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Research Article

An Extensive Overview of Polysaccharide-Derived Biopolymers in Food Packaging Applications

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Abstract **–** This review provides a comprehensive overview of biopolymers based on polysaccharides and their uses in food packaging. It highlights current technologies and recent advancements, focusing on the functional properties that enable these biopolymers to maintain food quality and prolong shelf life. The growing environmental concerns of traditional packaging materials, particularly plastics, have sparked a global transition towards sustainable alternatives. Biopolymers have emerged as a promising solution, offering renewable and biodegradable properties that align with the increasing demand for eco-friendly packaging solutions. Among these biopolymers, polysaccharide-derived materials such as cellulose, starch, and chitosan have demonstrated exceptional effectiveness in food packaging applications due to their superior film-forming capabilities, gas barrier properties, and inherent biodegradability. Polysaccharide-based biopolymers play a crucial role in preserving food quality and extending shelf life by effectively minimizing oxygen penetration and moisture loss. Their versatility is further enhanced by the unique functional properties of specific polysaccharides, particularly the antimicrobial activity exhibited by chitosan, which makes them particularly suitable for active packaging systems aimed at ensuring food safety and freshness. The adoption of these sustainable materials is driven not only by regulatory pressures and consumer preferences but also by their capacity to meet functional requirements while simultaneously reducing environmental impact. As advancements in biopolymer technology continue to enhance their mechanical and barrier properties, polysaccharide-derived biopolymers are increasingly recognized as viable alternatives to conventional petroleum-based plastics. Their integration into industrial applications represents a critical step towards achieving global sustainability goals while ensuring the quality and safety of packaged foods. By addressing existing challenges and capitalizing on ongoing research, these materials possess the potential to revolutionize the packaging industry and make substantial contributions to mitigating plastic pollution.

Keywords – Biopolymer, Food packaging, Polysaccharide, Renewable polymers, Biodegradable film

I. INTRODUCTION

Traditional food packaging materials, such as glass and metal, have long been recognized for their effective barriers against oxygen and moisture, which are critical for preserving food quality. However, the high costs and substantial weight of these materials have limited their widespread adoption in the food industry [1]. The advent of plastic-based packaging, particularly single-use containers, has revolutionized the packaging landscape by providing a more affordable and versatile solution that meets the demands of modern consumers [2]. Despite these advantages, the environmental concerns associated with plastic waste have prompted a renewed focus on developing sustainable packaging alternatives that can mitigate the negative impacts of plastic pollution [3]. This shift towards sustainability is increasingly influencing consumer behavior and perceptions, as there is a growing demand for packaging solutions that are both functional and environmentally friendly [4, 5]. In response to these demands, biopolymers have emerged as promising alternatives, offering the potential to address both environmental concerns and packaging functionality.

Biopolymers are naturally occurring, high-molecular-weight polymers that are produced by living organisms and are essential for various biological functions. The term "biopolymer" is derived from the Greek words "bio," meaning life, and "polymer," referring to large molecules made up of smaller, repeating units [6]. These materials have emerged as potential alternatives to traditional petroleum-based plastics due to their renewable and biodegradable nature [7-9]. Among biopolymers, which are categorized into natural and synthetic based on their origins, the natural ones can be grouped into two primary types: polysaccharides and proteins [10, 11]. Polysaccharide-based biopolymers, such as cellulose, starch, and chitosan, are extensively utilized in food packaging applications due to their remarkable film-forming capabilities, gas barrier properties, and biodegradability. These materials play a crucial role in maintaining the quality and extending the shelf life of perishable food products by effectively minimizing oxygen penetration and moisture loss [12, 13]. Additionally, certain polysaccharides, particularly chitosan, exhibit inherent antimicrobial properties, which further enhance their utility in active packaging systems designed to preserve food safety and freshness [14]. The combination of these advantageous characteristics positions polysaccharide-derived biopolymers as a sustainable alternative to conventional plastic packaging, aligning with the growing demand for environmentally friendly materials in the food industry.

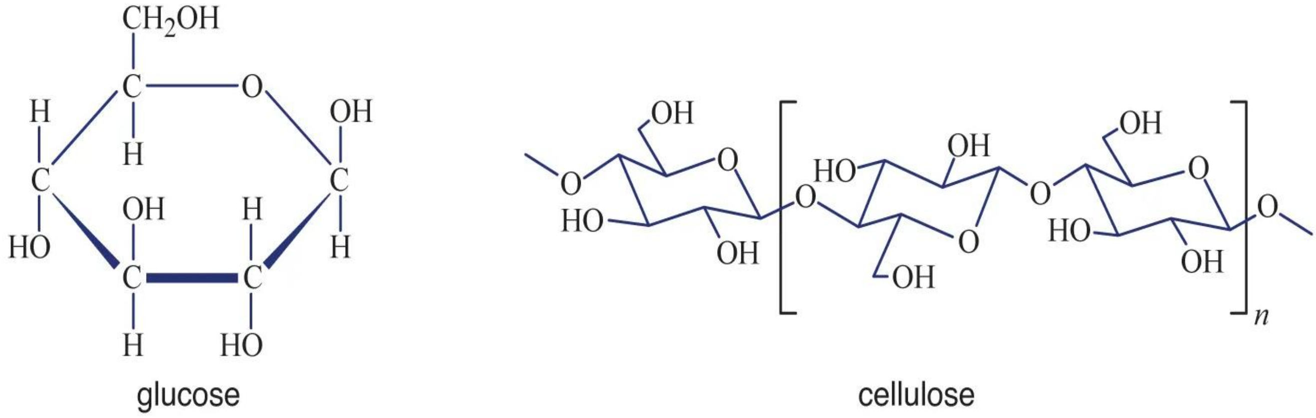
II. POLYSACCHARIDE DERIVED BIOPOLYMERS

Polysaccharide-based biopolymers, which are natural macromolecules formed from long chains of sugar molecules linked by glycosidic bonds, have garnered significant attention due to their unique properties and diverse applications. These biopolymers are characterized by their biodegradability, biocompatibility, and availability from renewable sources, making them suitable for various industrial applications, including food packaging, drug delivery, and biomedical engineering. The biodegradability of polysaccharide-based biopolymers is a crucial attribute that distinguishes them from synthetic polymers. For instance, Mohan et al. highlight that corn starch-derived biopolymer films exhibit significant water uptake changes, indicating their biodegradation potential in aqueous environments [15]. This property is essential for applications in food packaging, where materials must decompose without leaving harmful residues. Dirpan et al. further emphasize that biodegradable films made from biobased polymers, including polysaccharides, are increasingly utilized in food packaging due to their environmental benefits [16]. The ability of these materials to break down naturally aligns with the growing demand for sustainable packaging solutions in response to plastic pollution concerns [17].

Cellulose

Cellulose, a natural polysaccharide composed of β-D-glucose units linked by β-1,4-glycosidic bonds, is recognized as the most abundant organic polymer on Earth (Figure 1). It serves as a crucial structural component in the cell walls of plants, algae, and certain bacteria. The linear and crystalline structure of cellulose contributes to its remarkable mechanical strength and stability, making it a vital material in various applications. Cellulose is a complex carbohydrate that consists of numerous glucose units, forming a linear chain that contributes to its high tensile strength and rigidity [18]. This linear arrangement allows for extensive hydrogen bonding between adjacent chains, resulting in a crystalline structure that enhances its stability [19]. Furthermore, Aulin et al. discuss how the crystalline nature of cellulose influences its barrier properties, which are essential for applications in packaging and coatings [20].

The physical properties of cellulose are primarily influenced by its crystalline structure and the arrangement of its polymer chains. Cellulose exhibits a high degree of crystallinity, which contributes to its mechanical strength and stability. According to Driemeier and Calligaris, cellulose is characterized by two distinct crystalline forms, cellulose I and cellulose II, each with unique structural properties that affect its functionality [22]. The high crystallinity of cellulose, which can range from 84% to 89%, imparts significant tensile strength, making it suitable for reinforcing biodegradable composites [23]. Additionally, the microfibril structure of cellulose enhances its surface area, which is beneficial for applications in nanocomposites and hydrogels [24].



glucose

cellulose

Figure 1. The chemical structure of cellulose biopolymer [21]

Cellulose displays significant chemical reactivity owing to the hydroxyl groups located within its polymer backbone. The presence of hydroxyl groups enables various chemical modifications, including esterification and etherification, to improve the properties of cellulose for particular uses. Cellulose also demonstrates hydrophilicity, which affects its interaction with water and other solvents. This property can be advantageous in applications such as wound dressings and hydrogels, where moisture retention is critical. The hydrophilic nature of cellulose can, however, pose challenges in terms of moisture absorption resistance, as noted by Thakur et al. [25]. This characteristic can be mitigated through chemical modifications, which can improve the moisture resistance of cellulose-based materials [26].

Cellulose is a versatile polysaccharide that can be sourced from a variety of natural materials, including plants, algae, and bacteria. Its extraction and characterization are crucial for numerous applications in industries such as textiles, packaging, and biomedicine. Cellulose is a common component in both primary and secondary plant cell walls, primarily derived from wood types, cotton, and crop by-products like corn stalks and wheat straw. For instance, cellulose and carboxymethyl cellulose were synthesized by Karataş and Arslan from grapefruit peel, and their flow properties were investigated [27]. Similarly, Canilha et al. report on the chemical composition of sugarcane bagasse, which contains approximately 45% cellulose, making it a significant source for cellulose extraction [28]. Other plant materials such as banana pseudostems also yield cellulose, as demonstrated by Merais et al., who extracted cellulose nanofibers from this source [29].

In addition to plants, bacterial cellulose is produced by microorganisms like *Gluconacetobacter xylinus*, known for its high purity and unique properties such as exceptional water retention and porosity. This biopolymer has garnered significant attention due to its remarkable properties, including high purity, excellent water retention capacity, and notable porosity. According to Halib et al., these bacteria secrete cellulose fibers into their surrounding environment, forming a gel-like structure that can be harvested. The production process typically involves the fermentation of a carbohydrate source, such as glucose or sucrose, under controlled conditions to optimize cellulose yield. The resulting cellulose is often free from lignin and hemicellulose, which are commonly found in plant-derived cellulose, making it highly pure [30].

Certain algae and fungi also produce cellulose with distinct characteristics, expanding its versatility and applications. Algal cellulose is primarily derived from certain species of algae, such as *Cladophora glomerata*. This type of cellulose has garnered attention due to its distinct properties compared to terrestrial cellulose. Mihhels demonstrates that algal cellulose exhibits higher resistance to degradation and dissolution by sulfuric acid than cellulose sourced from terrestrial plants, indicating its robustness and stability under harsh conditions. Furthermore, dynamic thermogravimetric analysis has shown that algal cellulose is thermally more stable than wood cellulose, which enhances its potential for applications that require durability and resistance to thermal degradation [31]. Fungal cellulose is produced by various fungi, including filamentous fungi such as *Trichoderma reesei* and *Daldinia caldariorum*. These fungi are known for their ability to degrade cellulose and produce cellulolytic enzymes that facilitate the breakdown of plant biomass. Eichorst and Kuske note that certain fungal communities, particularly chytrids, are capable of degrading cellulose in both aquatic and terrestrial ecosystems, showcasing their ecological role in cellulose decomposition [32]. The ability of fungi to break down cellulose is crucial for nutrient cycling in ecosystems.

Cellulose is a fundamental component in the textile industry, where it is used to produce fabrics such as cotton and rayon. In the paper industry, cellulose fibers are the primary raw material for manufacturing paper and cardboard products. The inherent properties of cellulose, including its strength and flexibility, make it an ideal choice for these applications [33]. Cellulose-based materials are emerging as eco-friendly alternatives to traditional plastics in packaging due to their biodegradability and renewability. Liu et al. highlight that cellulose-based bioplastics derived from waste paper exhibit high tensile strength and can effectively replace polyethylene and polypropylene films in packaging applications. These cellulose films are lightweight, transparent, and possess excellent barrier properties against oxygen and oils, which are crucial for preserving food quality and extending shelf life [34]. Qin et al. describe the development of multifunctional superelastic cellulose nanofibrils aerogels, which demonstrate significant absorption capacity and potential for use in various applications, including environmental remediation and biomedical fields [35]. In the biomedical field, bacterial cellulose is particularly valuable for wound dressings and drug delivery systems. It provides a moist environment conducive to healing and can be engineered to release drugs in a controlled manner. Various cellulose derivatives, such as cellulose acetate, carboxymethyl cellulose (CMC), and nitrocellulose, have specialized uses in filters, stabilizers, explosives, and coatings. For instance, CMC is widely used as a thickener and stabilizer in food products and pharmaceuticals due to its ability to form gels and retain moisture [36]. The food industry employs cellulose as dietary fiber, thickener, and stabilizer. Environmentally, cellulose is pivotal in replacing single-use plastics and purification systems. It also contributes to renewable energy via bioethanol production and nanocellulose-based energy storage devices.

Cellulose-based materials are gaining popularity as environmentally friendly alternatives to conventional plastic packaging because they are biodegradable and can be replenished naturally. Cellulose films are lightweight, transparent, and possess excellent barrier properties against oxygen and oils, making them suitable for preserving food quality and extending shelf life. These films are frequently employed for encasing perishables and are becoming more widely used in the manufacturing of compostable food containers and laminates [37]. Additionally, advancements in cellulose nanocomposites have enhanced the strength, flexibility, and functionality of packaging materials, enabling their use in various industrial and consumer applications [38]. Cellulose-based packaging materials have a vital function in advancing sustainable packaging options by lessening dependence on synthetic polymers.

Chitin and Chitosan

Chitin and chitosan are natural polysaccharide-based biopolymers derived from renewable resources, recognized for their biocompatibility, biodegradability, and non-toxic nature. These properties make them suitable for various applications across multiple industries, including pharmaceuticals, agriculture, and food.

Chitin is a structural polysaccharide found predominantly in the exoskeletons of arthropods, such as crabs, shrimp, and lobsters, as well as in the cell walls of fungi. It is the second most abundant polysaccharide in nature after cellulose [39]. Chitin consists of N-acetylglucosamine units linked by β-1,4-glycosidic bonds, contributing to its structural integrity and resistance to degradation (Figure 2).

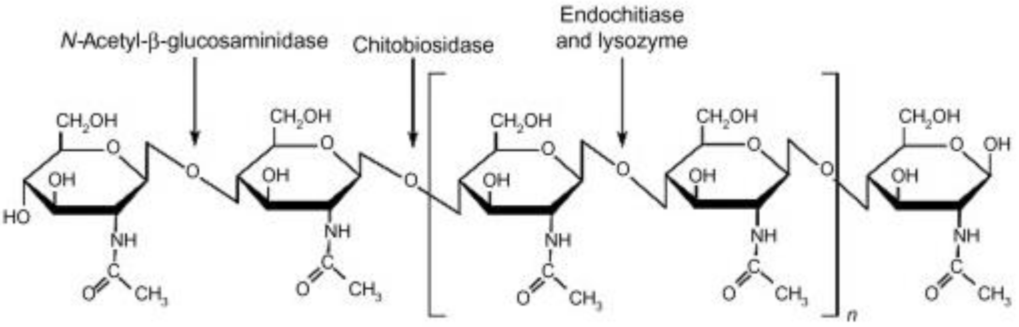


Figure 2. The structure of chitin [40]

This substance, chitin, is characterized as white, hard, and crystalline due to its robust tensile strength, which can be attributed to the strong intermolecular hydrogen bonding and its crystalline structure, making it insoluble in water and the majority of organic solvents. It exists in three allomorphic forms: tightly packed α-chitin (common in crustaceans), less tightly packed β-chitin (found in squid pens), and the rare γ-chitin (present in fungi), each with distinct structural arrangements suited to their biological roles [41]. Due to the presence of acetyl groups, chitin is chemically inert and less reactive than chitosan. This property limits its functionalization but also contributes to its stability in various environments [42].

Chitin has versatile applications across various fields. In biomedicine, it is used as a wound-healing agent due to its biocompatibility, serves as a structural scaffold in tissue engineering, and acts as a source of glucosamine for cartilage repair supplements. Shen et al. demonstrated that chitin membranes can induce tissue regeneration in full-thickness skin defects, highlighting their potential in regenerative medicine [43]. Chitin acts as a source of glucosamine, which is important for cartilage repair supplements. This property is beneficial for joint health and is often utilized in dietary supplements aimed at alleviating osteoarthritis symptoms. It also functions as a natural pesticide and nematicide, helping to control pests and pathogens in agricultural settings. Its application can reduce the reliance on synthetic chemicals, promoting sustainable agricultural practices. The use of chitin in biodegradable packaging materials is gaining popularity due to its long-lasting properties and environmentally friendly attributes, which allow it to decompose, thus contributing to a reduction in plastic waste and offering a more environmentally sustainable choice within the packaging industry [44].

The naturally occurring compound chitosan is synthesized from chitin through a process called deacetylation, which can be achieved using chemical, enzymatic, or microwave-assisted methods (Figure 3). The chitosan structure comprises two distinct components, which are N-acetyl-2-amino-2-deoxy-D-glucopyranose (the acetylated unit) and 2-amino-2-deoxy-D-glucopyranose (the deacetylated unit). These repeating units are connected via β-(1→4)-glycosidic linkages [45]. This structural modification enhances the reactivity of chitosan compared to chitin, resulting in improved solubility in acidic aqueous solutions ($pH < 6.5$). Chitosan typically appears as a white to off-white powder and is less crystalline than chitin, which contributes to its excellent film-forming capabilities, antimicrobial properties, and biocompatibility.

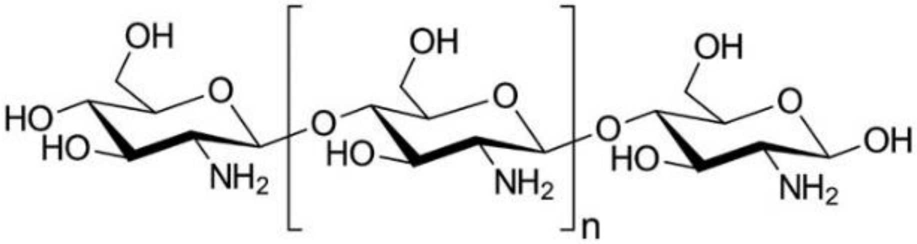


Figure 3. The structure of chitosan [46]

The distinctive physical and chemical characteristics of chitosan make it a suitable material for various industrial uses. Chitosan is commonly used in wound dressings within the biomedical sector because it facilitates the healing process and guards against infection. It serves as a structural material for tissue engineering scaffolds, facilitating cell adhesion and proliferation, which is crucial for bone and cartilage repair [47]. Additionally, chitosan-based nanoparticles and hydrogels are employed as carriers for controlled drug delivery and gene therapy, ensuring targeted and sustained release of therapeutic agents [48]. In agriculture, chitosan acts as a natural growth promoter and defense elicitor, enhancing plant immunity against pests and diseases while also serving as a seed coating agent and controlled-release matrix for fertilizers and pesticides. Chitosan is effective in water treatment, where it serves as a flocculant for removing heavy metals, dyes, and organic pollutants from wastewater.

Chitosan has gained significant attention for its applications in food packaging due to its unique properties such as biodegradability, biocompatibility, and antimicrobial activity. Its ability to form films makes it an excellent candidate for developing biodegradable packaging materials that can extend the shelf life of food products. Muthulakshmi et al. highlight that chitosan can be easily combined with other natural fillers, such as polysaccharides, proteins, and nanoparticles, to create composite films with tailored physicochemical properties suitable for various food packaging applications [49]. These nanocomposite films have been developed over the past two decades and are increasingly used for coating and wrapping food items, providing a sustainable alternative to conventional plastic packaging. In addition to its film-forming capabilities, chitosan exhibits significant antimicrobial properties, which are crucial for food preservation. Orgaz et al. demonstrated that chitosan is effective against biofilms formed by food-related bacteria, including *Salmonella enterica* and *Listeria monocytogenes*, making it a valuable component in active food packaging systems [50]. The incorporation of chitosan into packaging materials not only helps inhibit microbial growth but also enhances the overall safety and quality of food products. Furthermore, Wang et al. reported that chitosan films can be enhanced with natural extracts, such as honeysuckle flower extract, to improve their mechanical properties and provide additional antimicrobial effects, further supporting their use in food preservation [51]. Chitosan's versatility extends to its application in active packaging, where it can be combined with bioactive compounds to create functional materials that respond to environmental changes. For instance, Mesquita et al. explored the incorporation of carotenoids into chitosan films, demonstrating the potential for developing packaging materials that not only preserve food but also provide nutritional benefits [52]. Additionally, Aydogdu and Kaya developed oleuropein-incorporated chitosan films, showcasing the potential for antioxidant-active food packaging applications [53]. These advancements in chitosan-based packaging materials highlight their role in promoting sustainability in the food industry while ensuring food safety and quality.

Starch

Starch is a natural polysaccharide composed of α-D-glucose units linked by α-1,4-glycosidic bonds in its linear form (amylose) and α-1,6-glycosidic bonds in its branched form (amylopectin) (Figure 4). This biopolymer is one of the most abundant and renewable carbohydrates on Earth, predominantly found in plants, where it serves as a crucial energy storage compound, particularly in seeds, tubers, and roots. The structure of starch, consisting of amylose and amylopectin, significantly influences its physicochemical properties, such as gelatinization, retrogradation, and water absorption capacity [54]. Starch gelatinization is a critical process where granules absorb water, swell, and lose their crystalline structure upon heating, which is essential for many industrial applications. High-amylose starches exhibit greater thermal stability and reduced solubility, while low-amylose starches are more prone to rapid gelatinization and retrogradation. The retrogradation behavior of starch, influenced by its molecular arrangement, affects the shelf life and texture of starch-based products [55].

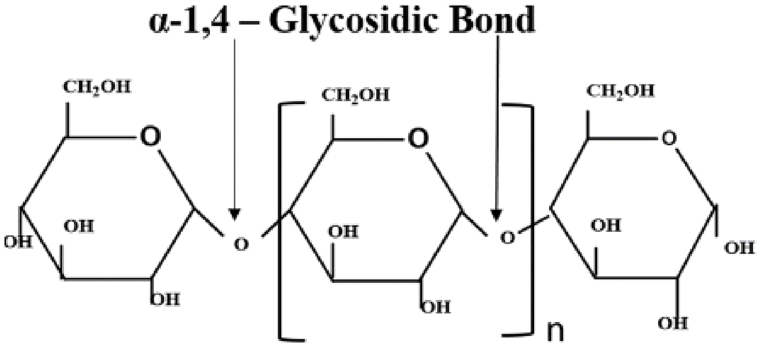


Figure 4. The structure of starch [56]

Chemically, starch is highly reactive due to the hydroxyl groups present in the glucose units, allowing for modifications that tailor its properties for specific applications. Modifications such as oxidation, etherification, and esterification enhance the performance of starch in adhesives, films, and biodegradable materials [57]. Moreover, cross-linking starch molecules improves its thermal and mechanical stability, making it suitable for applications such as encapsulation in the pharmaceutical and food industries.

In food applications, starch functions as a thickener, stabilizer, and gelling agent, enhancing the texture and consistency of products such as sauces, desserts, and bakery items. Modified starches, which are chemically altered to improve their functional properties, significantly enhance the stability and shelf life of these products. Resistant starch, a form of dietary fiber, is increasingly recognized for its health benefits, including promoting gut health and managing blood sugar levels in functional foods. It can improve digestive health by acting as a substrate for fermentation in the large intestine, thereby providing physiological benefits [58].

Starch also finds significant applications in the textile and paper industries, where it is utilized as a sizing agent to improve the strength and printability of fibers and papers. It enhances the smoothness and stiffness of paper products, making them suitable for high-quality printing and packaging. Furthermore, starch-based adhesives are valued for their strong bonding capabilities, particularly in the assembly of cardboard and paperboard products [59].

Alginate

Alginate is a naturally occurring anionic polysaccharide primarily composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) units, linked by 1,4-glycosidic bonds (Figure 5). It is predominantly found in the cell walls of brown seaweeds such as *Laminaria*, *Ascophyllum*, and *Macrocystis*, where it serves as a structural component, providing flexibility and strength. The unique ability of alginate to form gels and bind water has made it a valuable material across numerous industries, including food, pharmaceuticals, and environmental engineering. The gelation properties of alginate are influenced by the mannuronic acid/ guluronic acid ratio and the molecular weight of the polymer, which can vary depending on the source of the alginate [60].

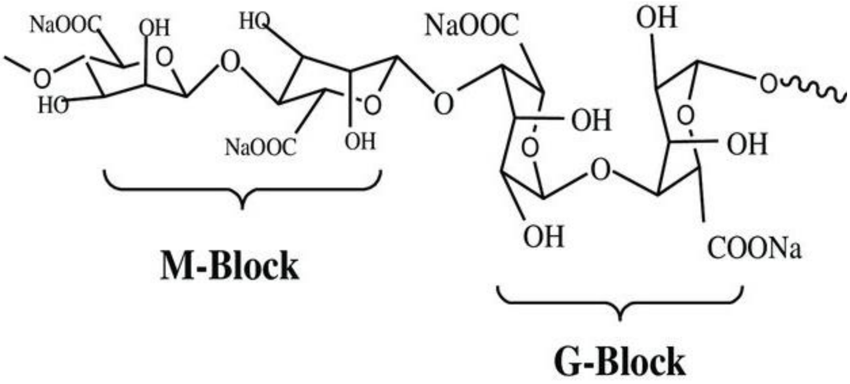


Figure 5. Molecular structure of sodium alginate [61]

The physical properties of alginate are determined by the arrangement of M and G blocks within its polymer chains. G-blocks are responsible for the formation of strong, rigid gels, while M-blocks contribute to softer, more flexible gels. The crystalline structure of alginate granules can be classified into different types, which influences their hydration characteristics and gelation behavior. This ability to chelate divalent cations facilitates the formation of hydrogels via ionic cross-linking, which is essential for many of its applications in drug delivery and tissue engineering [62].

Alginate is widely utilized in the food industry due to its unique properties as a thickener, stabilizer, and gelling agent. Its ability to form gels without the application of heat makes it particularly advantageous for cold food processing. Alginate is commonly employed in the production of restructured foods, such as artificial caviar through the spherification process, which encapsulates liquids in a gel-like membrane, creating a unique culinary experience. Additionally, its moisture retention properties enhance the texture and shelf life of baked goods and frozen products, making it a valuable ingredient in various food formulations [63]. The versatility of alginate in food applications is further supported by its role in creating edible films and coatings, which have gained attention for their ability to extend the shelf life of fresh produce and protect food from microbial contamination [64].

In the food industry, alginate is utilized as a thickening agent, stabilizer, and gelling agent, while in environmental engineering, it serves as an effective flocculant for wastewater treatment [65]. The versatility of alginate underscores its importance as a critical material in advancing sustainable practices across multiple industries.

Beyond cellulose, chitin, chitosan, starch, and alginate, polysaccharide-based biopolymers provide various functionalities and expand opportunities in food packaging applications. Pectin, predominantly obtained from citrus peels and apple pomace, is commonly utilized for its outstanding gelling and film-forming characteristics, rendering it suitable for coatings and active packaging systems. When combined with other biopolymers, Xanthan gum, a microbial polysaccharide, enhances film reinforcement and improves barrier properties. A polysaccharide called pullulan, which is derived from fungi and is soluble in water, produces transparent, pliable films with outstanding oxygen barrier properties, rendering it suitable for packaging fresh foods and snacks. Guar gum and locust bean gum function as thickening and stabilizing agents in edible coatings, thereby improving their mechanical and moisture barrier properties. Carrageenan, a substance obtained from red seaweed, is prized for its ability to form gels and is frequently used in conjunction with other polysaccharides to enhance film quality. These biopolymers, whether alone or as components of complex systems, continue to enhance the functionality, environmental sustainability, and performance of bio-based packaging materials.

III. APPLICATIONS IN FOOD PACKAGING

Polysaccharide-derived biopolymers have emerged as versatile and adaptable materials in the food packaging industry, particularly in the development of edible coatings and films. These materials are favored for their excellent functional properties, including film-forming capability, biodegradability, and compatibility with active packaging technologies.

Edible Coatings and Films

Polysaccharide-based biopolymers are extensively utilized to create edible coatings and films that serve as protective barriers against moisture, oxygen, and microbial contaminants. These coatings are particularly advantageous for extending the shelf life of perishable foods while being safe for direct consumption. Common polysaccharides employed in edible coatings include starch, cellulose derivatives, alginate, and pectin. Each of these materials offers unique properties that can be tailored for specific applications in food preservation [66]. For instance, a study by Zhou et al. demonstrated that coatings based on alginate form a gel-like barrier that reduces water vapor permeability, effectively minimizing moisture loss. Alginate coatings can also provide antimicrobial properties, further protecting fruits and vegetables from spoilage [67].

The distinctive physical and chemical characteristics of chitosan make it a suitable material for various industrial uses. Polysaccharide films are applied to bakery products to prevent staling and maintain freshness. Research by Fan et al. highlighted that edible films incorporate bioactive substances, such as essential oils, which can enhance moisture resistance and antimicrobial properties of the film, further preserving bread quality [68]. Edible wraps made from polysaccharides like pectin and alginate offer a sustainable alternative to traditional plastic packaging, addressing environmental concerns while enhancing food safety and quality. These biopolymers not only provide effective barriers against moisture and oxygen but can also be functionalized with flavors and nutrients, adding value to food products. Additionally, polysaccharide-based coatings can protect frozen items such as fruits, vegetables, and seafood against freeze-thaw damage and ice crystal formation [69].

Polysaccharide-based edible coatings and films have numerous benefits, but they are hindered by issues including limited mechanical strength, water solubility, and a lack of scalability. Exploration is underway into composite materials, nanotechnology, and the inclusion of hydrophobic agents to overcome the existing limitations. The future of edible coatings and films relies on enhancing their performance to meet a wider range of uses, while also ensuring affordability and environmental advantages are preserved.

Fresh Produce Packaging

Recent films have been developed from cellulose and alginate, proving to be an effective means of prolonging the shelf life of fruits and vegetables. These materials, sourced from renewable and biodegradable origins, tackle major hurdles in preserving fresh produce by establishing a controlled environment that sustains the ideal moisture and gas exchange levels [70]. For instance, Li et al. demonstrated that polysaccharide-based edible coatings significantly reduce enzymatic browning and oxidative senescence in fresh-cut lettuce, thereby extending shelf life and maintaining quality [71]. The ability of these coatings to form a semipermeable barrier helps regulate moisture levels, preventing dehydration while minimizing the risk of microbial growth, which is crucial for maintaining the freshness and appearance of fruits and vegetables.

In addition to moisture retention, polysaccharide films are engineered to control gas exchange, which is vital for preserving the quality of fresh produce. Hyun and Lee highlighted that modified atmosphere packaging (MAP) techniques, combined with polysaccharide films, can effectively maintain optimal gas concentrations around fruits and vegetables, reducing spoilage and off-flavors [72]. The incorporation of antimicrobial agents, such as nisin in polysaccharide-based films, has also been explored to enhance the preservation of fresh-cut fruits, as shown by Song et al., who reported that such films significantly extend the shelf life of watermelon by inhibiting microbial growth [73]. This controlled environment not only slows down the ripening process but also helps retain the texture and flavor of the produce.

Unlike conventional plastic packaging, alginate and chitosan films are biodegradable and compostable, reducing environmental impact. Research by Sun et al. emphasized the potential of chitosan blended with natural extracts, such as ginseng residue polysaccharides, to create antioxidant packaging that prolongs the shelf life of fresh-cut melon while being environmentally friendly [74]. The versatility of polysaccharides in food packaging not only minimizes food waste but also contributes to a more sustainable supply chain, making them a critical component in the future of food preservation.

Meat and Seafood Packaging

Polysaccharide-derived biopolymers, particularly alginate and chitosan, have emerged as effective materials for packaging meat and seafood, where microbial spoilage and lipid oxidation are significant concerns. These materials not only serve as physical barriers but also provide active protection through their inherent antimicrobial properties. For instance, Wei et al. demonstrated that polysaccharide-based films can be designed to act as food spoilage indicators, monitoring freshness by detecting changes in pH associated with microbial activity in food products [75]. This innovative approach enhances food safety by allowing consumers to assess the quality of meat before consumption.

The moisture retention capabilities of polysaccharide films are particularly beneficial in meat and seafood packaging. The hydrophilic nature of alginate and chitosan helps regulate moisture levels, preventing dehydration while minimizing excess condensation that could promote microbial growth. Ahmadi et al. reported that active packaging films made from cellulose nanofiber reinforced with zinc oxide nanoparticles effectively extended the shelf life of chicken fillets during storage by maintaining optimal moisture levels and inhibiting microbial growth [76]. Additionally, polysaccharide films can be engineered to control gas exchange, which is crucial for preserving the quality of fresh produce. By facilitating appropriate gas permeability, these films help slow down the natural spoilage processes, thereby extending the shelf life of meat and seafood products.

Moreover, the eco-friendly characteristics of polysaccharide-based packaging materials align with the growing demand for sustainable packaging solutions. Unlike conventional plastic packaging, alginate and chitosan films are biodegradable and compostable, reducing environmental impact. Research by Martiny et al. emphasized the potential of carrageenan films enriched with olive leaf extract to extend the shelf life of lamb meat, showcasing the effectiveness of natural antimicrobial agents in polysaccharide-based packaging [77]. The versatility of polysaccharides in food packaging not only minimizes food waste but also contributes to a more sustainable supply chain, making them a critical component in the future of food preservation.

Active Packaging

Polysaccharide-derived biopolymers play a crucial role in active packaging systems, which are designed to interact with the packaged food or its environment to improve quality and extend shelf life. These materials are excellent carriers for bioactive compounds, such as antioxidants and antimicrobials, enabling the creation of smart and functional packaging solutions. One prominent application is in antioxidant packaging, where polysaccharides like starch and alginate are used to incorporate natural antioxidants such as essential oils, vitamin E, or plant extracts [78]. These materials help prevent lipid oxidation in fatty foods, including nuts, oils, and processed meats, thereby maintaining their quality and extending their shelf life.

In addition to antioxidant properties, antimicrobial packaging is another significant application of polysaccharide-based materials. Chitosan and other polysaccharides can be infused with natural antimicrobials like nisin, lysozyme, or essential oils to inhibit microbial growth. This application is especially beneficial for packaging dairy products, poultry, and seafood, where spoilage due to microbial contamination is a major concern. Popescu et al. reported that chitosan-based edible coatings containing essential oils significantly preserved the shelf life and postharvest quality of organic strawberries and apples during cold storage, demonstrating the effectiveness of these coatings in enhancing food safety [79].

Furthermore, polysaccharide films can be designed to address moisture and odor absorption. These films can include additives that absorb excess moisture or neutralize odors, improving the storage environment for foods like cheese and baked goods. For example, Jeong and Yoo developed sodium bicarbonate-incorporated films that exhibited deodorizing functions for kimchi packaging, effectively controlling odors during fermentation [80]. Additionally, polysaccharide-based active packaging can be engineered to release bioactive compounds gradually, maintaining protective effects throughout the shelf life of the product. This capability enhances the overall effectiveness of the packaging, ensuring that food products remain fresh and safe for consumption over extended periods.

Conclusions

Polysaccharide-based biopolymers are increasingly recognized as sustainable alternatives to conventional plastics in food packaging, offering unique functional properties that enhance food preservation. These materials are derived from renewable resources and exhibit film-forming capabilities, excellent gas barrier performance, and biodegradability, making them suitable for extending shelf life and maintaining food quality. This review provides a comprehensive overview of polysaccharide-based biopolymers and their uses in food packaging applications. Polysaccharides including cellulose, starch, chitin, chitosan, and alginate have shown considerable potential for creating edible coatings, active packaging systems, and innovative wrapping solutions. This further boosts their value in active and intelligent packaging systems by allowing them to be infused with bioactive substances such as antioxidants and antimicrobials, particularly to meet the increasing need for food safety and quality. By addressing current challenges and leveraging emerging technologies, these materials have the potential to revolutionize the packaging industry, aligning with global sustainability goals while ensuring the safety, freshness, and quality of food products.

References

[1] Marasinghe, W. N., Jayathunge, K. G. L. R., Dassanayake, R. S., Liyanage, R., Bandara, P. C., Rajapaksha, S. M., … & Gunathilake, C. (2024). *Structure, properties, and recent developments in polysaccharide- and aliphatic polyester-based packaging—a review*. Journal of Composites Science, 8(3), 114.

[2] Walker, T. R., McGuinty, E., Charlebois, S., & Music, J. (2021). *Single-use plastic packaging in the canadian food industry: consumer behavior and perceptions.* Humanities and Social Sciences Communications, 8(1). https://doi.org/10.1057/s41599-021-00747-4

[3] Sonia, P., Kumar, A. S., Khan, I., Pahwa, S., Salman, Z. N., & Singh, N. (2023). *Sustainable manufacturing of high-performance composites from recycled materials*. E3S Web of Conferences, 430, 01105.

[4] Nešić, A., Cabrera-Barjas, G., Dimitrijević-Branković, S., Davidovic, Z. S., Radovanović, N., & Delattre, C. (2019). *The prospect of polysaccharide-based materials as advanced food packaging*. Molecules, 25(1), 135.

[5] Teixeira-Costa, B. E. and Andrade, C. T. (2021). *Natural polymers used in edible food packaging—history, function and application trends as a sustainable alternative to synthetic plastic*. Polysaccharides, 3(1), 32-58.

[6] Baranwal, J., Barse, B., Fais, A., Delogu, G., & Kumar, A. (2022). *Biopolymer: a sustainable material for food and medical applications*. Polymers 14(5): 983.

[7] Poole-Warren, L. A., & Patton, A. J. (2016). Introduction to biomedical polymers and biocompatibility. In Biosynthetic Polymers for Medical Applications (pp. 3-31). Woodhead Publishing.

[8] Yates, M. R., & Barlow, C. Y. (2013). Life cycle assessments of biodegradable, commercial biopolymers—A critical review. Resources, Conservation and Recycling, 78, 54-66.

[9] Udayakumar, G. P., Muthusamy, S., Selvaganesh, B., Sivarajasekar, N., Rambabu, K., Banat, F., ... & Show, P. L. (2021). *Biopolymers and composites: Properties, characterization and their applications in food, medical and pharmaceutical industries*. Journal of Environmental Chemical Engineering, 9(4): 105322.

[10] Mohamed, S. A., El-Sakhawy, M., & El-Sakhawy, M. A. M. (2020). *Polysaccharides, protein and lipid-based natural edible films in food packaging: A review*. Carbohydrate polymers, 238: 116178.

[11] De Kruif, C. G., & Tuinier, R. (2001). *Polysaccharide protein interactions*. Food hydrocolloids, 15(4-6): 555-563.

[12] Díaz-Cruz, C. A., Caicedo, C., Jiménez-Regalado, E. J., León, R. D. d., López-González, R., & Aguirre-Loredo, R. Y. (2022). *Evaluation of the antimicrobial, thermal, mechanical, and barrier properties of corn starch–chitosan biodegradable films reinforced with cellulose nanocrystals*. Polymers, 14(11): 2166.

[13] Cesur, S., Köroğlu, C., & Yalçın, H. T. (2017). *Antimicrobial and biodegradable food packaging applications of polycaprolactone/organo nanoclay/chitosan polymeric composite films.* Journal of Vinyl and Additive Technology, 24(4): 376-387.

[14] Lozano-Navarro, J. I., Díaz-Zavala, N. P., Velasco-Santos, C., Martínez-Hernández, A. L., Tijerina-Ramos, B., Hernández, M., … & Torre, A. R. l. (2017). *Antimicrobial, optical and mechanical properties of chitosan–starch films with natural extracts. International Journal of Molecular Sciences*, 18(5): 997.

[15] Mohan, T. P., Devchand, K., & Kanny, K. (2016). Barrier and biodegradable properties of corn starch-derived biopolymer film filled with nanoclay fillers. Journal of Plastic Film &Amp; Sheeting, 33(3), 309-336.

[16] Dirpan, A., Ainani, A. F., & Djalal, M. (2023). A review on biopolymer-based biodegradable film for food packaging: trends over the last decade and future research. Polymers, 15(13), 2781.

[17] Low, J. T., Yusoff, N. I. S. M., Othman, N., Wong, T., & Wahit, M. U. (2022). Silk fibroin-based films in food packaging applications: a review. Comprehensive Reviews in Food Science and Food Safety, 21(3), 2253-2273.

[18] Selikane, D., Gumede, T. P., Shingange, K., & Malevu, T. D. (2022). A brief overview on the extraction of cellulose from medicinal plants for advanced applications. Materials Science Forum, 1059, 81-85.

[19] Liu, Y. and Chen, J. Y. (2016). Enzyme immobilization on cellulose matrixes. Journal of Bioactive and Compatible Polymers, 31(6), 553-567.

[20] Aulin, C., Karabulut, E., Tran, A., Wågberg, L., & Lindström, T. (2013). Transparent nanocellulosic multilayer thin films on polylactic acid with tunable gas barrier properties. ACS Applied Materials &Amp; Interfaces, 5(15), 7352-7359.

[21] https://www.britannica.com/science/cellulose#/media/1/101633/239925, Encyclopædia Britannica, October 30, 2024.

[22] Driemeier, C. and Calligaris, G. A. (2010). Theoretical and experimental developments for accurate determination of

crystallinity of cellulose i materials. Journal of Applied Crystallography, 44(1), 184-192.

[23] Wasim, M., Mushtaq, M., Khan, S. U., Farooq, A., Naeem, M. A., Khan, M. R., … & Wei, Q. (2020). Development of bacterial cellulose nanocomposites: an overview of the synthesis of bacterial cellulose nanocomposites with metallic and metallic-oxide nanoparticles by different methods and techniques for biomedical applications. Journal of Industrial Textiles, 51(2_suppl), 1886S-1915S.

[24] Nagarajan, K., Rangappa, S. M., K., S. B., R, R. G., R., A. K., Siengchin, S., … & Khan, A. (2022). Extraction of cellulose nanocrystals from red banana peduncle agro-waste and application in environmentally friendly biocomposite film. Polymer Composites, 43(8), 4942-4958.

[25] Thakur, M. K., Gupta, R. K., & Thakur, V. K. (2014). Surface modification of cellulose using silane coupling agent. Carbohydrate Polymers, 111, 849-855.

[26] Kabir, S. M. F., Sikdar, P., Haque, B., Bhuiyan, M. A. R., Ali, A., & Islam, M. N. (2018). Cellulose-based hydrogel materials: chemistry, properties and their prospective applications. Progress in Biomaterials, 7(3), 153-174.

[27] Karataş, M., & Arslan, N. (2016). Flow behaviours of cellulose and carboxymethyl cellulose from grapefruit peel. Food Hydrocolloids, 58, 235-245.

[28] Canilha, L., Santos, V. T. O., Rocha, G. J. M., Silva, J. B. d. A. e., Giulietti, M., Silva, S. S., … & Carvalho, W. (2011). A study on the pretreatment of a sugarcane bagasse sample with dilute sulfuric acid. Journal of Industrial Microbiology &Amp; Biotechnology, 38(9), 1467-1475.

[29] Merais, M. S., Khairuddin, N., Salehudin, M. H., Siddique, M. B. M., Lepun, P., & Chuong, W. S. (2022). Preparation and characterization of cellulose nanofibers from banana pseudostem by acid hydrolysis: physico-chemical and thermal properties. Membranes, 12(5), 451.

[30] Halib, N., Ahmad, I., Grassi, M., & Grassi, G. (2019). The remarkable three-dimensional network structure of bacterial cellulose for tissue engineering applications. International journal of pharmaceutics, 566, 631-640.

[31] Mihhels, K., Yousefi, N., Blomster, J., Solala, I., Solhi, L., & Kontturi, E. (2023). Assessment of the alga cladophora glomerata as a source for cellulose nanocrystals. Biomacromolecules, 24(11), 4672-4679.

[32] Eichorst, S. A. and Kuske, C. R. (2012). Identification of cellulose-responsive bacterial and fungal communities in geographically and edaphically different soils by using stable isotope probing. Applied and Environmental Microbiology, 78(7), 2316-2327.

[33] Xia, G., Ji, X., Peng, J., & Ji, X. (2022). Cellulose/poly(meta-phenylene isophthalamide) light-management films with high antiultraviolet and tunable haze performances. ACS Applied Polymer Materials, 4(11), 8407-8417.

[34] Liu, M., Tong, S., Tong, Z., Guan, Y., & Sun, Y. (2023). A strong, biodegradable and transparent cellulose-based bioplastic stemmed from waste paper. Journal of Applied Polymer Science, 140(13).

[35] Qin, H., Zhang, Y., Jiang, J., Wang, L., Song, M., Bi, R., … & Jiang, F. (2021). Multifunctional superelastic cellulose nanofibrils aerogel by dual ice-templating assembly. Advanced Functional Materials, 31(46).

[36] Qi, X., Liu, S., Chu, F., Pang, S., Liang, Y., Guan, Y., … & Sun, R. (2015). Preparation and characterization of blended films from quaternized hemicelluloses and carboxymethyl cellulose. Materials, 9(1), 4.

[37] Fotie, G., Amoroso, L., Limbo, S., Muratore, G., & Piergiovanni, L. (2019). Food life extension by cellulose nanocrystals coatings. Italian Journal of Food Science, 8-14.

[38] Chen, G. G., Qi, X. M., Guan, Y., Peng, F., Yao, C. L., & Sun, R. C. (2016). High strength hemicellulose-based nanocomposite film for food packaging applications. ACS Sustainable Chemistry & Engineering, 4(4), 1985-1993.

[39] Iber, B. T., Kasan, N. A., Torsabo, D., & Omuwa, J. W. (2022). A review of various sources of chitin and chitosan in nature. Journal of Renewable Materials, 10(4), 1097.

[40] Nunes, C. S., & Kumar, V. (Eds.). (2018). Enzymes in human and animal nutrition: principles and perspectives. Academic Press, 361-362.

[41] Bai, L., Liu, L., Esquivel, M., Tardy, B. L., Huan, S., Niu, X., ... & Rojas, O. J. (2022). Nanochitin: chemistry, structure, assembly, and applications. Chemical reviews, 122(13), 11604-11674.

[42] Rinaudo, M. (2006). Chitin and chitosan: Properties and applications. Progress in polymer science, 31(7), 603-632.

[43] Shen, Y., Dai, L., Li, X., Liang, R., Guangxiong, G., Zhang, Z., … & Chen, H. (2014). Epidermal stem cells cultured on collagen-modified chitin membrane induce in situ tissue regeneration of full-thickness skin defects in mice. PLoS ONE, 9(2), e87557.

[44] Hai, L., Choi, E. S., Zhai, L., Panicker, P. S., & Kim, J. (2020). Green nanocomposite made with chitin and bamboo nanofibers and its mechanical, thermal and biodegradable properties for food packaging. International Journal of Biological Macromolecules, 144, 491-499.

[45] Aranaz, I., Alcántara, A. R., Civera, M. C., Arias, C., Elorza, B., Heras Caballero, A., & Acosta, N. (2021). Chitosan: An overview of its properties and applications. Polymers, 13(19), 3256.

[46] KK, R., Jang, W., Kim, S., & Kim, T. H. (2022). Chitosan-grafted-gallic acid as a nature-inspired multifunctional binder for high-performance silicon anodes in lithium-ion batteries. ACS Applied Energy Materials, 5(3), 3166-3178.

[47] Haider, A., Khan, S., Iqbal, D. N., Khan, S. U., Haider, S., Mohammad, K., ... & Haider, A. (2024). Chitosan as a tool for tissue engineering and rehabilitation: Recent developments and future perspectives–A review. International Journal of Biological Macromolecules, 134172.

[48] Santiago, T. R., Bonatto, C. C., Rossato, M., Lopes, C., Lopes, C. A., Mizubuti, E. S. G., … & Silva, L. (2019). Green synthesis of silver nanoparticles using tomato leaf extract and their entrapment in chitosan nanoparticles to control bacterial wilt. Journal of the Science of Food and Agriculture, 99(9), 4248-4259.

[49] Muthulakshmi, L., Annaraj, J., Ramakrishna, S., Ranjan, S., Dasgupta, N., Rangappa, S. M., … & Siengchin, S. (2020). A sustainable solution for enhanced food packaging via a science-based composite blend of natural-sourced chitosan and

microbial extracellular polymeric substances. Journal of Food Processing and Preservation, 45(1), e15031.

[50] Orgaz, B., Lobete, M. M., Puga, C. H., & José, C. S. (2011). Effectiveness of chitosan against mature biofilms formed by food related bacteria. International Journal of Molecular Sciences, 12(1), 817-828. https://doi.org/10.3390/ijms12010817

[51] Wang, L., Wang, Q., Jin, T., & Zhou, J. (2015). Physicochemical properties of chitosan films incorporated with honeysuckle flower extract for active food packaging. Journal of Food Process Engineering, 40(1).

[52] Mesquita, L. M. d. S., Martins, M., Maricato, É., Nunes, C., Quinteiro, P., Dias, A. C., … & Ventura, S. P. M. (2020). Ionic liquid-mediated recovery of carotenoids from the bactris gasipaes fruit waste and their application in food-packaging chitosan films. ACS Sustainable Chemistry &Amp; Engineering, 8(10), 4085-4095.

[53] Aydoğdu, A. and KAYA>, F. (2023). Development of oleuropein incorporated chitosan films for antioxidant active food packaging applications. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi, 12(1), 158-165.

[54] Donmez, D., Pinho, L., Patel, B., Desam, P., & Campanella, O. H. (2021). Characterization of starch–water interactions and their effects on two key functional properties: Starch gelatinization and retrogradation. Current Opinion in Food Science, 39, 103-109.

[55] Scott, G., & Awika, J. M. (2023). Effect of protein–starch interactions on starch retrogradation and implications for food product quality. Comprehensive Reviews in Food Science and Food Safety, 22(3), 2081-2111.

[56] Surendren, A., Mohanty, A. K., Liu, Q., & Misra, M. (2022). A review of biodegradable thermoplastic starches, their blends and composites: Recent developments and opportunities for single-use plastic packaging alternatives. Green Chemistry, 24(22), 8606-8636.

[57] Watcharakitti, J., Win, E. E., Nimnuan, J., & Smith, S. M. (2022). Modified starch-based adhesives: A review. Polymers, 14(10), 2023.

[58] Jiang, F., Du, C., Jiang, W., Wang, L., & Du, S. K. (2020). The preparation, formation, fermentability, and applications of resistant starch. International Journal of Biological Macromolecules, 150, 1155-1161.

[59] Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O. V., & García, M. A. (2023). Sustainable and bio-based food packaging: A review on past and current design innovations. Foods, 12(5), 1057.

[60] Dorochesi, F., Barrientos-Sanhueza, C., Díaz-Barrera, Á., & Cuneo, I. F. (2023). Enhancing soil resilience: bacterial alginate hydrogel vs. algal alginate in mitigating agricultural challenges. Gels, 9(12), 988.

[61] Salisu, A., Sanagi, M. M., Naim, A. A., Ibrahim, W. A. W., & Abd Karim, K. J. (2016). Removal of lead ions from aqueous solutions using sodium alginate-graft-poly (methyl methacrylate) beads. Desalination and Water Treatment, 57(33), 15353-15361.

[62] Omtvedt, L. A., Dalheim, M. Ø., Nielsen, T. T., Larsen, K. L., Strand, B. L., & Aachmann, F. L. (2019). Efficient grafting of cyclodextrin to alginate and performance of the hydrogel for release of model drug. Scientific Reports, 9(1).

[63] Demirbilek, M., Türkoğlu, N., & Aktürk, S. (2017). N-acetylglucoseamine modified alginate sponges as scaffolds for skin tissue engineering. Turkish Journal of Biology, 41, 796-807.

[64] Dong, H., Wang, L., Du, L., Wang, X., Li, Q., Wang, X., … & Ma, G. (2022). Smart polycationic hydrogel dressing for dynamic wound healing. Small, 18(25).

[65] Bi, D., Xu, Y., Yao, L., Hu, Z., Li, H., Xu, X., … & Lu, J. (2022). Potential food and nutraceutical applications of alginate: a review. Marine Drugs, 20(9), 564.

[66] Sharma, P., Shehin, V. P., Kaur, N., & Vyas, P. (2019). Application of edible coatings on fresh and minimally processed vegetables: a review. International Journal of Vegetable Science, 25(3), 295-314.

[67] Zhou, T., Wang, H., Han, Q., Song, Z., Yu, D., Li, G., ... & Chen, X. (2024). Fabrication and characterization of an alginate-based film incorporated with cinnamaldehyde for fruit preservation. International Journal of Biological Macromolecules, 274, 133398.

[68] Fan, S., Yin, X., Liu, X., Wang, G., & Qiu, W. (2024). Enhancing bread preservation through non-contact application of starch-based composite film infused with clove essential oil nanoemulsion. International Journal of Biological Macromolecules, 263, 130297.

[69] Sun, X., Wu, Y., Song, Z., & Chen, X. (2022). A review of natural polysaccharides for food cryoprotection: Ice crystals inhibition and cryo-stabilization. Bioactive Carbohydrates and Dietary Fibre, 27, 100291.

[70] Lei, Y., Yao, Q., Jin, Z., & Wang, Y. C. (2023). Intelligent films based on pectin, sodium alginate, cellulose nanocrystals, and anthocyanins for monitoring food freshness. Food chemistry, 404, 134528.

[71] Li, L., Yi, P., Li, C., Xin, M., Jian, S., He, X., … & Tang, Y. (2021). Influence of polysaccharide-based edible coatings on enzymatic browning and oxidative senescence of fresh-cut lettuce. Food Science &Amp; Nutrition, 9(2), 888-899.

[72] Hyun, J. and Lee, S. (2017). Effect of modified atmosphere packaging on preserving various types of fresh produce. Journal of Food Safety, 38(1).

[73] Song, X., WANG, X., ZHANG, H., Zhang, D., LI, Z., Wang, H. J., … & YU, J. (2023). Characterization of polysaccharide-based antibacterial films properties of loaded with nisin and preservation of fresh-cut watermelon. Food Science and Technology, 43.

[74] Sun, J., Li, Y., Cao, X., Fan, Y., & Shi, L. (2022). A film of chitosan blended with ginseng residue polysaccharides as an antioxidant packaging for prolonging the shelf life of fresh-cut melon. Coatings, 12(4), 468.

[75] Wei, Y. C., Cheng, C. H., Ho, Y. C., Tsai, M. L., & Mi, F. L. (2017). Active gellan gum/purple sweet potato composite films capable of monitoring pH variations. Food Hydrocolloids, 69, 491-502.

[76] Ahmadi, A., Ahmadi, P., & Ehsani, A. (2020). Development of an active packaging system containing zinc oxide nanoparticles for the extension of chicken fillet shelf life. Food Science & Nutrition, 8(10), 5461-5473.

[77] Martiny, T. R., Raghavan, V., Moraes, C. C. D., Rosa, G. S. D., & Dotto, G. L. (2020). Bio-based active packaging: Carrageenan film with olive leaf extract for lamb meat preservation. Foods, 9(12), 1759.

[78] Hashemi, M., Hashemi, M., Daneshamooz, S., Raeisi, M., Jannat, B., Taheri, S., & Noori, S. M. A. (2020). An overview on antioxidants activity of polysaccharide edible films and coatings contains essential oils and herb extracts in meat and meat products. Adv. Anim. Vet. Sci, 8(2), 198-207.

[79] Popescu, P. A., Palade, L. M., Nicolae, I., Popa, E. E., Miteluț, A. C., Drăghici, M., … & Popa, M. E. (2022). Chitosan-based edible coatings containing essential oils to preserve the shelf life and postharvest quality parameters of organic strawberries and apples during cold storage. Foods, 11(21), 3317.

[80] Jeong, S. and Yoo, S. (2017). Preparation and properties of sodium bicarbonate-incorporated ldpe films with deodorizing function for

kimchi packaging. Packaging Technology and Science, 30(12), 781-790.