can be engineered to exhibit enhanced barrier properties against gases like oxygen and moisture. This is particularly advantageous in preserving the freshness of perishable foods and preventing oxidative reactions that can lead to food spoilage [49].

In addition to cellulose derivatives, cellophane stands out as a highly fascinating product derived from regenerated cellulose. Cellophane is a thin, transparent material renowned for its excellent barrier properties against moisture, grease, water, and bacteria rendering it exceptionally well-suited for applications within the food packaging industry. Notably, cellophane has been in commercial use for packaging fresh fruits, vegetables, sandwiches, cookies, and bakery products since as early as 1930 [11].

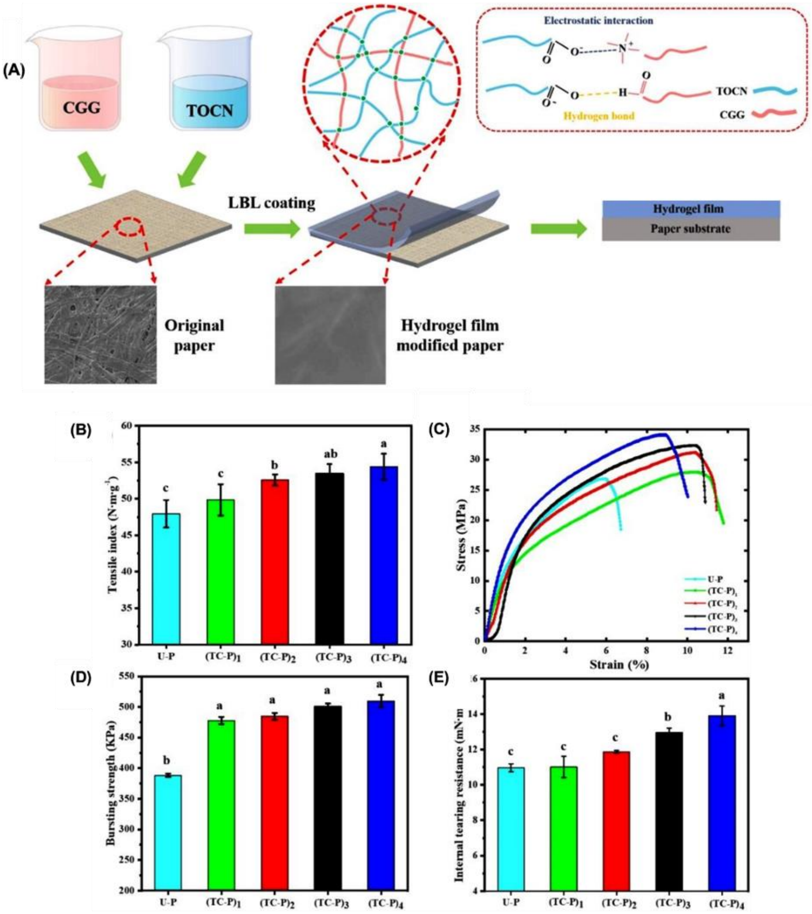

Figure 1. Schematic illustration of the TOCN/CGG self-assembled hydrogel film-modified paper for food packaging **(A)**; TOCN and CGG readily generate hydrogel because of their strong electrostatic interactions. Consequently, TOCN and CGG were cast onto the base paper via a layer-by-layer process to obtain the hydrogel film-modified paper. Mechanical properties of the unmodified paper (U–P) and hydrogel film modified paper (1 to 4 layers) "tensile index **(B)**; the tensile index of the samples increased with the increase of hydrogel film layers. Specifically, the tensile index of the unmodified paper was 47.94 N·m·g^{-1} while that of the 4-layer hydrogel film modified one reached 54.38 N·m·g^{-1}, stress-strain curves **(C)**; the 4-layer hydrogel film modified paper exhibited the tensile strength of 34.03 MPa while the unmodified control had the value of 26.78 MPa. Interestingly, the elongation at break of the modified paper also showed obvious improvement compared to the unmodified control which might be due to the enhancement of the inter-fiber bonding force, bursting strength **(D)**; the hydrogel film modification significantly improved the bursting strength of papers. An increase of 31.4% was observed when comparing the (TC-P)$_4$ (510 kPa) with the U–P (388 kPa), and internal tearing resistance **(E)**; the improvement of the internal tearing index of the paper with the hydrogel film modification. The tearing index of unmodified paper was 10.97 mN·m^{-2}·g^{-1} while the value of (TC-P)$_4$ was 13.92 mN·m^{-2}·g^{-1}" with significant values different (p < 0.05). Abbreviations; 2,2,6,6-Tetramethylpiperidine-1-oxyl (TEMPO), TEMPO-oxidized cellulose nanofibers (TOCN), cationic guar gum (CGG) hydrogel films, layer-by-layer (LBL), unmodified paper (U–P) and 4-layer hydrogel film modified one ((TC-P)$_4$). Reprinted with permission from [42].

3.1.1. Hemicelluloses

Hemicelluloses are complex carbohydrates derived from plant materials or generated as byproducts during the processing of wood and various plant materials. The extraction of hemicelluloses can be challenging due to the presence of lignin, ester, and ether-linked lignin-carbohydrate compounds, and hydrogen bonds between polysaccharides in the plant cell wall, which can impede their isolation [50]. In 2019, cellulose molecules were found to feature a β-(1→4)-linked backbone consisting of glucose, mannose, or xylose units in equatorial conformation. In general, hemicellulose is good for gelling and film forming. Since hemicelluloses primarily consist of xylans, glucomannans, and β-glucans, the main focus for food packaging applications is on these three biopolymers [51,52]. *Arundo donax* waste biomass has been effectively utilized to extract various degrees of purified cellulosic fractions and aqueous bioactive extracts. These extracts were subsequently combined to create advanced superabsorbent bioactive aerogels. In the context of aqueous extracts, subjecting *A. donax* stems to hot water treatment (HW) facilitated the extraction of polysaccharides and polyphenols resulting in the extract denoted as S-HW which exhibited the highest antioxidant capacity. The hybrid aerogels exhibited significant promise for applications as bioactive pads in food packaging (**Figure 2**) [53].

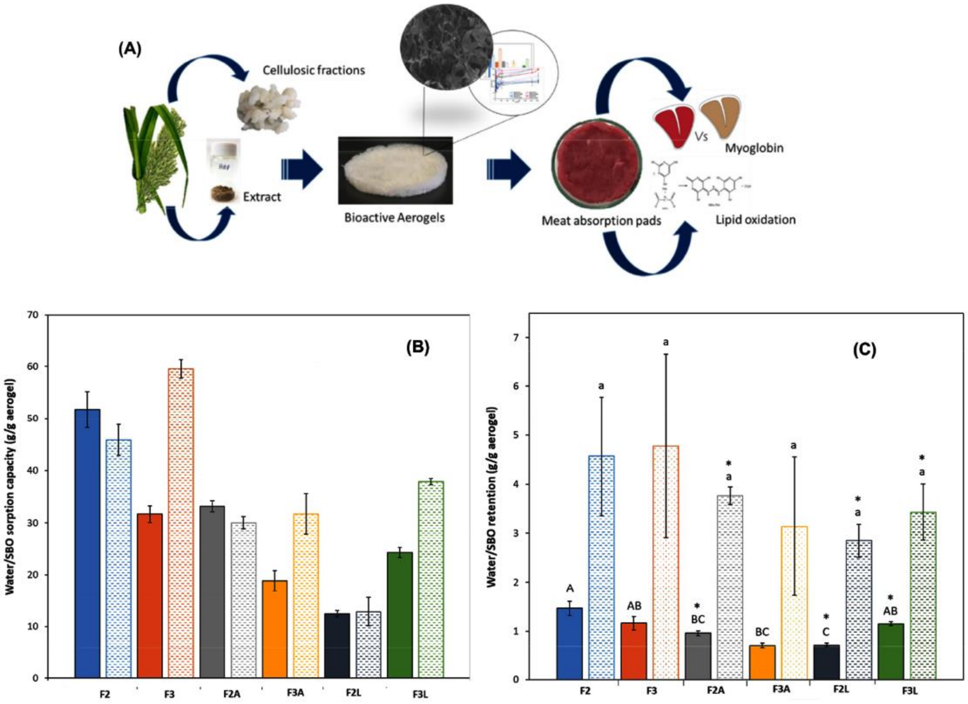

Figure 2. Schematic illustration of the superabsorbent food packaging bioactive cellulose-based aerogels from *Arundo donax* waste biomass (stems and leaves) **(A)**. Fractions containing hemicelluloses produced more hydrophilic and porous aerogels. Water and soybean oil sorption capacity of the *A. donax* cellulosic aerogels after drying at ambient conditions **(B)**. Water and soybean oil retention capacity of the *A. donax* cellulosic aerogels after drying at ambient conditions **(C)**. Solid bars represent the water sorption/retention values and patterned bars represent the soybean oil sorption/retention values. The presence of hemicelluloses in the F2 and F2A aerogels conferred them a less dense, more porous structure, as well as a more hydrophilic character promoting water sorption through diffusion and water hemicelluloses interactions. This, together with the inherent antioxidant capacity of the F2A fraction resulted in a high inhibitory effect on the β-carotene bleaching upon heating. All the tested aerogels showed promising results to be used as bioactive food packaging pads. Different fractions labeled abbreviations; F2, stem biomass subjected to a soxhlet treatment followed by a delignification step with $NaClO_2$; F3, hemicelluloses removed by alkali treatment of KOH; F2A and F3A (obtained from the stem biomass), F2L and F3L (obtained from the leaf biomass) obtained by omitting the initial Soxhlet treatment from the previous process for F3. Different letters indicate significant differences in ($P \leq 0.05$). Reprinted with permission from [53].

3.2. Starch

Starch, another common polysaccharide is extracted from grains and tubers including corn, wheat, and potatoes [54]. Naturally, starch is a polysaccharide made up of two main components: amylose and amylopectin. Amylose is a linear polymer consisting of α-1,4-linked d-glucose units, while amylopectin is a highly branched polysaccharide composed of short chains of α-1,4-linked D-glucose units. It also contains approximately 4–5% branch points formed by 1,6 linkages which occur at regular intervals of about every 20–30 anhydroglucose units [55]. This particular polysaccharide possesses several attractive attributes: it is renewable, biodegradable, and can be easily modified both physically and chemically, and also cost-effective [50].These characteristics render it an excellent raw material for the production of food packaging items. A notable distinction between starch and other polysaccharides is its ability to transform into a thermoplastic material under shear and in the presence of plasticizers such as water, glycerol, and oils [57,58]. This resulting product is referred to as thermoplastic starch (TPS) and is among the commercially available starch-based products [58].

Furthermore, derivatizing starch is another method for enhancing the properties of films. Chemical modification reduces the matrix polarity by replacing the -OH groups with highly hydrophobic groups [59]. Starch derivatization can be structured by succinylation [60], fatty acid modification [58], or polymer grafting [61]. functional properties of starch film containing different bioactive compounds such as gallic acid, chitosan, and carvacrol were improved [62]. To illustrate, starch films have been employed in antimicrobial packaging to regulate foodborne pathogens and microorganisms in ham. In another investigation, cassava starch films incorporating rosemary antioxidant extracts offered excellent antioxidant and UV-blocking properties within the film. Additionally, films containing cowpea starch and maqui berry extract were evaluated as biodegradable active films for safeguarding salmon. These films exhibited strong antioxidant and UV-blocking characteristics [63]. Moreover, cross-linked starch can be used to create strong and flexible biodegradable packaging materials that maintain their integrity even under stress. Starch is composed of two main components: amylose which forms a linear chain, and amylopectin which forms a highly branched structure. These structural variations along with modifications like cross-linking or esterification enable polysaccharides to be tailored to meet the specific requirements of food packaging including enhanced barrier properties, mechanical strength, and biodegradability that make them valuable components in sustainable packaging solutions [38,54].

In recent years, smart films designed as sensors for monitoring food quality have emerged. Films based on a blend of starch and Polyvinyl alcohol (PVA) enriched with betalains from red pitaya peel extract were developed. The incorporation of the extract enhanced the film's antimicrobial, antioxidant, and barrier properties. This particular film was designed to detect the presence of NH_3 produced during shrimp storage. Changes in film color were indicative of the accumulation of volatile nitrogen compounds and the alkaline pH shift resulting from shrimp spoilage suggesting its potential as a food quality indicator [64]. Lastly, various starch aerogel systems, including those produced using supercritical carbon dioxide ($scCO_2$) were investigated. These aerogels could be impregnated with active substances like quercetin. The resulting material exhibited favorable dissolution characteristics and minimized burst-like effects [65,66].

3.3. Dextrin

Dextrin is a cost-effective, water-soluble polymer formed from α-(1→4) D-glucose units through the process of partial starch hydrolysis making them an environmentally friendly choice for food packaging purposes such as binding, thickening, and as a protective agent against oxygen-and-crystallization. Dextrin-based materials have also gained significant attention in the matter of food packaging due to their unique properties and sustainable characteristics. These materials are known for their excellent film-forming capabilities allowing them to create a protective barrier around food products which preserves their freshness and quality [29,67].

One of the key advantages of dextrin-based materials in food packaging is their biodegradability. As concerns about plastic pollution and environmental sustainability continue to grow, dextrin-based films and coatings offer a promising solution. When these materials eventually reach the end of their useful life, they can break down naturally in the environment leaving minimal ecological impact [68]. This makes them an eco-conscious choice for consumers and food manufacturers looking to reduce their carbon footprint. Furthermore, dextrin-based materials can be engineered to exhibit specific properties tailored to the needs of different food products. They can be designed to be moisture-resistant, grease-resistant, and even edible. This versatility allows for the customization of packaging solutions for a wide range of food items, from baked goods to snacks and ready-to-eat meals. Dextrin-based materials are particularly adept at controlling moisture levels which is crucial for extending the shelf life of products and preventing spoilage [69].

In addition to their eco-friendly nature and functional attributes, dextrin-based materials are also cost-effective making them an attractive choice for food packaging. They can be produced from readily available starch sources such as corn or potato which helps keep production costs in check. As the demand for sustainable and effective food packaging solutions continues to grow, dextrin-based materials are likely to play an increasingly important role in reducing the environmental impact of the food industry while ensuring product quality and safety. However, the preparation of polysaccharide-based films often leads to challenges like high water absorption, low mechanical strength, and increased brittleness. To address these issues, composite mixtures are employed to fine-tune the material properties [70].

Several polymers including poly(ethylene glycol), poly(caprolactone), and poly(vinyl alcohol) can enhance the properties of composite films. Among these, poly(vinyl alcohol) stands out due to its hydrophilicity, oxygen barrier characteristics, biocompatibility, and satisfactory mechanical attributes. Additionally, antimicrobial nanocomposites can be developed by incorporating metal/metal oxide nanoparticles like ZnO, TiO_2, Ag, and CuO into the polymer matrix. These nanoparticles effectively inhibit the growth of microbes by reducing the number of live microorganisms. In this regard, biodegradable nanocomposite films with antimicrobial and antioxidant properties were created for use in bioactive food packaging. These films were fabricated using dextrin, poly(vinyl alcohol), and TiO_2 nanoparticles through a solvent casting technique. The inclusion of TiO_2 nanoparticles in the Dex@PVA films improved their mechanical properties and increased the contact angle. However, it is worth noting that the water sorption (WS) and water vapor permeability (WVP) of the Dex@PVA@TiO_2 nanocomposite films were increased with higher dextrin content. In conclusion, Dex@PVA@TiO_2 nanocomposite films proved to be promising materials for qualifying environmental pollution, inhibiting microbial growth, and providing antioxidant capabilities for light-sensitive food products (**Figure 3**) [29].

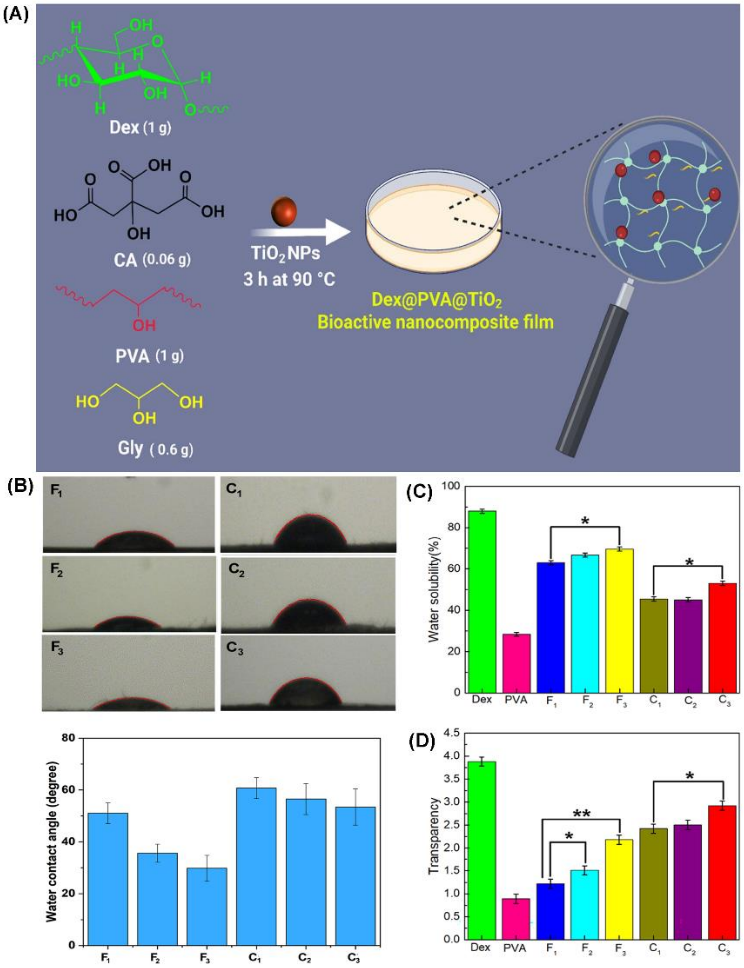

Figure 3. Fabrication of Dex@PVA@TiO_2 bioactive nanocomposite film (**A**). The bioactive nanocomposite films with different compositions were constructed through solvent casting. Photographs and histogram of water contact angle measurement of F_1, F_2, F_3, C_1, C_2, and C_3 films (**B**). The increase of Dex content in the films led to a decrease in the water contact angle of films owing to the Dex hydrophilicity. Furthermore, by the addition of TiO_2 nanoparticles in the Dex@PVA blends, the water contact angle of films increased. Water solubility (**C**) and transparency (**D**) of the Dex, PVA, F_1, F_2, F_3, C_1, C_2, and C_3 films. The solubility of the samples increased with increasing dextrin content. Since Dex has excellent solubility up to 95–100%, this solubility was very high for the films with a higher dextrin content. With the increase of the Dex content, the transparency of the nanocomposite was decreased. In addition, by loading TiO_2 nanoparticles in the polymer matrix, the film transparency was also reduced. Abbreviations, Dex, Dextrin; PVA, polyvinyl alcohol; Dex@PVA@TiO_2 films (50:50:0, F_1) (60:40:0, F_2) (70:30:0, F_3) (50:50:5, C_1) (60:40:5, C_2) and (70:30:5, C_3). Reprinted with permission from [29].

3.4. Alginate

Alginate derived from brown seaweeds is well-known for its gel-forming capabilities. It is often employed in edible coatings and the encapsulation of flavors and nutrients [40,41]. Alginate is primarily sourced from the cell walls of marine seaweeds (*Phaeophyceae*) with notable content ranging from 20% to 40% of the dry weight. From a chemical perspective, alginates are composed of (1→4)-linked α-l-guluronic acid (G) and β-d-mannuronic acid (M). Prominent seaweed sources include *Ascophyllum nodosum*, various *Laminaria* and *Fucus* species, *Macrocystis pyrifera*, and *Ecklonia* spp. [71–73]. In addition to seaweeds, alginates are found in lower quantities from bacterial sources such as exopolysaccharides produced by *Azetobacter* and *Pseudomonas* spp. [74]. Another prominent application of polysaccharides is in the encapsulation of flavors, colors, and nutrients. Polysaccharides such as alginate and pectin can be used to create protective microcapsules that house sensitive ingredients. This technology allows for the controlled release of these components and enhances flavor retention and color stability in food products. An example is the encapsulation of essential oils in alginate beads for use in flavored beverages and confectionery items providing a burst of flavor upon consumption [40].

3.5. Pullulan

Pullulan is a homopolysaccharide that is derived from the fermentation medium of the yeast-like microorganism *Aureobasidium pullulans*. It is composed of repeating maltotriose units that are linked together by α-(1→6) glycosidic bonds with glucose molecules within each maltotriose connected by α-(1→4) linkages. This structural arrangement imparts notable characteristics to pullulan including remarkable flexibility, a lack of crystalline structure, and high solubility in water [75]. The molecular weight of pullulan can vary depending on factors such as the strain of microorganisms, culture conditions, and fermentation time, typically falling within the range of 10 to 400 kDa [76].

Materials based on pullulan exhibit excellent mechanical strength, exceptional barriers against oxygen and CO_2, and strong adhesive properties making them capable of forming fibers and films. Notably, the viscosity of a pullulan solution remains consistent regardless of changes in temperature, pH, or the presence of various metal ions including sodium chloride [75,77]. To enhance the water vapor resistance of pullulan films, they are commonly combined with proteins [78] and/or waxes [79,80]. Cozzolino and colleagues innovatively crafted coatings comprising pullulan/silica nanoparticles and pullulan/microfibrillated cellulose/borax on bi-oriented polypropylene films that create surface materials that exhibit exceptional oxygen and CO_2 barrier properties. These coatings were effectively utilized in the context of modified atmosphere packaging (MAP) for food products [81,82]. Various methods were employed to integrate these coatings into the MAP food packaging process [81,82]. Another noteworthy example is the use of pullulan films in single-serve coffee pods. These films not only provide an oxygen barrier to maintain coffee freshness but also biodegrade reducing the environmental impact associated with single-use coffee packaging. Also, polysaccharide-based adhesives are used in labeling and sealing applications in the food packaging industry offering a safe and non-toxic option for adhering labels and seals to packaging materials. This ensures that labels stay securely attached to products throughout their shelf life providing consumers with important information and tamper-evidence [83].

3.6. Chitosan

Chitosan as a polysaccharide sourced from the shells e.g., shrimp and crabs is also known for its antimicrobial properties and finds application in antimicrobial food packaging. Chitosan with excellent moisture resistance prevents the loss of moisture from packaged food products, thereby maintaining their freshness and quality [17,84]. Since, chitin, the second most abundant agricultural polymer found in nature that occurs in the exoskeletons of arthropods and the cell walls of fungi and yeasts and it is an acetylated polysaccharide consisting of N-acetyl-D-glucosamine and is typically produced through chemical extraction processes from the discarded shells of prawns and crabs. Although alternative methods like enzyme hydrolysis and fermentation have been explored and these processes are not yet economically viable on an industrial scale [85]. Therefore, chitosan, derived from chitin through deacetylation has its properties influenced by various factors such as alkali concentration, incubation time, the chitin-to-alkali ratio, temperature, and the source of chitin. Chitosan is generally insoluble in water but readily dissolves in acidic solutions. Its uniqueness among polysaccharides lies in the presence of cationic groups along its molecular backbone and its notable antimicrobial properties against bacteria, yeasts, and fungi [86]. Moreover, chitosan's excellent film-forming qualities make it suitable for producing membranes with thicknesses greater than 30 µm and coatings less than 30 µm which are often used for food preservation [87–89]. These chitosan membranes are biodegradable, biocompatible, non-toxic, renewable, and readily available in the market. Additionally, they exhibit semipermeability to gases offering low oxygen permeability, crucial for preserving certain food products, and moderate water vapor resistance. Despite these remarkable features, extensive research has focused on enhancing chitosan membranes. By incorporating glycerol and employing thermo-mechanical treatments like mechanical pressure, it is possible to create a type of thermoplastic material with favorable mechanical properties [90].

The functional properties of chitosan-based membranes can also be improved by combining them with other hydrocolloids. Blending chitosan with anionic polymers has been shown to enhance mechanical and barrier properties compared to pure chitosan membranes. This improvement is attributed to the formation of polyelectrolyte complexes through electrostatic interactions between the protonated amino groups of chitosan and the negatively charged side-chain groups in the other biopolymer at the operating pH [26,29]. Combinations of chitosan with other polysaccharides like starch, pectin, or alginate as well as proteins such as gelatin and whey proteins have been reported to lead to improvements in mechanical properties, water vapor permeability, and water solubility when compared to chitosan membranes only [90]. Silver nanoparticles can be incorporated into chitosan-based films or coatings to create packaging materials with antimicrobial activity. This integration helps extend the shelf life of packaged food products by inhibiting the growth of spoilage microorganisms and pathogens. For instance, chitosan-silver nanoparticle composite films have been employed to enhance the preservation of fruits, vegetables, and seafood. To impart hydrophobicity and reduce moisture transfer, lipids are often added to films and membranes. A variety of lipid components including natural waxes, resins, fatty acids, and vegetable oils are available for this purpose. Chitosan-based membranes incorporating components like beeswax, oleic acid, neem oil, and cinnamon essential oil have shown reduced water susceptibility and decreased water vapor permeability [87–89]. In this matter, the study concentrated on creating composite films by integrating orange peel powder into CS/PVA (Chitosan/Polyvinyl alcohol) materials. It examined how the inclusion of orange peel affects the barrier, color, mechanical, morphological, optical, structural, thermal, wettability, and antioxidant activity properties of these biocomposite films [91]. Some applicable polysaccharides in food packaging are shown in (**Table 1**).

Table 1. Properties of common polysaccharides used in food packaging

Homopolysaccharide	**Water solubility**	**Properties**	**Source**	**Ref.**
Chitin (CH)	Insoluble	Biodegradable, antimicrobial, biocompatible, non-toxic, and highly transparent	Exoskeleton of non-mammal	[37]
Chitosan (CS)	Soluble under acidic conditions	Biodegradable, antimicrobial, biocompatible, forming and filming capacity	N-Deacetylation process of chitin from crustacean shells	[12,37]
Cellulose (CL)	Insoluble	Renewable, biodegradable, low-cost, and modifiable	Wood, cotton, plant cell walls, bacterial sources	[19]
Dextrin (DEX)	Soluble	Adhesive and film-forming	Bacterial hydrolysis of starch	[24]
Starch	Insoluble in cold water	Abundant, low-cost, and thermoplastic potential	Corn, potatoes, wheat, cassava, rice	[28,36]
Pullulan (PL)	Soluble	Flexible, high mechanical strength, lacks crystallinity, and modifiable	Fermentation of *Aureobasidium pullulans*	[32]
Heteropolysaccharide				

Alginate	Soluble (sodium or potassium salt)	Components of α-l-guluronic acid (G) and *β*-d-mannuronic acid (M) Gel-forming, gelling agent, and biodegradable	Extracted from marine seaweeds (e.g., *Ascophyllum nodosum*), bacterial sources	[34,38]
Carrageenan (CRG)	Soluble in hot water	Gel-forming, thickening agent, stabilizing, and water-binding capacity	Red seaweed *Rhodophyceae* like *Eucheuma* and *Kappaphycus* spp.	[31]
Hyaluronic acid (HA)	Soluble	Analgesic effects, excellent viscoelasticity, high moisture retention capacity, and hygroscopic properties	Mammals	[93,94]
Pectin	Soluble in pure water	Gelling properties	Citrus fruit peel, apple pomace, sugar beet, and sunflower heads	[95,96]
Xanthan gum	Soluble in both cold and hot water	High viscosity, stabilizing in a wide range of temperatures, and pseudoplastic	Fermentation of *Xanthomonas campestris*	[97,98]
Gellan gum	Partially soluble in cold water and is dissolved by heating to 70 °C or greater	Gel-forming, thermally reversible, and versatile	*Sphingomonas elodea*, *Sphingomonas paucimobilis*	[99]
Dextran gum	High water solubility	High water solubility, biodegradable, easily filtered, low concentrations, and high concentrations (pseudoplastic)	Lactic acid bacteria	[100]
Guar gum	High water swellability	Thickening agent and stabilizer	Seeds of *Cyamopsis tetragonoloba* L	[101,102]
Arabic gum	Soluble in hot and cold water	Emulsifying and thickening	The stems and branches of two acacia species: *Acacia Senegal* and *Acacia Seyal*	[103,104]
FucoPol	Water soluble anionic	Biodegradable, transparent high gas barrier, and poor water resistance	*Enterobacter* A47 (DSM 23139)	[105]
ß-Glucan	Soluble in cold water	Soluble dietary fiber and health benefits	Oats, barley, mushrooms, and some grains	[51]
Hemicellulose	Soluble under alkaline conditions	Water-absorbing, adhesive, and structural component	plant materials	[106,107]
Agar	Soluble in boiling water	Gel-forming ability and compatibility	Red algae including *Gelidium* and *Gracilaria* spp.	[108,109]
Konjac Gum	Soluble	Viscosity, gelling, and stabilizing properties	Konjac plant (*Amorphophalus konjac*) tubers	[110,111]
Inulin	Moderate solubility in water	Soluble dietary fiber and prebiotic	Extracted from chicory roots and other plants	[112–114]

Lentinan	Soluble	Immune-enhancing and anticancer properties	Extracted from *shiitake* mushrooms	[114,115]
Galactomannan	Soluble	Viscosity, film-forming, and binding agent	Seeds of *legumes*	[116,117]
Arabinoxylan	Either soluble or insoluble depending on a variety	Soluble dietary fiber and health benefits	Cereals, wheat bran, and other grains	[118–120]
Tara Gum	Soluble in hot water and partially soluble in cold water	Viscosity and water retention capabilities	Seeds of the *Caesalpinia Spinosa* trees	[121–124]
Psyllium Husk	Soluble	High-soluble dietary fiber for thickening and binding	Seeds from the *Plantago ovata* plant	[125,126]
Locust Bean Gum	Soluble cold water	Thickening agent and water binding properties	Seeds of the carob tree (*Ceratonia siliqua*)	[127–129]
Quinoa Starch	Low solubility	High amylose content for film-forming properties	Quinoa seeds	[130,131]
Non polysaccharides material				
Polycaprolactone (PCL)	Insoluble	Biocompatible, biodegradable, low-set processing temperature (60°C), superior strength, and good barrier properties	Ring-opening polymerization of ε-caprolactone	[132]
Polyethylene (PE)	Insoluble	Low cost, nontoxicity, superior sealing performance, excellent mechanical strength, and thermal and chemical resistance	Polymerization	[133]
Polylactic Acid (PLA)	Insoluble	Good mechanical strength, biocompatibility, and environmentally friendly	Fermentation of plant starch such as corn, cassava, sugarcane or sugar beet pulp	[134,135]
Polypropylene (PP)	Insoluble	Low cost, low water vapor transportation, gas permeability, and excellent resistance to chemicals	Chain-growth polymerization of propene	[136]
Polyvinyl Chloride (PVC)	Insoluble	Low cost, lightweight, superior chemical resistance, and barrier toward burning	Polymerization of the vinyl chloride monomer (VCM)	[137]
Polyhydroxyalkanote (PHA)	Insoluble	Excellent moisture barrier, mechanical performance, crystallinity, biocompatibility and is naturally compostable under both aerobic and anaerobic conditions	Microbial fermentation	[138–140]
Polybutylene Succinate (PBS)	Insoluble	Low cost, good processability, improved thermal stability, and chemical resistance	Polymerization of butylene succinate	[141,142]

4. Polysaccharides in food products

The diverse properties of polysaccharide-based materials make them invaluable in the food industry, contributing to the improvement of texture, stability, and overall quality across a range of food products including meat, bakery items, dairy, and beyond [3,11]. One significant category where these materials are applied is in meat products [62,136]. Polysaccharides such as carrageenan and alginate are often employed as additives in meat processing to enhance texture, improve water retention, and provide better stability during cooking and storage [39,73,143,144]. For instance, carrageenan is utilized in the production of processed meats like sausages where it helps maintain the desired texture and juiciness [145]. In bakery products, polysaccharide-based materials are applied as thickeners, stabilizers, or even as substitutes for traditional ingredients. Additionally, these materials might contribute to extended shelf life and improved freshness in bakery items. For example, pectin is commonly used in the production of fruit fillings for pastries and pies contributing to the desired gel-like texture and enhancing the overall sensory experience [146]. Additionally, polysaccharides like xanthan gum and guar gum are employed in bakery formulations to improve dough rheology, increase water retention, and enhance the volume and structure of baked goods [24,97,98,124].

In the context of dairy products, polysaccharides have been utilized to modify texture, stability, and sensory attributes. For instance, pectin and carrageenan are employed in the production of dairy desserts to achieve the desired texture and mouthfeel. These materials contribute to the stabilization of the product preventing phase separation and ensuring a smooth and creamy consistency. Furthermore, the application of polysaccharide-based materials extends to various other food categories including beverages, sauces, and confectionery. In beverages, pectin, and gum Arabic are used as stabilizers, while agar and carrageenan find application in the production of gelled desserts and confectionery items. Examples of these applications underscore the importance of polysaccharides as functional ingredients in the formulation and enhancement of various food products [95,97,98,103,104,146].

5. Safety assessment

Polysaccharide-based materials play a vital role in ensuring the safety of food packaging due to deriving from natural sources, thereby contributing to enhanced human health. One of the key contributions of polysaccharide-based materials to human health safety lies in their ability to create a protective barrier against external contaminants. As essential components in various food packaging applications such as wraps, coatings, and sachets, these materials act as a shield, safeguarding food products from potential contamination by microorganisms, moisture, and other environmental factors. By preserving the integrity of the packaged food, polysaccharide-based materials mitigate the risk of foodborne illnesses, contributing directly to human health safety [13,70,147].

Moreover, the biodegradability of polysaccharides aligns with the broader goal of reducing environmental pollution associated with non-biodegradable packaging materials. As these materials break down naturally over time, they lessen the accumulation of plastic waste which is crucial for the health of ecosystems and indirectly impacts human health by mitigating the potential harm caused by environmental degradation [5,12]. Polysaccharide-based materials are often employed in the development of active packaging systems, where they can incorporate antimicrobial agents or antioxidants. These active components actively conflict with the growth of harmful microorganisms or oxidation processes in packaged food, extending the shelf life and enhancing the safety of consumables. This controlled-release capability not only improves the quality of the packaged food but also contributes to reducing foodborne hazards [29,119,130]. In principle, the use of polysaccharide-based materials in food packaging serves as a crucial element in the broader framework of ensuring human health safety, thereby positively impacting the overall health and well-being of consumers.

6. Conclusion and perspective

In conclusion, the utilization of polysaccharides in food packaging represents a remarkable step forward in addressing the pressing challenges of sustainability, food waste reduction, and consumer safety. The inherent biodegradability, non-toxicity, and renewable sources of polysaccharides make them a compelling choice for eco-conscious packaging solutions. Their diverse properties from creating oxygen and moisture barriers to encapsulating flavors and nutrients demonstrate their versatility across the food industry. However, the field continues to develop with ongoing research focused on enhancing the mechanical, barrier, and functional properties of polysaccharide-based materials. As environmental concerns intensify and consumer demands for sustainable packaging grow, the future holds promise for polysaccharides to play an increasingly prominent role in revolutionizing food packaging practices. With continued innovation and collaboration between researchers, manufacturers, and policymakers, we can expect polysaccharides to contribute significantly to a greener and more responsible packaging landscape with benefits for both the industry and the planet.

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