Quality Assurance and Safety of Crops & Foods, 2025; 17(4): 257–283

Polysaccharide-based biopolymers: exploring film fabrication techniques, molecular interactions, and their potential food applications

Pir Mohammad Junaid[1*], Akuleti Saikumar[2], Rayees Ul Islam[1], Manoj Kumar Patel[3], Don Hettiarachchige Udana Eranda[4], Makdud Islam[5], Sadaf Zaidi[1*], Laxmikant S. Badwaik[2]

[1]Department of Post-Harvest Engineering and Technology, Faculty of Agricultural Science, Aligarh Muslim University, Aligarh, Uttar Pradesh, India; [2]Department of Food Engineering and Technology, Tezpur University, Tezpur, Assam, India, 784028; [3]Manufacturing Science and Instrumentation (MSI) Division, CSIR-Central Scientific Instruments Organization, Chandigarh, India; Academy of Science and Innovative Research, Ghaziabad, Uttar Pradesh, India; [4]Food Technology and Innovation Research Center of Excellence, Division of Food Science and Innovation, Department of Food Industry, School of Agricultural Technology and Food Industry, Walailak University, Nakhon Si Thammarat, Thailand; [5]Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab, India

***Corresponding Authors:** Pir Mohammad Junaid and Sadaf Zaidi, Department of Post-Harvest Engineering and Technology, Faculty of Agricultural Science, Aligarh Muslim University, Aligarh, Uttar Pradesh, India. Emails: pmjunaid@myamu.ac.in; szaidi@myamu.ac.in

Academic Editor: Slim Smaoui, PhD, Laboratory of Microbial, Enzymatic Biotechnology and Biomolecules (LBMEB), Center of Biotechnology of Sfax, University of Sfax-Tunisia, 3018 Sfax, Tunisia

Received: 16 September 2024; Accepted: 12 July 2025; Published: 8 October 2025

REVIEW ARTICLE

Highlights

- Biodegradable polysaccharide-based materials are suitable replacements for conventional petrochemical polymers.
- Polysaccharides display biocompatibility, biodegradability, non-toxicity, and edibility.
- The interactions between polysaccharides and active ingredients are crucial for designing adequate functional packaging.
- Addition of plasticizers, surfactants, cross-linkers, and other functional additives improves the physiochemical properties of polysaccharide films.
- Polysaccharides offer sustainable packaging solutions for food preservation.

Abstract

Polysaccharide-based biopolymers have emerged as sustainable alternatives to conventional petroleum-derived plastics in food packaging because of their natural abundance, biodegradability, and film-forming ability. Common polysaccharides, such as starch, cellulose, alginate, and chitosan, offer eco-friendly packaging solutions that reduce environmental impact while maintaining food quality. This review explores the development of polysaccharides-based films, emphasizing recent advances in their mechanical, barrier, and functional properties. Various fabrication methods and the incorporation of bioactive compounds have significantly improved their antimicrobial and antioxidant performance, contributing to enhanced shelf life and safety of packaged foods. The integration of nanomaterials has addressed limitations, such as poor water resistance and mechanical weakness, enabling the creation of nanocomposite systems with superior properties. The review discusses regulatory aspects, biodegradability, and challenges in commercializing these materials, including cost, scalability, and compliance. A special focus is placed on the molecular-level interactions between polysaccharides and additives, which play a crucial role in determining the stability and functionality of films. Polysaccharide-based biopolymers present a promising pathway toward environmentally responsible, active, and intelligent packaging solutions in the food industry.

Keywords: biopolymers; food packaging; functional ingredients; packaging films; polysaccharides

Introduction

Food packaging plays a crucial role in preserving the quality, safety, and shelf life of food products. Conventional food packaging materials, such as glass, metal, and plastic, are widely used for their effectiveness in protecting food from environmental factors. However, the growing environmental concerns and the need for sustainable practices have prompted the exploration of more eco-friendly packaging alternatives. Traditionally, a variety of materials are employed for different types of food packaging, including primary, secondary, and tertiary packaging (Junaid *et al.*, 2023). These materials are selected carefully to provide the desired mechanical, physical, and thermal resistance, optical barrier, and antibacterial properties. Petroleum-based polymers, such as polyethylene (PE), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET), are widely used in food packaging because of their high mechanical strength, high barrier properties, lightweight quality, and low cost. However, these materials often pose significant environmental challenges, such as non-biodegradability, substantial carbon footprint, high energy consumption during production, and potential marine and microplastic pollution (Law and Narayan, 2022). Their production also consumes a lot of water and produces toxic pollutants, which pollute the environment and water during the production and disposal stages. The search for sustainable packaging solutions has become a pressing concern for the food industry, driven by environmental concerns and changing consumer preferences. Eco-friendly approaches that prioritize environmental sustainability, while maintaining the essential protective functions of food packaging, are gaining credence. Innovative materials, such as bionanocomposites and nature-based packaging are actively researched and developed to address sustainability challenges in food packaging. These advanced solutions seek to enhance key functional characteristics of packaging, including barrier performance, mechanical strength, and thermal stability. Biopolymers derived from plant sources are increasingly recognized as excellent and safe alternatives of food packaging (Udayakumar *et al.*, 2021). Their exceptional solubility and gel-forming abilities make them promising candidates for food packaging applications. Biopolymers, mainly polysaccharides, have gained significant attention as sustainable and cost-effective materials for food packaging applications. Their abundance and renewable nature make them attractive alternatives to traditional petroleum-based polymers. Moreover, the organoleptic characteristics and optical properties of polysaccharide-based biopolymers often align well with food packaging requirements. However, these materials often demonstrate poor barrier and mechanical properties because of their hydrophilic nature and weak intermolecular interactions (primarily hydrogen and covalent bonds), ultimately compromising their protective functionality in food packaging applications. To address the limitations, the incorporation of functional ingredients and the use of copolymers are effective strategies. Adding functional additives, such as nanoparticles (NPs) or active compounds, significantly enhances the physical, chemical, and barrier properties of these materials, as depicted in Table 1. Similarly, employing copolymers, which consist of two or more different polymers, results in a synergistic improvement in the overall performance of the packaging system. These strategies aim to develop advanced and versatile food packaging solutions that ensure the quality, safety, and shelf life of food products. The effectiveness of incorporating functional ingredients into biopolymer films is influenced by several factors, including the fabrication technique, the chemical properties of additives, and the biopolymer's ability to rearrange and accommodate these additives effectively. By leveraging these approaches, researchers and manufacturers can design more robust and sustainable food packaging solutions, ensuring better protection and preservation of food items while addressing environmental concerns associated with traditional packaging materials. This review comprehensively explores the integration of polysaccharide-based biopolymers with functional additives to overcome the inherent limitations of conventional biopolymer films. Unlike previous studies that often focus on individual polysaccharides or basic composites, this work synthesizes recent advancements in fabrication techniques, molecular interactions, and multifunctional modifications, leading to advanced nanocomposite films. By critically examining innovations with scalable potential, as well as regulatory and commercialization challenges, this review offers valuable insights into the development of sustainable, active, and intelligent food packaging systems.

Table 1. An overview of recent studies demonstrating the functionalization of polysaccharide matrices with plant-based extracts, nanoparticles, probiotics, and other bioactive agents.

Polysaccharide	Functional ingredient	Function properties	References
Cellulose	Silver and copper nanoparticles + *Vitex negundo* leaf extract	Antimicrobial activity against Gram-positive and Gram-negative bacteria	Mamatha *et al.*, 2021
	Blueberry and red grape skin extract	Higher antioxidant activity in grape skin extract vs. blueberry extract	Kurek *et al.*, 2019
	Carnauba wax + cellulose nanofibers (CNFs)	Reduced water vapor transmission rate (WVTR) and oxygen transmission rates (OTR)	Zhu *et al.*, 2024
	Zinc oxide (ZnO) nanoparticles	Ultraviolet (UV) shielding (UPF increased from 1.31 to 1603.98 at 90% ZnO)	Liao *et al.*, 2023
Chitosan	Nickel oxide nanoparticles	Antibacterial activity against *S. aureus* and *S. typhimurium*	Ardebilchi *et al.*, 2021
	Plant extracts + nano-keratin/cellulose nanocrystals (CNCs)	42% reduction in water vapor permeability (WVP)	Khanzada *et al.*, 2023
	α-Tocopherol (0.2 wt.%)	Reduced UV transmittance	Martins *et al.*, 2012
	Lactobacillus casei + *Bacillus coagulans*	Extended shelf life of chicken fillets by reducing oxidative/microbial spoilage	Salimiraad *et al.*, 2022
Alginate	Lemon essential oil	Antimicrobial and antifungal properties	Hammoudi *et al.*, 2020
	Gum tragacanth + hydroxypropyl methylcellulose	Increased WVP; decreased oxygen permeability (OP)	Hadi *et al.*, 2023
	Copper sulfide nanoparticles	UV blocking (dose-dependent reduction in transmittance)	Wang *et al.*, 2017
	Lactobacillus plantarum	High probiotic survival during drying/storage	Akman *et al.*, 2021
Starch	Silver + ZnO nanoparticles	Antimicrobial activity against *S. aureus* and *E. coli*	Zhai *et al.*, 2022
	Rosemary extract	High antioxidant activity in lipophilic simulants	Estevez-Areco *et al.*, 2019
	Chitin nanofibers	Reduced WVP	Tanpichai *et al.*, 2023
	Carvacrol	UV-C shielding (near-zero transmittance at 200–280 nm)	Mao *et al.*, 2023
	Lactobacillus rhamnosus	Probiotic viability dependent on film composition/pH	Singh *et al.*, 2019
Carrageenan	*Rosmarinus officinalis L.* extract	Antibacterial activity against *B. cereus*, *E. coli*, *P. aeruginosa*, and *S. aureus*	Nouri *et al.*, 2018
	Grapefruit essential oil	Significant antioxidant activity (DPPH/ABTS radical scavenging assays)	Bhatia *et al.*, 2024
	CNCs	Significant improvement in water barrier properties	Gupta *et al.*, 2023
	ZnO nanoparticles (ZnO)	Optimal UV barrier at 1.0% ZnO; 1.5% ZnO showed highest UV screening but reduced transparency	Khoirunnisa *et al.*, 2018
	Lactobacillus acidophilus, L. plantarum, and mixed culture (*Lactobacillus* spp., *Lactococcus* spp., *Bifidobacterium* spp.)	Enhanced probiotic survival during storage	Sogut *et al.* 2022
Agar	Silver nanoparticles	Strong antimicrobial activity against *L. monocytogenes* and *E. coli*	Rhim *et al.*, 2013
	Melanin nanoparticles	Concentration-dependent antioxidant activity (DPPH/ABTS assays)	Roy and Rhim, 2019
	Montmorillonite nanoclay	WVP decreased 10.53% with increasing nanoclay content	Lee *et al.*, 2019
	Melanin nanoparticles	Significant UV-blocking enhancement	Wang *et al.*, 2017
	Lactobacillus plantarum	Effective gastric fluid protection and intestinal fluid resistance for controlled delivery	Albadran *et al.*, 2020

(*continues*)

Table 1. Continued.

Polysaccharide	Functional ingredient	Function properties	References
Pectin	Silver/zinc/copper nanoparticles	Bactericidal activity against *E. coli* and *S. aureus*	Panneerselvam *et al.*, 2023
	Curcumin	Increased antioxidant activity (DPPH: 73.0%; ABTS: 95.2%)	Ezati and Rhim, 2020
	CNCs + sodium montmorillonite nanoparticles	35% reduction in WVP	Souza *et al.*, 2022
	ZnO nanoparticles	Improved UV barrier properties	Hari *et al.*, 2021
	Lactobacillus casei, B. bifidum, L. acidophilus, L. rhamnosus	1.5-log reduction in *L. monocytogenes*; 2-log reduction in probiotic viability after 30 days at 4°C	Nisar *et al.*, 2022
Gums	Silver-copper alloy nanoparticles	Antimicrobial activity against *L. monocytogenes* and *S. typhimurium*	Arfat *et al.*, 2017
	Grape skin extract	DPPH/ABTS radical scavenging activity	Kang *et al.*, 2021
	Nanoclay (2.5 wt.%)	Maximum reduction in WVTR	Saurabh *et al.*, 2015
	Lignin	Dose-dependent UV transmittance reduction	Rukmanikrishnan *et al.*, 2020
	Lactococcus lactis + cranberry extract	Enhanced antibacterial and antioxidant activities	Yang *et al.*, 2023

UPF: ultraviolet protection factor; DPPH: 2,2-diphenyl-1-picrylhydrazyl; ABTS: 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid).

Polysaccharide-Based Biopolymers

The widespread application of polysaccharide-based biopolymers in food, pharmaceuticals, agriculture, and environmental remediation has gained significant importance. These naturally occurring biopolymers exhibit remarkable features, such as biodegradability, biocompatibility, and susceptibility to chemical or enzymatic modification, making them excellent alternatives to synthetic polymers. Growing public awareness of the environmental impact of non-biodegradable, petroleum-based plastics has further driven interest in polysaccharide-derived biopolymers. Derived from natural sources such as cellulose, starch, chitin, and alginates, these biopolymers are increasingly recognized as sustainable replacements for synthetic polymers across diverse applications.

Common polysaccharides used in food packaging

To address the need for sustainable food packaging, naturally occurring polysaccharides have emerged as promising alternatives to petroleum-based plastics. Biopolymers, such as starch, cellulose, chitosan, and alginate, have attracted significant attention as film-forming materials because of their inherent biodegradability and susceptibility to enzymatic, microbial, and environmental degradation (Awasthi *et al.*, 2022). Cellulose abundantly available in nature, demonstrates excellent film-forming ability. Its advantages include biocompatibility, low cost, wide availability, minimal environment pollution, rapid degradation, and recyclability for food packaging (Islam *et al.*, 2024). Structurally, cellulose consists of linear (1,4)-linked β-D-glucan chains with three hydroxyl (-OH) groups per anhydro glucopyranose ($C_6H_{10}O_5$) unit (Vijayanand *et al.*, 2020). Sourced from wood, cotton, bark, and agro-residues, cellulose is commercially available as fiber. Nanocrystalline cellulose, produced through acid hydrolysis, offers nanoscale advantages, such as high strength, stiffness, and low weight, making it valuable for nanocomposites with enhanced mechanical, thermal, and barrier properties. Starch, a versatile biopolymer derived from crops such as corn, potato, and wheat, has expanded beyond nutritional uses to applications in food packaging, textiles, and biomedicine. Its chemical and physical properties can be tailored through mechanical, chemical, or enzymatic modifications. As a renewable material, starch is processed into films, coatings, foams, and rigid containers for eco-friendly packaging. Chitosan, the second most abundant natural polymer after cellulose, is derived from chitin (determined in crustacean exoskeletons) via deacetylation (Hamed *et al.*, 2016). Its structure comprises randomly distributed β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units, conferring unique properties. The cationic disposition of chitosan grants inherent antimicrobial activity by disrupting microbial cell membranes (Kong *et al.*, 2010), making it suitable for edible packaging. This antimicrobial activity allows chitosan to be used as a natural edible food packaging material. Chitosan is chemically modified to improve its solubility, mechanical strength, and other functional characteristics, further expanding its utility in diverse industries, including agriculture, water treatment, and cosmetics.

The other examples of biopolymers derived from brown and red seaweeds are alginate and carrageenan. Alginate is composed of varying proportions of two uronic acid monomers—α-L-guluronic acid (G) and β-D-mannuronic acid (M). The ratio of G and M determines the chemical and physical properties of alginate. The properties of film-forming, emulsifying, and gel-forming, make alginate an excellent biopolymer for food packaging applications. Alginate forms gels in the presence of divalent cations, such as calcium, allowing it to be used for encapsulation and sustained release of active compounds (Tønnesen and Karlsen, 2002).

Carrageenan is another family of sulfated polysaccharides extracted from red seaweed, with the three main types being kappa (κ), iota (ι), and lambda (λ), each exhibiting distinct structural and functional characteristics. Carrageenan is primarily valued for its gelling, thickening, and stabilizing properties, which make it a common additive in food, cosmetic, and pharmaceutical formulations, with kappa and iota carrageenan forming firm and elastic gels, and lambda carrageenan acting as a viscosifier without gel formation. Both alginate and carrageenan are renewable, biodegradable, and generally recognized as safe (GRAS) for use in food and other consumer products, making them attractive alternatives to synthetic polymers. In addition, the use of pectin as a film-forming agent is explored for various food applications. These biodegradable and renewable polysaccharide-based biopolymers offer an effective solution to plastic food packaging (Bashir *et al.*, 2025).

Physicochemical properties of polysaccharide-based biopolymers

Polysaccharide-based biopolymers possess diverse physicochemical properties that make them valuable for food packaging. Their film-forming, gelling, and coating capabilities depend on degree of polymerization, molecular weight, and functional groups. Monomer ratios (e.g., amylose–amylopectin in starch, and mannuronic–guluronic acids in alginate) and carrageenan types (kappa, iota, or lambda) influence gel strength and functionality (Afoakwah *et al.*, 2023). Their swelling and water-holding capacities support applications in hydrocolloids, wound dressings, and drug delivery. Solubility and dispersibility enable active compound incorporation, while chemical modifications (e.g., plasticizers and charged groups) enhance film properties and biodegradability (Das *et al.*, 2023).

Molecular structure and configuration

Polysaccharides consist of long monosaccharide chains linked by glycosidic bonds. Their physical properties depend on linkages (α or β), molecular weight, and branching. Cellulose (β-1,4) forms a rigid structure, while starch (α-1,4 and α-1,6) is more amorphous, enabling thermoplastic behavior and enzymatic degradation. Cellulose's crystallinity confers strength and stability, making it suitable for ultraviolet (UV)-barrier films. Alginate (mannuronate/guluronate) forms hydrogels, while lignin's phenolic structure provides UV-blocking and antioxidant properties. Availability of high functional group allows extensive modifications for enhanced barrier and mechanical traits (Kocira *et al.*, 2021).

Degree of polymerization (DP)

Degree of polymerization defines the number of linked sugar units, influencing crystallinity and physical performance. High DP improves viscosity, strength, and barrier properties (Chaudhary *et al.*, 2022). Cellulose (DP: 7,000–15,000) offers high strength; starch (lower DP) varies between amylose and amylopectin. DP affects enzymatic degradation and application suitability across food, pharma, and material sectors (Megashah *et al.*, 2020).

Crystallinity and morphology

Polysaccharides exhibit varying degrees of crystallinity based on the arrangement of their monosaccharide units, glycosidic linkages, and branching (Lin *et al.*, 2012). Highly crystalline polysaccharides, such as cellulose and chitin, have tightly packed structures, offering excellent mechanical strength, thermal stability, and resistance to degradation. In contrast, polysaccharides, such as starch and glycogen, display mixed amorphous and crystalline morphologies, resulting in properties such as increased swelling and enzymatic susceptibility. The overall morphology, whether linear, branched, or globular, further influences their physicochemical behavior and functional performance across food, pharmaceutical, and material applications.

Thermal and mechanical properties

The thermal and mechanical properties of polysaccharides are strongly influenced by their molecular structure, degree of polymerization, and crystallinity, which together determine their performance in diverse applications. Highly crystalline polysaccharides, such as cellulose and chitin, demonstrate superior thermal stability, higher glass transition temperatures, and excellent mechanical strength because of their ordered molecular arrangements and extensive hydrogen bonding (Benalaya *et al.*, 2024). In contrast, amorphous or semi-crystalline polysaccharides such as starch and glycogen exhibit lower thermal stability and greater flexibility, with properties further modulated by plasticizers or moisture content. Mechanical characteristics, such as tensile and compressive strength, are closely linked to polymer chain arrangement and the presence of reinforcing elements, as summarized in Table 2.

Table 2. Percentage changes in tensile strength (TS) and elongation at break (EAB) result by the addition of various active agents to chitosan, alginate, and cellulose films.

Polymer	Active agent	Change in TS	Change in EAB	References
Chitosan	Xanthan gum (50:50 w/w)	48% increase	55.81% decrease	Morais Lima *et al.*, 2017
	Nettle extract (250 mL/L)	57.49% decrease	70.70% increase	Flórez *et al.*, 2023
	Yam extract (60 wt.%)	58.38% decrease	41.29% decrease	Li *et al.*, 2023c
	Rose essential oil (2 v/v%)	≈60% decrease	≈2% decrease	Liu *et al.*, 2023
	Silica nanoparticles (8 mg/mL)	23.63% increase	52.6% decrease	Dong *et al.*, 2022
Sodium alginate	Gallnut extract (2.5–25 wt.%)	48–103% increase	135–185% increase	Aloui *et al.*, 2021
	Soybean oil (1.5 v/v%)	118% increase	196.6% increase	Gutiérrez-Jara *et al.*, 2020
	Zinc oxide (2 wt.%)	20.4% increase	41.7% decrease	Satriaji *et al.*, 2020
	Halloysite nanotubes (5 wt.%)	154% increase	7.55% decrease	Kouser *et al.*, 2021
	Co-MOF nanopowder (9 wt.%)	16.84% increase	16.67% decrease	Feng *et al.*, 2023
Cellulose	*Zataria multiflora Boiss.* essential oil (3 v/v%)	4.45% decrease	22.6% decrease	Dashipour *et al.*, 2015
	Falcaria vulgaris extract (0.3 wt%)	18.4% decrease	29.41% increase	Hassanloofard *et al.*, 2023
	Chitosan-citric complex (3 wt%)	6.45% decrease	59.32% decrease	Song *et al.*, 2021
	Curcumin (1 wt.% of cellulose laurate)	53.87% decrease	45.85% decrease	Song *et al.*, 2021
	Zinc oxide nanoparticles (2 wt.%) + Oleic acid (0.3 mL)	73.85% decrease	28.36% increase	Noshirvani *et al.*, 2017

Co-MOF nanopowder: nanoscale cobalt-based metal-organic framework.

Fabrication Techniques for Polysaccharide-Based Packaging

Polysaccharide-based food packaging materials exhibit a wide range of properties depending on their source, molecular structure, preparation technique, and degree of cross-linking between polymer chains. The specific fabrication methods employed for incorporating these polysaccharide-based materials into functional food packaging films can significantly influence the final porosity, compactness, and surface rearrangement morphology, necessitating careful consideration of material compatibility and sensitivity to various external environmental factors. Efficient and effective incorporation of diverse functional ingredients, such as antimicrobials, antioxidants, and nutraceuticals, into polysaccharide-based film matrices can be achieved through the utilization of a variety of techniques, such as solvent casting, extrusion processing, hydrocolloid gelation, electrospinning, microencapsulation, and emulsion coating. Understanding the chemical composition and molecular interactions between polymeric materials and functional ingredients is crucial for selecting the most appropriate and efficient fabrication method for a food packaging application.

Film and coating formation

The solvent casting technique allows for the uniform incorporation of active ingredients into biopolymer-based films by dispersing them in the casting solution before drying under controlled conditions, as shown in Figure 1. Reinforcing polysaccharides with nanomaterials or creating nanofibrous mats enhances mechanical properties and enables applications in drug delivery, pharmaceuticals, and food packaging. While techniques such as solvent casting and electrospinning are challenging for irregularly shaped food surfaces, bioactive food coatings offer a practical alternative by forming protective layers that extend shelf life and maintain quality.

Solvent casting

Solvent casting is a widely used and reliable method for producing biopolymer-based packaging films by dissolving functional ingredients in a film-forming solution, spreading it on a flat surface, and drying it under controlled conditions (Othman *et al.*, 2023). This technique is particularly common for polysaccharide-based films, including starch and alginate, and allows for the incorporation of additives and composites to enhance film properties. Uniform polymer dissolution, often achieved through heat and continuous mixing, is essential for producing films with consistent strength, flexibility, and barrier performance. While solvent casting enables the development of robust and homogeneous films, it faces limitations such as slow production, sensitivity to environmental conditions, and challenges in maintaining hygienic processing.

Coating

Food coatings offer an effective and sustainable approach to preserving food quality and extending shelf life by

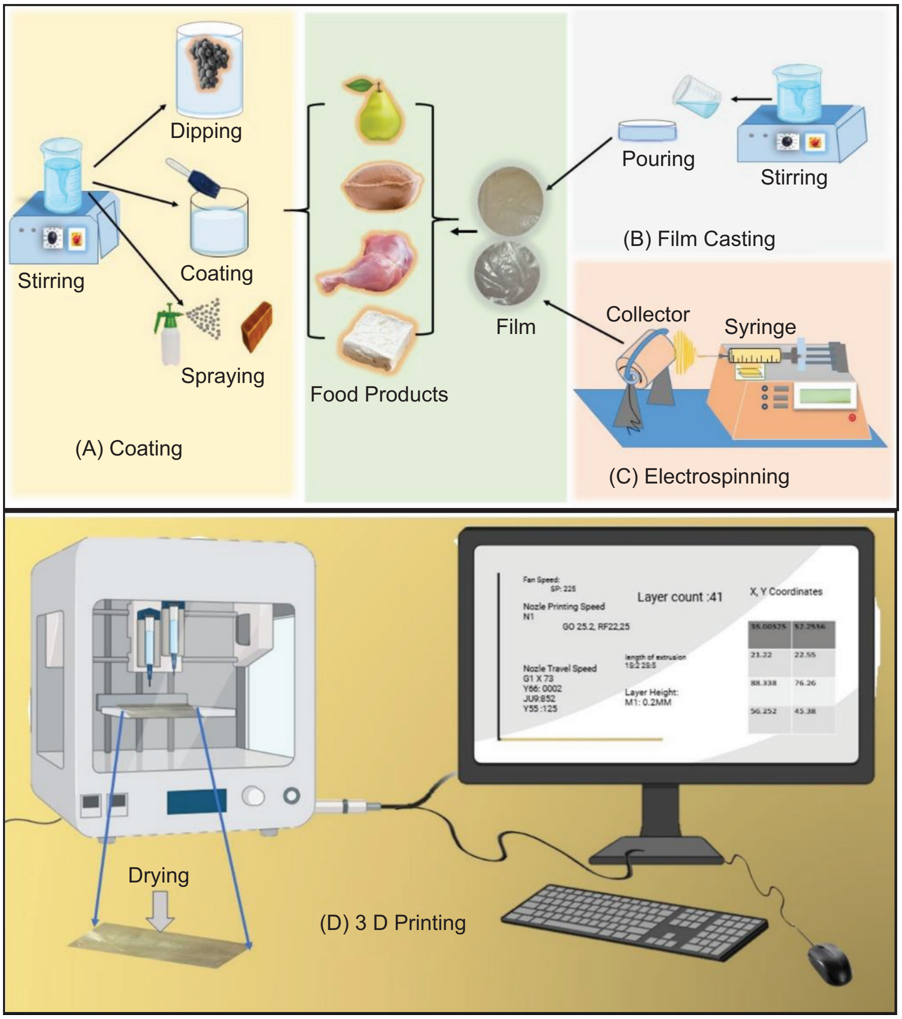

Figure 1. Schematic overview of polysaccharide-based film fabrication techniques. Illustrated are four common methods used to produce composite and nanocomposite films: (A) coating, (B) film casting, (C) electrospinning, and (D) 3D printing.

forming a thin, protective film around the product. These coatings, often developed from water-soluble biopolymers, can be enriched with bioactive compounds to provide antimicrobial and antioxidative properties. Polysaccharide-based coatings are commonly used but require plasticizers, such as oils or plant extracts, to reduce hygroscopicity and improve performance (Junaid *et al.*, 2024). Applied through dipping, spraying, or brushing, coatings act as barriers against moisture loss, oxygen, and light, helping to reduce flavor degradation, ripening, and post-harvest losses. Their edibility and compatibility with various food surfaces make them particularly suitable for perishable items, such as fruits, vegetables, dairy products, and meats.

Electrospinning

Electrospinning is a versatile and cost-effective technique for producing polymer-based nanofiber mats using an electrodynamic process. By applying a high-voltage electric field to a polymer solution, a charged jet is ejected from a Taylor cone, stretching into ultrafine fibers that deposit onto a grounded collector. As solvent evaporates, the fibers form a non-woven mat with tunable morphology, ranging from micro- to nanoscale. The method is continuous, non-thermal, and mechanically simple, making it ideal for preserving heat-sensitive compounds such as natural extracts and bioactive agents. Electrospun nanofibers offer a high surface area-to-volume ratio, enhanced porosity, and customizable composition, making them valuable for applications, such as food packaging and tissue engineering. Starch-based nanofibers (20–30% concentration) improve barrier and mechanical properties, while the incorporation of plant extracts further enhances performance. Electrospinning ensures uniform distribution of functional ingredients within fibers, enhancing their efficacy in bioactive delivery systems.

3D printing

Three-dimensional (3D) printing offers various advantages over traditional solvent casting for producing polysaccharide biopolymer films, enabling precise control over structure and functionality. This technology facilitates rapid prototyping and the creation of complex multilayered structures for drug delivery and tissue engineering applications while improving mechanical properties (Patrocinio *et al.*, 2023). Studies comparing 3D printed and solvent-cast films reveal distinct differences. Films made with pectin, carboxymethyl cellulose (CMC), and ZnO nanoparticles showed denser microstructures in 3D prints. Research on various polysaccharides demonstrates that polyvinyl alcohol (PVA) enhances printability, with 7% PVA improving sodium alginate's printing accuracy by 20 times while increasing strength and flexibility (Tang *et al.*, 2024). The addition of plasticizers, such as glycerol, improves film properties, with 4% glycerol yielding optimal flexibility in cornstarch-gelatin films. Incorporating hawthorn berry extract enhances antibacterial properties and color characteristics. The technology also allows the inclusion of reinforcing agents, such as nanoclay to improve durability (Leaw *et al.*, 2021).

Fabrication of Composite and Nanocomposite Films

The intentional incorporation of functional additives into biopolymer-based packaging effectively mitigates several inherent limitations, such as inadequate barrier properties and low mechanical strength, which are associated with polysaccharide films. Essential interactions at molecular level between active ingredients and polymeric film matrix form the basis for developing novel approaches in advanced polymer design and engineering. Nanocomposite materials are fabricated with multi-structural components ranging from 1 nm to 3 nm. The integration of nanostructured agents, such as nanofibers, nanoparticles, nanorods, and nanoclays, to produce nanocomposite films represents a promising way of enhancing the functionality of food packaging materials (Xu *et al.*, 2024). Numerous thin films developed through the incorporation of nanofillers have demonstrated extensive applications in food packaging and coatings.

Nanocomposites are formed by integrating polymer matrices with organic or inorganic fillers, each exhibiting distinct shapes and sizes (fibers, particulates, spheres, and flakes). The incorporation of nanofillers with higher aspect ratios into polymer matrices offers an increased surface area, which is associated with enhanced reinforcing properties (Kapila *et al.*. 2024). These nanofillers are defined by their particle size, typically ranging from 1 nm to 100 nm. Nanofillers are used in various food applications because of their distinctive chemical structure and outstanding physical and biological properties. They enhance the performance of composites by improving key physical characteristics, such as mechanical strength, thermal stability, and barrier properties. Nanofillers can be inorganic or organic substances that reinforce or impart functional properties to food packaging films. Organic nanofillers include cellulose, while inorganic nanofillers include different types of nanoclays and various metal oxide nanoparticles. Commonly used metal oxide nanoparticles for food packaging applications include zinc, silver, gold, and copper. Well-known examples of nanoclay substances include montmorillonite, kaolinite, bentonite, and org-modified clay. The breakdown of biodegradable cellulose fibers by different high-intensity mechanical and chemical processes results in cellulose nanoparticles. There are primarily three forms of cellulose nanoparticles, such as cellulose nanocrystals (CNCs), bacterial nanocellulose, and cellulose nanofiber (CNF), each vary in their physicochemical properties (degree of crystallinity, transparency, and tensile strength [TS]). Adding different forms of cellulose nanoparticles in different bio-based polysaccharides matrix enhances the composite film's mechanical strength and thermal and barrier properties (Islam *et al.*, 2023). The optimization of nanofiller characteristics, including their chemical composition, size, shape, and dispersion, is crucial for designing food packaging materials tailored to the specific requirements of diverse food products to enhance physical, thermal, and barrier properties of packaging composites.

Incorporating nanoclay structures in food packaging applications to address issues of weak barrier, mechanical, and functional qualities of biopolymers is a promising approach. Clay is one of the most popular nanomaterials for developing food packaging because of its natural origin, making it suitable for packaging applications. Because of their low cost, biocompatibility, and availability, nanoclays are frequently employed for producing biodegradable films and coatings, and synthetic films with high barrier and thermal stability. Nanaoclay structures are explored to reduce permeation across food films because of their strong interactions, which block the ingress of gas and water molecules. Various studies have explored nanoclay structures for UV blocking in films (Lim *et al.*, 2021). The halloysite composite incorporated in alginate, chitosan, and starch films is studied for its mechanical and barrier properties. Similarly, bentonite, montmorillonite, sepiolite, and laponite are used in biopolymer food packaging applications. The use of metal oxide nanoparticles has increased the scope of food preservation strategies due to their antimicrobial and antioxidant properties. Metal oxides and their produced ions exhibit antimicrobial and antioxidant properties. While both forms are active, the dominant mechanism depends on environmental conditions, such as pH, nanoparticle size, and concentration. These mechanisms often act synergistically, making it difficult to isolate dominant contributor to antimicrobial activity. ZnO nanoparticle exhibit antimicrobial activity through three primary mechanisms: (1) Oxidative stress via reactive oxygen species (ROS) generation (H_2O_2, OH^-, and O_2^-), which damage bacterial cellular components such as proteins, lipids, and DNA; (2) membrane disorganization via nanoparticle accumulation and their cellular internalization; and (3) released Zn^{2+} ions from ZnO nanoparticles binding to microbial membranes, disrupting metabolic pathways and enzyme (Jiang *et al.*, 2020).

Metal oxides also impart structural integrity to fabricated films, helping to enhance their mechanical and barrier properties. The coordination bonds are formed between the hydroxyl groups of polysaccharides and nanofillers, such as metal nanoparticles or other functionalized materials. This interaction improves the barrier qualities and functionality of composite materials. The antibacterial and UV-blocking properties of TiO_2 nanotubes are explored by incorporating them in chitosan films (Díaz-Visurraga *et al.*, 2010). Similarly, zinc and silver nanoparticles in polysaccharide-based films are studied for their antimicrobial, physicochemical, and antioxidant properties. Nanoscale carbon-based materials, known as carbonquantum dots (CQDs), possess unique properties, such as excellent biocompatibility and tunable surface functionalities, for enhancing mechanical strength and barrier performance of biopolymer films. Research indicates that incorporating CQDs in packaging applications enhances antibacterial and antioxidant properties, thereby maintaining food quality and prolonging shelf life (Singh *et al.*, 2024). Another study demonstrated that incorporating 1 wt.% green carbon dots derived from apple pomace and rosemary powder in the high methoxylated pectin and sodium caseinate-based bio-nanocomposite films enhanced the radical inhibiting capacity by 42% and 62%, respectively. As a result, the bio-composite film acts as an active film by preserving oil-based products from oxidation (Rodríguez-Varillas *et al.*, 2022). The incorporation of CQDs into pectin-based composite films resulted in a complete eradication of bacterial and fungal populations because of the production of ROS, exhibiting strong antibacterial action against pathogenic bacteria (*L. monocytogenes* and *E. coli*) and antifungal activity against molds (*Aspergillus flavus*). Additionally, these composite films also enhanced UV protection by converting UV radiation into blue light (Ezati and Rhim, 2022). Lim and coworkers (2021) established that cross-linked casein-based nanocomposites loaded with up to 15% w/w CQDs increased TS of the film by 36%. Moreover, UV transmission significantly decreased by 99.09% and 97.46% for UV-C and UV-A radiation, respectively (Khoshkalampour *et al.*, 2024). The CQD loading exhibited strong antioxidant activity, which increased 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging from 18.1% to 94% and 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) scavenging from 16.4% to 89.3%. An oxidation-reduction process was evidenced by the reduction of thiobarbituric acid reactive substances (TBARS) and peroxide value (PV) after 60 days of coating butter products with these composite films.

Sulfur quantum dots (SQDs) provide several benefits in bio-based packaging films, from enhancing mechanical strength, promoting environmental sustainability, and providing increased antibacterial and antioxidant properties as well as sensing capabilities. Their unique characteristics make them essential for developing intelligent and eco-friendly packaging solutions. A study demonstrated that SQDs improved the UV-barrier properties of gelatin/agar mix composite films without sacrificing transparency or color. Additionally, these films exhibited a moderate bactericidal effect against *L. monocytogenes*, an inhibitory effect on *E. coli*, and a strong antioxidant activity (Priyadarshi *et al.*, 2021). The addition of SQDs not only increased the mechanical strength of the films but also enhanced their functional properties, such as antioxidant and antibacterial functions. Another study discovered that addition of 3 wt.% SQD in chitosan-based films improved mechanical strength by 30%. Moreover, compared to pure chitosan films, the antioxidant properties were significantly enhanced, with DPPH and ABTS free radical scavenging capacities increasing by 270% and 170%, respectively. The combined action of SQDs and chitosan effectively eliminated both *E. coli* and *L. monocytogenes* (Min *et al.*, 2023). Apart from packaging films, adding 5 wt.% SQD into an alginate-based coating for kraft paper resulted in impressive antioxidant activity, reducing DPPH free radicals by 60% and ABTS by 100%. The bacterial cell viability of *E. coli* and *L. monocytogenes* was considerably decreased by the addition of SQD, by about 2 log colony-forming unit (CFU)/mL and 4.5 log CFU/mL, respectively (Priyadarshi *et al.*, 2024). Furthermore, the application of SQDs extends to electrochemical devices. Sulfur-doped graphene quantum dots integrated into sodium alginate-based biopolymer electrolytes may pave the way for sophisticated packaging solutions that can both preserve food and track its status over time.

Modification Strategies

Biopolymer-based packaging materials are characterized by their source, structural arrangement, preparation technique, and degree of cross-linking, which impact their properties when incorporated with filler materials. The method of incorporation affects porosity, compactness, and surface rearrangement, requiring consideration of the material's compatibility with biopolymer and sensitivity to external factors. Efficient incorporation of functional ingredients into polysaccharide film matrix is achieved through various approaches, such as solvent casting, extrusion, hydrocolloid gelation, encapsulation, and emulsion coating (Stoica *et al.*, 2024). Understanding the chemistry of ingredients and polysaccharide polymer is crucial for selecting the most appropriate method. Integrating bioactive or functional compounds into biopolymer packaging films enhances their protective properties, overcomes limitations in food applications, improves functionality, and paves the way for innovative food products. These approaches combine encapsulation and packaging technologies to safeguard active properties until the compounds are released into food.

Functional modifications

The crystalline and hydrophilic nature of polysaccharide films consistently poses challenges in achieving optimal barrier and mechanical properties. To address these limitations, various researchers have utilized several functional modification techniques. These functional modification approaches are either accomplished by the use of foreign materials, such as various functional agents, or by using physical, chemical, and enzymatic modification processes (Dutta and Sit, 2024; Tao *et al.*, 2024). These functional modifications result in the enhanced functional properties of polysaccharide-based food packaging films, as shown in Figure 2.

Plasticization

The inadequate barrier and mechanical properties of polysaccharide-based films limit their applicability in food packaging. Polysaccharide-based films are generally brittle because of their polymer chain interaction. Plasticization offers a promising strategy to address these limitations by improving film flexibility for practical use (Li *et al.*, 2023b). The addition of plasticizing materials such as polyols (glycerol, sorbitol, and polyethylene glycol [PEG]), citrate esters, and fatty acid derivatives is widely used in fabricating polysaccharide films. These substances are typically nonvolatile and of low molecular weight, and their incorporation enhances the film's extensibility, flexibility, and workability. Incorporating plasticizers reduces intermolecular hydrogen bonding between polymer chains and increases molecular mobility and free volume of film structure (Sun *et al.*, 2024). The addition of plasticizers modifies barrier properties and typically leads to an increase in water vapor permeability (WVP). This alteration typically leads to increased WVP, as the disrupted polymer structure creates more pathways for moisture diffusion. Hydrophobic plasticizers decrease the water uptake of polysaccharide films and reduce their affinity for moisture, decreasing the overall water absorption and permeability. The resultant polysaccharide-based packaging films exhibit improved elongation at break (EAB), TS, and barrier performance. In a study done by Dong *et al.* (2023), hydrophilic polyols (glycerol, sorbitol, and PEG) were used to evaluate plasticization in soybean polysaccharide-based films. Improvement in film ductility, moisture content, TS, and elongation was observed by adding these polyols, compared to the control film. Various researchers suggest that the concentration and the type of plasticizing material are critical to determining the mechanical, optical, and barrier properties of polysaccharide films. Adding glycerol to an alginate–quince seed gum film reduced the degree of swelling and contact angle while increasing solubility and WVP (Abedini *et al.*, 2022). The authors attributed these observations to the hydrophilic nature of glycerol. For enhancing the performance of polysaccharide-based food packaging films, plasticization is an important strategy to improve processing and flexibility for making them suitable for their application.

Derivatization

Polysaccharides exhibit diverse structures and properties because of their variable chemical compositions, high molecular weights, and different reactive functional groups. The arrangement of functional groups scattered around their polymer chains induces them to drive for chemical modification or to bind with other polymers, resulting in polysaccharide derivatives. Derivatization, which introduces functional groups, enhances the polymer's bioadhesive strength, compared to its native form. Natural polysaccharides and their derivatives are extensively used in the pharmaceutical and food industries because of their biocompatibility, biodegradability, and nontoxicity. These polysaccharides serve various functions, such as thickening agents, gelling agents, emulsifying agents, binders, encapsulating agents, swelling agents, and foam stabilizers (Reddy *et al.*, 2021). The derivatives of starch are the result of oxidation, esterification, or etherification to a chemical structure of D-glucopyranosyl units in the molecule. The resultant derivatives possess change in their water-holding capacity, gelling, dispersion, and film-forming properties. Ionic ether derivatives such as carboxymethyl starch (CMS) and CMC exhibit enhanced solubility and increased film-forming ability (Wilpiszewska *et al.*, 2020). The use of unique bonding mechanisms, such as intramolecular and intermolecular hydrogen bonds, as well as Van der Waals forces in cellulose, for modification to produce remarkable materials has attracted interest in food packaging. Various researchers used these cellulose-derivative materials to fabricate food packaging films. Hydroxyethyl methyl cellulose (HEMC) and hydroxypropyl methylcellulose (HPMC) are examples of cellulose-based derivatives used in food packaging applications. Table 3 summarizes the key advantages and limitations of plasticization and derivatization techniques for polysaccharide modification, highlighting their respective impacts on material properties.

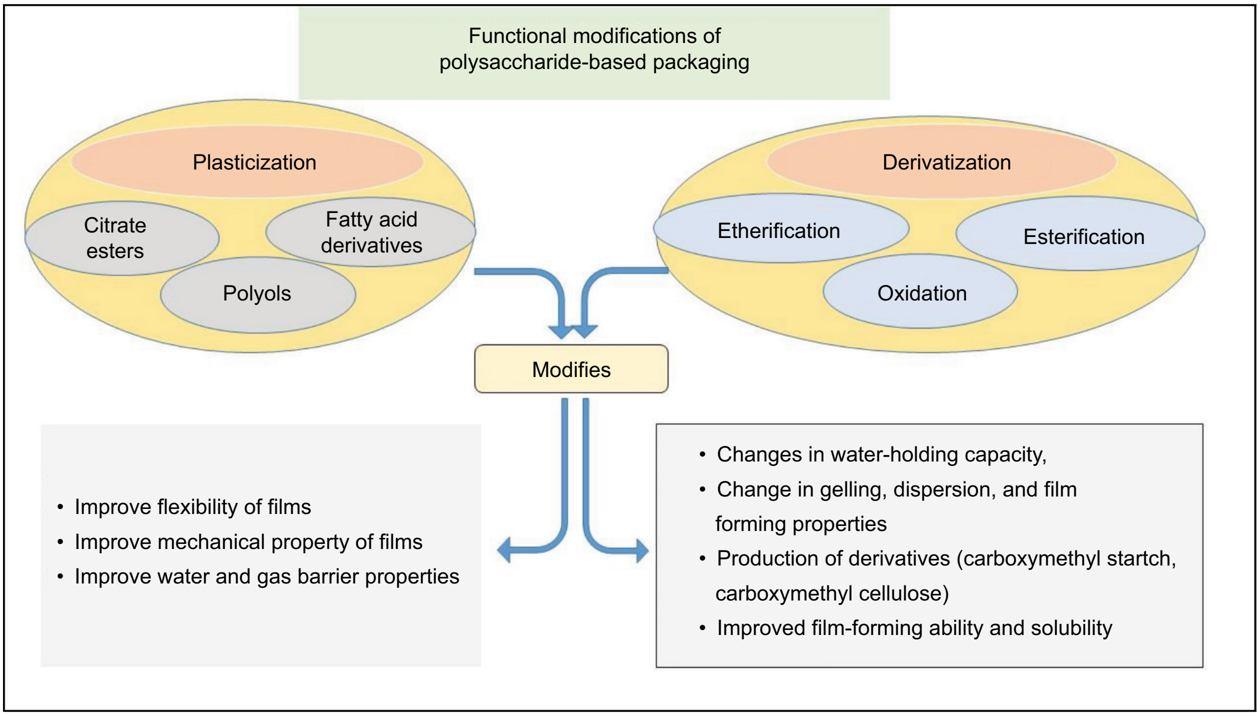

Figure 2. Improvement in film characteristics by plasticization and derivatization.

Table 3. Advantages and disadvantages of plasticization and derivatization.

Method	Advantages	Disadvantages	References
Plasticization	It reduces brittleness and improves the flexibility, and elongation of films	It may leach out over time, potentially affecting food safety	Han *et al.*, 2024
	Certain bio-based plasticizers enhance the thermal stability of polymers	Some plasticizers disrupt polymer interactions, making the film more sensitive to moisture	Gao *et al.* 2025
	Hydrophobic plasticizers decrease water absorption, water permeability, and oil absorption capacity of films	At higher concentrations, some plasticizers reduce the mechanical strength of films	Sanyang *et al.*, 2015
Derivatization	It increases the hydrophobicity, water-holding capacity, and gelling capacity of biopolymers	It requires a complex synthesis process that includes multiple steps and chemical reagents	Ma *et al.*, 2008
	It enhances mechanical strength, flexibility, and film-forming properties	Concerns regarding toxicity, and some reagents may not be considered safe for foods	Teramoto, 2015
	It may introduce functional properties (e.g., antimicrobial, antioxidant effects) and improve barrier properties of films	It reduces the biodegradability of films	Sarfraz *et al.*, 2024
	It improves miscibility with hydrophobic polymers	It is not always suitable for industrial production	Szefer *et al.*, 2021

Molecular Interactions in Polysaccharide-Based Packaging

The effectiveness of active film formation in food packaging is governed by several scientific approaches, such as material chemistry, interface between the food and the film, and interactions between the film and its ingredients. Interaction between biopolymers and functional ingredients should validate the activity of the film, which can be visualized during gel conversion and film development phases. Incorporating nanofillers or cross-linking agents can further modulate intermolecular interactions, leading to enhanced mechanical strength, thermal stability, and gas barrier properties of films. Understanding these molecular-scale phenomena is essential for the rational design of advanced polysaccharide-based food packaging materials that possess tailored functionalities to meet the evolving demands of the food industry. A comprehensive understanding of these interrelated factors is essential for developing effective packaging solutions that ensure food safety and quality while minimizing environmental impact. Table 4 classifies

Table 4. Molecular interactions and its effects on the mechanical and barrier properties of polysaccharide-based packaging materials.

S. No.	Polysaccharides and their combinations	Type of interaction	Effect	References
1.	Hydroxypropyl methylcellulose (HPMC) and pectin	Hydrogen bonding	Increase in elastic modulus and decrease in TS and EAB	Athanasopoulou *et al.*, 2024
2.	Chitosan and starch	Hydrogen bonding	Increase in TS and water vapor barrier properties	Pan *et al.*, 2024
3.	kappa (κ)-carrageenan and gelatin	Hydrophobic interactions	Increase in thermal stability, TS, and mechanical properties	Derkach *et al.*, 2022
4.	Starch and cellulose	Hydrogen bonding	Increase in film cohesion and mechanical strength	Rostamabadi *et al.*, 2024
5.	Chitosan, sodium alginate, oregano (EOO), or thyme (EOT) essential oil	Electrostatic interactions, hydrogen bonding	Increased water vapor barrier properties and EAB with decrease in TS	Guzmán-Pincheira *et al.*, 2025
6.	Corn starch, methylcellulose, and cocoa butter or soybean oil	Hydrophobic interactions	Decrease in water vapor permeability (WVP) with least change in TS and EAB	Bravin *et al.*, 2004
7.	Sargassum pallidum polysaccharide nanoparticles (nSPP) + chitosan (CH) + thymol	Hydrogen bonding and non-covalent bonds	Increase in TS and elastic modulus with decrease in WVP	Zhang *et al.*, 2023
8.	Hydroxypropylmethylcellulose (HPMC) + κ-carrageenan (KCG) + encapsulated grape seed tannins (TLS)	Hydrogen bonding	Increase in surface stiffness and elastic recovery	Monasterio *et al.*, 2023

molecular interactions governing the mechanical properties of polysaccharide-based packaging materials.

Intermolecular interactions

The interactions observed in polysaccharide-based films include hydrogen bonding, van der Waals forces, ionic interactions, hydrophobic interactions, coordination bonding, and π–π stacking (a noncovalent attractive interaction between the π systems of aromatic rings). Hydrogen bonding frequently occurs in polysaccharides containing hydroxyl groups, such as starch and cellulose, where the hydroxyl, ketone, or ester groups of functional ingredients, such as essential oils and extracts, form stable complexes. Dipole–dipole interactions and London dispersion forces between nanoparticles, extracts, and oils also contribute to the stabilization of film matrix (Hassani *et al.*, 2024). Electrostatic interactions, driven by the presence of charged species or particles, lead to the formation of complexes and micellar structures, particularly with the incorporation of essential oils and extracts. Hydrophobic–hydrophilic interactions also play a role, where the hydrophobic ends of oil molecules associate with the hydrophobic regions of polysaccharides, facilitating entrapment or encapsulation, as observed in hydrogels and oleogels. Coordination bonding, primarily observed with the incorporation of metallic nanoparticles, involves attaching metal binding sites to active sites on polysaccharide molecules, resulting in the formation of coordination complexes within the film. Ionic interactions between charged groups on different film components also contribute to the overall film structure. In addition, π–π stacking interactions between the aromatic residues of functional ingredients and polysaccharides influence molecular interactions and performance of the resulting composite films. Understanding these complex molecular interactions is crucial in designing and formulating efficient food packaging systems, as the efficiency of the polymer–functional compound interactions directly impacts the properties and performance of the resulting composite films.

Hydrogen bonding

The characteristic structure of polysaccharide-based films is the presence of various hydroxyl and polar functional groups, which participate in extensive hydrogen bonding interactions. These hydrogen bonds play a crucial role in *the structural formation* of polysaccharide-based food packaging films. The enhancement of mechanical, barrier, and structural properties of the films can be attributed to both intra- and intermolecular hydrogen bonding. The addition of active agents, such as nanofillers, plays a crucial role in this process by actively participating in the formation of hydrogen bonds. This interaction leads to effective cross-linking within the polymer matrix, which significantly improves the overall performance of films. The addition of succinic anhydrite-modified CNCs (SCNCs) in the composite film enhances the mechanical strength and thermal properties, compared to the unmodified CNCs, which may be due to the fewer sulfide groups in CNCs and more hydrogen bond interaction between SCNCs and polymeric matrix (Song *et al.*, 2019). A thorough understanding of structural rearrangement through hydrogen bonding is essential in designing specific type of packaging film with enhanced functionalities and sustainability. The formation of starch-based films using deep eutectic solvents, specifically those containing ammonium acetate and glycerol, results in films that are more resistant due to complex hydrogen bonding interactions. Hydrogen bonding interaction with the incorporation of nanofillers and Jamaica flower extract in starch films produced more hydrophilic surfaces with greater surface energy and rougher morphology (Gutiérrez *et al.*, 2019). In another study, reduction in internal friction within the alginate films combined with glycerol and calcium chloride was observed due to strong hydrogen bonds (Azucena Castro-Yobal *et al.*, 2021). The solubility and gel formation characteristics of polysaccharide-based biopolymers are attributed to the extent of hydrogen bonding of polymer with solvent. The potential interactions of wheat starch (WS) with varying concentrations (2–10%) of CMC or microcrystalline cellulose (MCC) during short-term retrogradation were investigated by dynamic rheological and Fourier transform infrared spectroscopy (FTIR) analyses. The chains of water-soluble CMC may infiltrate continuous phase during paste gelation. The amylose network structure was disrupted, and the inter- and intramolecular hydrogen bonds of WS were weakened during gelation (Xiong *et al.*, 2017).The formation of inter- and intramolecular hydrogen bonds between wheat starch cellulose is shown in Figure 3.

According to Mahmood and coworkers (2022), the regular interaction mechanism of kraft paper extended with both surface-modified and unmodified nanoparticles is illustrated in Figure 4.

Ionic interaction

Polysaccharide-based polymers have garnered significant importance, exhibiting characteristics, such as hydrophilicity, biodegradability, and the ability to form ionic interactions, which can be leveraged in developing advanced composite materials. The ionic interactions of film constituents play an important role in the structural and physicochemical properties of films. This is achieved by incorporating multivalent ions (Mg^{2+}, Ca^{2+}, and Al^{3+}) to create bridges between the charged groups of biopolymers. Ionic interactions in biopolymer films occur between the functional groups of constituents, polymers with charged species, and between polymer chains. The materials, such as alginate, carrageenan, and chitosan, contain chargeable functional groups (carboxylic, amino, and sulfate), thus exhibiting polyelectrolyte behavior (Papagiannopoulos *et al.*, 2023). Variations in the degree of ionization and charge distribution along biopolymer chains are influenced by the presence of counter-ions, ionic strength, and pH. The extent and strength of ionic cross-linking depend on charge density, valency, and concentration of added multivalent ions as well as the accessibility of charged functional groups on polysaccharides. In biopolymer films, ionic interactions influence the stability and controlled release of active compounds, such as antioxidants, antimicrobials, and nutraceuticals. Negatively charged polysaccharides, such as alginate and carrageenan, form ionic complexes with

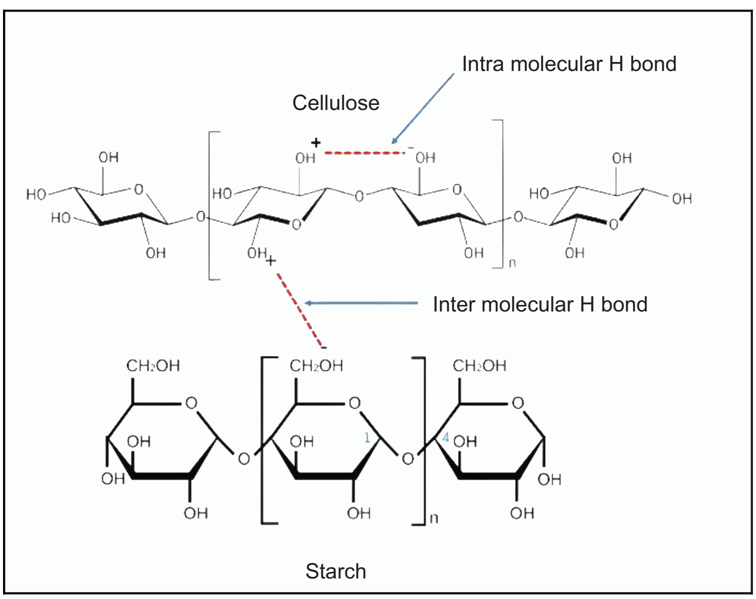

Figure 3. Establishment of inter- and intramolecular hydrogen between starch and cellulose.

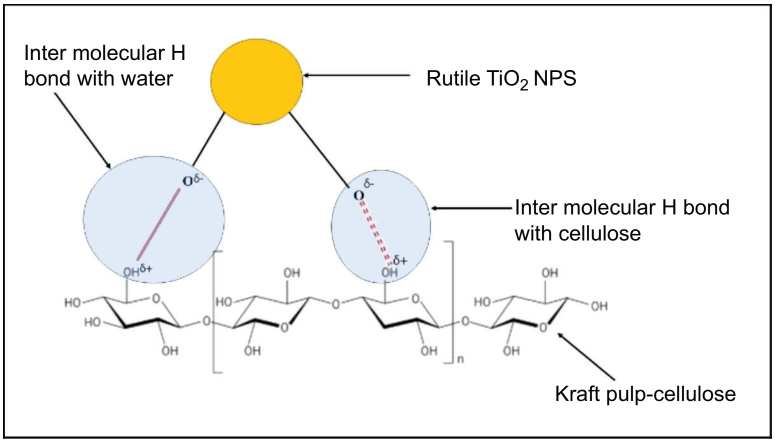

Figure 4. Intermolecular interactions of cellulose kraft paper with unmodified rutile-TiO_2 nanoparticles.

positively charged ingredients via electrostatic attractions. Similarly, cationic polysaccharides, such as chitosan, interact with negatively charged active compounds. These ionic interactions help to solubilize, disperse, and stabilize active components in film-forming solutions, allowing for effective integration into biopolymer matrix. A stronger ionic interaction between polymer chain and active ingredients results in a more sustained and controlled release of active ingredients (Zhao *et al.*, 2023). The intricate interactions between oppositely charged entities (the negatively charged groups of pentasodium tripolyphosphate (TPP) and the positively charged amino groups of chitosan) result in the ionic gelation of chitosan and the precipitation of spherical particles. Figure 5 illustrates the formation of ionic interactions between chitosan nanoparticles with pentasodium tripolyphosphate (Manivasagan and Oh, 2016).

Hydrophobic interactions

Polysaccharide-based biopolymer films exhibit a wide range of structures with different chemical and physical interactions. The hydrophobic interactions in polysaccharide-based films (chitosan, alginate, and cellulose) impact structural and other chemical properties. The varied degree of hydrophobicity shown by distinct monomer units leads to a variance in the interaction behaviors of films (Biehl and Zhang, 2024). Similarly, variations in the performance of these films are also evident from the interactions between polymer matrix and filler or reinforcing agent. Thus, hydrophobic interactions that are the outcome of nonpolar molecules or groups drastically influence the compatibility, rearrangement, adhesion, and encapsulation characteristics between polymer and incorporated ingredient (Uchida *et al.*, 2024). These interactions are particularly relevant in the context of polysaccharide-based composites, where the hydrophilic nature of polymer matrix can lead to compatibility issues with more hydrophobic fillers or reinforcing agents**.** Some biopolymers, such as cellulose, have poor inherent hydrophobicity; however, their modification similar to cellulose acetate enhances the overall hydrophobicity. Similarly, the presence of acetylated N-acetyl-D-glucosamine units in chitosan imparts the hydrophobic nature of polymer in the process of film development, strong interactions between polymer chains are encountered, leading to the removal of water with a rise in hydrophobic domains. This hydrophobic interaction is evident from increase in the physical and mechanical properties of film. Hydrophobic interactions also boost barrier characteristics of films and aid in the formation of hydrophobic interface. The overall hydrophobic interactions improve encapsulation efficiency, stability, and controlled release of active compounds as well as functionality of packaging films. The formation of electrostatic interactions in cellulose and chitosan with glycerol is depicted in Figure 6.

Interactions with active ingredients

The functional properties of developed films must be systematically evaluated, including thickness, solubility, moisture content, WVP, oxygen barrier capacity, transparency, color, TS, EAB, elastic modulus, and antimicrobial activity. In starch-based films, the dissolution of granules weakens hydrogen bonding, making the amorphous regions more susceptible to interactions with bioactive compounds, resulting in synergistic effects. The incorporation of cinnamon essential oil into starch films is reported to increase film thickness and modify surface morphology, leading to reduced WVP because of the oil's hydrophobic character and the formation of a dense emulsion matrix in the presence of glycerol. These changes hinder the passage of nonpolar gases, such as oxygen.

Chitosan–zinc nanoparticles incorporated into starch films are discovered to increase surface roughness

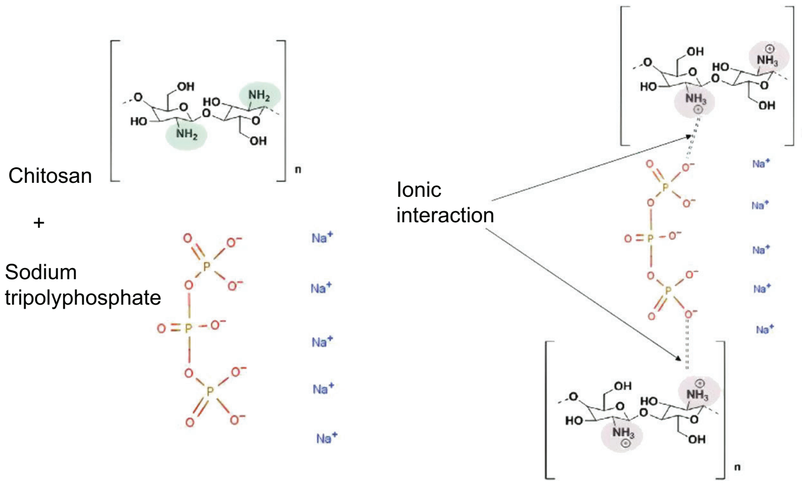

Figure 5. **Ionic bond formation between chitosan and pentasodium tripolyphosphate.**

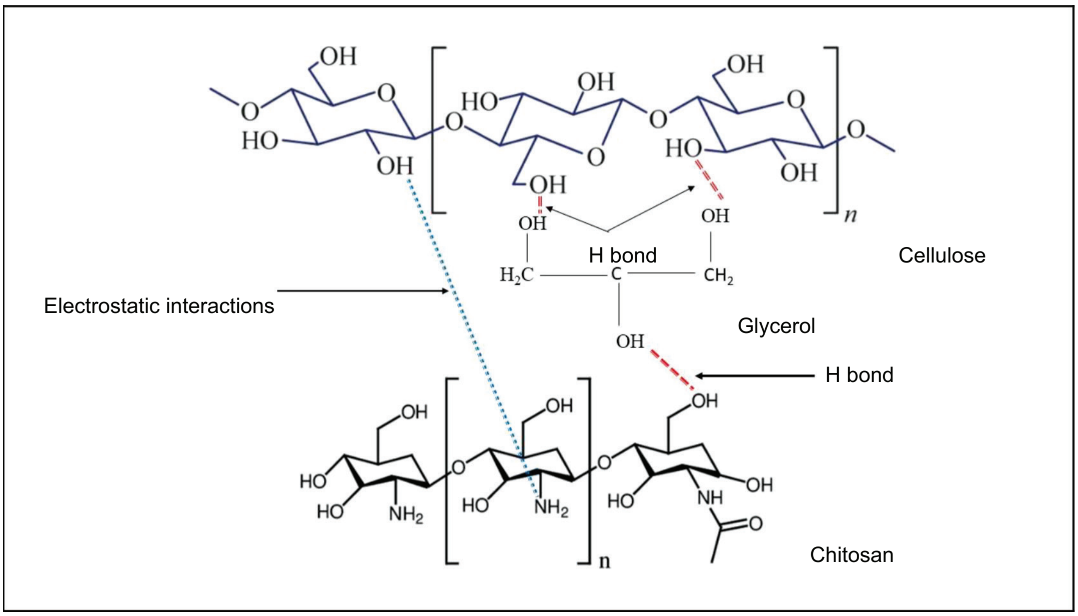

Figure 6. **Electrostatic interactions associated with cellulose, chitosan, and glycerol.**

because of nanoparticle aggregation, while silver nanoparticles synthesized using lemon juice improved flexibility by forming cross-links within the polymer matrix (Ortega *et al.*, 2021).

In chitosan-based films, the inclusion of plant-derived extracts are shown to reduce stiffness and enhance peel ability, probably because of weakened chitosan–chitosan interactions and the formation of chitosan–extract linkages (Bajić *et al.*, 2019). The incorporation of cinnamon essential oil into chitosan gum arabic films improved mechanical and barrier properties, facilitated by electrostatic interactions that retain oil within the composite matrix (Xu *et al.*, 2019). Oils function as plasticizers and improve flexibility by promoting intra- and intermolecular hydrogen bonding. In alginate-based films, additions such as Azolla pinnata leaf extract caused opacity and irregular surfaces at higher concentrations because of complex cross-linking and molecular rearrangement (Eltabakh *et al.*, 2021). Essential oils increased chain mobility and extensibility by disrupting intermolecular forces within the alginate matrix. The interactions between polymers and functional compounds during film formation depend on conditions such as temperature, pressure, humidity, and emulsion type, which influence dominant intermolecular forces (Wongphan and Harnkarnsujarit, 2020). Incorporation of green tea extract into chitosan films significantly enhanced mechanical and water vapor barrier properties and increased antioxidant activity because of higher concentration of polyphenols. These improvements probably result from synergistic interactions involving hydrogen bonding and π–π stacking between tea polyphenols and chitosan, strengthening the film matrix and improving stretchability and durability, which are essential for effective food packaging (Eranda *et al.*, 2024). The establishment of hydrogen bonds and electrostatic interactions between chitosan and tea polyphenols is depicted in Figure 7.

Diverse molecular interactions, such as hydrogen bonding, ionic and hydrophobic interactions, and π–π stacking, play a critical role in determining the structural, mechanical, and functional performances of polysaccharide-based packaging films. A clear understanding of these interactions enables the rational design of biopolymer composites with tailored properties, ensuring enhanced food protection, extended shelf life, and sustainability. By purposefully selecting and combining biopolymers with functional ingredients, it is possible to develop intelligent, active packaging systems that align with the evolving demands of the food industry and environmental regulations.

Potential Food Applications and Performance

Concerns regarding food sustainability have become increasingly urgent. According to the Food and Agriculture Organization of the United Nations (FAO), approximately one-third of the food produced for human consumption is lost or wasted globally annually (Marimuthu *et al.*, 2024b). Fruits and vegetables are particularly susceptible because of their perishable disposition, with about 40% of this produce being wasted due to poor packaging. Food safety is another major concern, as food-borne illness outbreaks frequently result from the consumption of contaminated products harboring pathogenic microorganisms. In the United States alone, there are an estimated 48 million cases annually, resulting in 128,000 hospitalizations and 3,000 fatalities (Saikumar *et al.*, 2024). Hence, ensuring microbial safety and quality is a challenge for researchers and the food industry. To address these urging issues, the development of active and intelligent packaging systems is required that are both sustainable and eco-friendly. These films and coatings reduce respiration rate in fruits and vegetables while providing a protective barrier against various environmental conditions. Additionally, incorporating antimicrobial ingredients into these films imparts properties that inhibit the growth of spoilage microorganisms. The addition of natural bioactive compounds facilitates decrease in photo-oxidation and enzymatic oxidation in various foods. Furthermore, blending additives such as filler materials, antioxidants, preservatives, and coloring agents with sustained release enhances the functional characteristics of active food packaging.

Active packaging

Polysaccharide-based films and coatings have emerged as effective and sustainable solutions for food packaging, particularly using low-cost or waste-derived polysaccharides. These materials enhance food safety and extend shelf life by incorporating active ingredients that absorb, release, or scavenge compounds to maintain freshness and prevent spoilage. The type of active agent can be

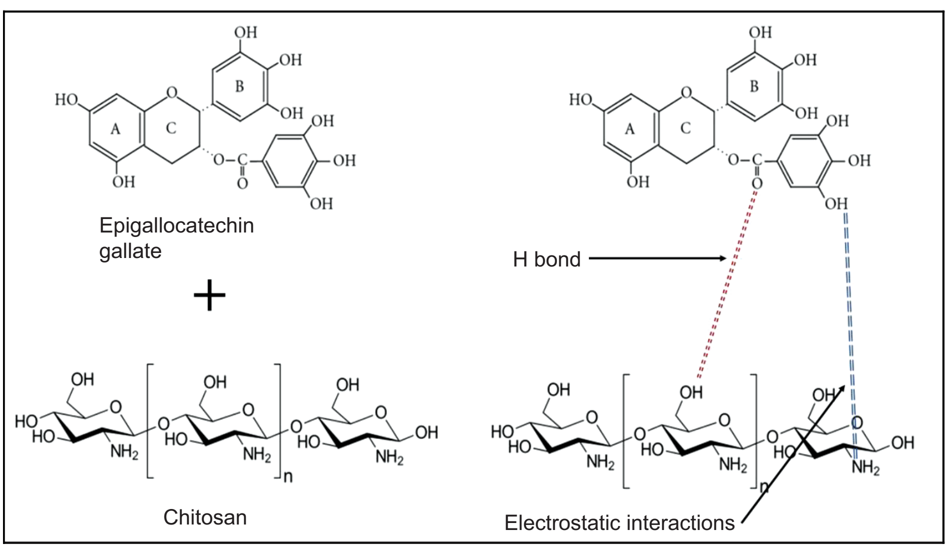

Figure 7. Formation of electrostatic interactions and hydrogen bonds between chitosan and tea polyphenols.

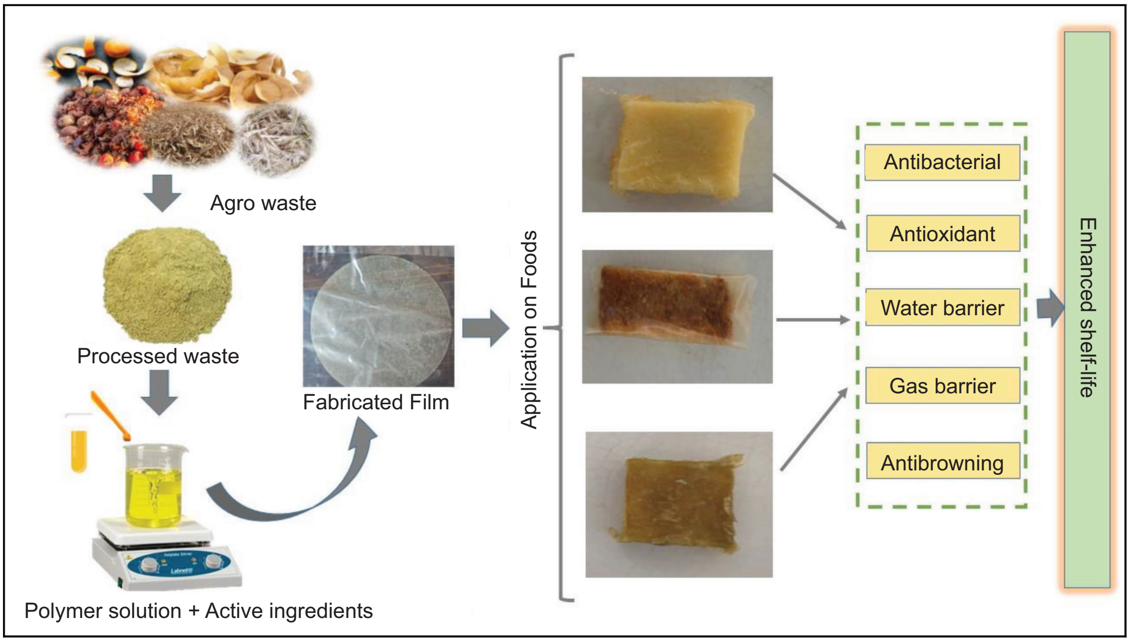

Figure 8. Active packaging film from agricultural waste with functional application for foods.

tailored to specific preservation needs, thereby improving the functional properties of packaging. Researchers have developed various formulations using different biological sources to fabricate protective packaging, as illustrated in Figure 8. Derived from agricultural by-products, these films are cost-effective, environment-friendly, and suitable for direct food contact, especially when made from edible biopolymers.

Polysaccharide-based packaging is widely used for meat, poultry, and dairy products. Incorporating functional additives, such as essential oils, plant extracts, organic acids, probiotics, and nanoparticles, has significantly improved the physicochemical and antimicrobial properties of these films. In meat and poultry applications, such films reduce dehydration, oxidative rancidity, and microbial spoilage, significantly extending shelf life. Alginate-based films containing plant extracts and nanoparticles are effective in preserving beef and poultry. In dairy packaging, particularly for cheese, starch-based films infused with essential oils offer advantages, including transparency, non-toxicity, biodegradability, and ease of fabrication. These coatings not only reduce spoilage but also improve sensory attributes such as texture and appearance, thus making them an attractive option for modern food packaging systems (Silva *et al.*, 2022).

Gas barrier properties

Maintaining the quality of fruits and vegetables, particularly firmness, color, and taste, depends heavily on regulating respiration and transpiration rates, which are key determinants of freshness. Polysaccharide-based films and coatings, often enriched with bioactive compounds, have proven effective in controlling these physiological processes and extending shelf life. Polysaccharide coatings are successfully applied to various berries to preserve freshness, and their incorporation into apple formulations has reduced post-harvest losses (Magri *et al.*, 2023). The incorporation of CNFs and CNCs into polysaccharide matrices has enhanced gas and moisture barrier properties (Lima *et al.*, 2025). Incorporating CNCs into alginate and chitosan matrices resulted in up to 45% reduction in oxygen transmission and improved moisture resistance because of increased hydrophobicity. Beyond nanocellulose, blending different polysaccharides or integrating plant-based additives, such as chia mucilage, also has been established to improve TS and reduce WVP, attributed to the formation of dense polymer networks. Chia mucilage improved the TS of films from 5.21 MPa to 12.38 MPa and reduced WVP by 30%, attributed to the formation of a more compact and cohesive polymer network (Li *et al.*, 2024). Moreover, multilayer films, such as bilayers of PVA and chitosan or layer-by-layer constructions of gelatin with green tea extract and alginate offer superior functionality, compared to single-component films.

Intelligent packaging

Intelligent packaging is defined by its ability to provide real-time information about the condition of packaged food to consumers. The core function of intelligent packaging is to facilitate communication between the packaged food item and the end user through sensing, indicating, or communicating technological design. Antimicrobial activity, moisture, oxygen absorption or release, carbon dioxide levels, temperature changes, and pH variations are detected by sensors that measure these changes. This detection of food properties to allow a visual change has significantly transformed the food packaging outlook. Integration of an intelligent packaging approach in polysaccharide biopolymer films has greatly impacted the human perception toward safety and sustainability.

Sensors, which are important aspects of intelligent packaging, use a transducer to detect and transform one sort of signal into another. Sensors in food packaging, such as chemical and biosensors, are integrated into biopolymer films to confer changes in pH, humidity, color, and other biochemical parameters. Biosensing devices integrated into intelligent packaging can detect allergens, toxic compounds, and pathogens, ensuring food safety. These systems use visual indicators to signal the presence or concentration of specific substances inside the package. Such indicators respond to changes in freshness, time, temperature, pH, and gas composition by producing observable visual cues, enabling consumers and suppliers to assess food quality in real time. In addition, using radio frequency identification (RFID) and barcode labels as data carriers to protect against theft and counterfeit formulates an essential part of intelligent packaging. A study done by Li *et al.* (2023a) developed bio-based packaging materials with real-time monitoring and sustained-release antibacterial chemicals to track the safety and freshness of food. Colorimetric indicators, such as alizarin, anthocyanins, betacyanins, chlorophyll, curcumin, and shikonin, are integrated into the films and undergo a visible change in response to environmental conditions, spoilage, or pathogen growth in food packages. In reaction to environmental variables, including temperature, humidity, pH, and oxygen levels, these sensors offer clear indicators of food freshness. The pectin-based pH sensors are used to detect spoilage in certain meat products. The cassava starch-based films incorporated with anthocyanins to detect changes in beef and meat spoilage over a period of time were studied by Vedove *et al.* (2021).

Regulations associated with packaging materials

Among primary, secondary, tertiary, and quaternary packaging, primary packaging is regarded as the most critical concern for health, as it directly contacts the food and the interaction between packaging materials and food can occur through migration, penetration, or sorption. These interactions can significantly influence the sensory characteristics of food products and pose risks of contamination with hazardous substances that may harm consumer health. Bioplastic items intended for direct contact with food, such as primary packaging materials, must adhere to the European Union (EU) Commission Regulation No. 10/2011 and the engineered nanomaterials governed by the EU Regulation No. 2015/2283. It is essential to acknowledge the migratory, allergic, and toxicological assessments of novel bio-based materials, regardless of the limited research in this area (Cruz *et al.*, 2022). Prolonged consumption of food-grade carrageenan may increase the risk of intestinal inflammation, particularly in individuals with pre-existing conditions, such as colitis. In certain cases, the interaction between packaging materials and food products can be advantageous when packaging incorporates antimicrobials and antioxidants. Nevertheless, it is crucial to assess the toxicological implications of migration of active compounds and nano-fillers into food to prevent health risks and ensure food safety. Nanoparticles in active/intelligent and food contact materials may only be utilized if specifically authorized or listed in Annex I of EU regulation No. 10/2011 (Ramos *et al.*, 2018). Moreover, the US Food and Drug Administration (FDA) has noted that contamination of food arises from using recycled packaging materials by exposing to dangerous substances or byproducts formed during treatments (thermal or chemical), which persists in repurposed packaging materials for extended periods (Díaz-Montes and Castro-Muñoz, 2021). The packaging must meet five fundamental criteria for commercial viability: (i) it must pose no risk to human health; (ii) it must not alter the physicochemical composition of food; (iii) it must not modify the organoleptic properties of food; (iv) it must be produced and processed in accordance with good manufacturing practices; and (v) it must not convey misleading information regarding the product contained within.

Conversely, the International Organization for Standardization (ISO) has implemented legislation that pertains to the production, distribution, and utilization of packaging materials, including ISO 18604:2013(E). These standards specify the prerequisites that must be fulfilled by the various food packaging materials for them to be assembled, processed, and recycled into new feedstock. While these standards facilitate to regulate the quality of food products by adopting packaging materials, there are also regulations that govern the environmental impact of waste production from packaging, and restrict the application of these materials that directly or indirectly contribute to the pollution of flora and fauna. Nevertheless, it is conceivable that the complete abolition of packaging is unfeasible, as the food requires practical protection during its distribution to ensure its preservation until consumption. However, all the materials that may ensue direct or indirect contact with food are covered by EU regulations, including production equipment, kitchen tools used for filling, and distribution containers and packaging (EU regulation No. 10/2011). The EU regulation No. 1935/2004 specifies that active and intelligent packaging is permitted to release only the substances approved as food additives and must be accompanied by a declaration of conformity.

Biodegradability Aspects of Polysaccharide-Based Films

The continuous and widespread disposal of non-degradable materials has resulted in their persistent accumulation, posing a significant environmental threat. To address these concerns, biodegradable polymers have gained attention due to their affordability, easy availability, and environment-friendliness, compared to synthetic products (Stoica *et al.*, 2024). Among these biodegradable polymers, polysaccharides offer the greatest opportunity as alternative packaging materials because of their biodegradability and environmental compatibility (Amin *et al.*, 2021). Biodegradation involves microorganisms, such as cellulolytic, hemicellulolytic, pectinolytic, and lignolytic species that convert biopolymer carbon into CO_2, supporting the carbon cycle. Soil moisture and microbial activity enhance this process. A study reported that starch–banana stalk foam plates lost 51.7% mass in soil and 43.54% in sand over 5 weeks, while conventional expanded polystyrene (EPS) showed minimal degradation (8.3% in soil) (Marimuthu *et al.*, 2024a). Polysaccharide-based films degrade into simpler substances through enzymatic or microbial activity and are compostable under controlled conditions. Madhu and coworkers (2019) demonstrated that cellulose-based films biodegraded effectively at 58°C and 50–60% relative humidity (RH) using a custom biodegradability test. Materials such as starch, cellulose, pectin, gum, alginate, and chitosan are widely explored for their biodegradability, offering sustainable alternatives to conventional plastics. Starch-, cellulose-, pectin-, gum-, alginate-, and chitosan-based materials are actively developed and studied for their biodegradability, offering promising sustainable alternatives to conventional plastics.

Challenges and commercial limitations of polysaccharide-based packaging materials

Polysaccharides are multifunctional biomaterials extensively utilized in the food industry for their texturizing, stabilizing, and gelling properties. Despite their advantages, several limitations hinder their large-scale commercial implementation. The extraction and purification processes for advanced polysaccharide-based materials, such as pullulan and nanocellulose, are expensive, with production costs ranging between \$50/kg and \$100/kg (Ciriminna *et al.*, 2023), making them less competitive than conventional synthetic polymers. Native polysaccharides often require chemical or physical modifications to enhance functional properties, which can further escalate production costs and pose challenges to regulatory compliance, especially for food contact applications. Inherent material drawbacks, such as moisture sensitivity (starch films) and pH-dependent stability (chitosan films), limit their effectiveness as barrier coatings, even though laboratory-scale studies report oxygen barrier improvements of 40–60% (Niranjana and Prashantha, 2018). A significant gap remains between laboratory research and industrial scalability, with some estimates indicating that fewer than 20% of studies adequately address challenges such as cost reduction, scale-up, and regulatory compliance (Jeya Jeevahan *et al.*, 2020). Key limitations include the need for cost-effective modification strategies, such as enzymatic treatments, absence of standardized testing protocols that accurately reflect real-world packaging conditions, and complexities associated with regulatory compliance when hybrid systems are formulated by combining polysaccharides with nanofillers or other biopolymers. The increasing demand for sustainable packaging, driven by initiatives such as the EU Green Deal, highlights the urgent need for research that focuses not only on performance enhancement but also on industrial applicability and regulatory feasibility.

Several companies are making significant progress in biodegradable and compostable packaging solutions. TIPA Compostable Packaging (USA) and TIPA Corp. (Israel) have developed bio-based films that are fully compostable (Rodov *et al.* 2021). In the United States, Elevate Packaging (Chicago), EcoEnclose (Louisville), Noissue, and JAM Packing (Ohio) are offering a variety of biodegradable packaging materials, derived from plant-based resources, such as cellulose, corn starch, and sugarcane. PepsiCo has launched compostable snack bags using plant-based materials, while Coca-Cola introduced PlantBottle, a partially bio-based PET alternative (Hamdi 2024). In Canada, Hytrend Investments Group advances eco-friendly packaging, alongside initiatives from PaperFoam (The Netherlands), and BioPak Packaging (Australia; Ellen McArthur Foundation, 2018) (Beukelaer *et al.*, 2024). Polysaccharide-based biopolymers have acquired commercial success in various applications. Mater-Bi®, developed by Novamont, is utilized for compostable bags and edible coatings for nuts, demonstrating improved mechanical strength through plasticizers and nanocellulose-based nanocomposites (Titone *et al.*, 2025). CHITOLY OM, a water-soluble fungal chitosan, is employed commercially for fruit coatings, while Algisite™ is used in wound dressings. Carrageenan-based Vegicaps® from Catalent offer a plant-based alternative to gelatin capsules, although chemical derivatization increases production expenses. The introduction of dissolvable edible wraps, such as Listerine PocketPaks, illustrate the expanding commercial use of biopolymer-based materials in consumer goods (Mortazavi *et al.*, 2025). Incorporating active compounds into chitosan films enhances their mechanical, barrier, and functional properties. Reflecting this innovation, J.P. Verwijs, a Dutch frozen fish supplier, adopted biodegradable packaging made from agricultural waste, aligned with circular economy principles. The new packaging reduces plastic waste and carbon emissions, and satisfies European Food Safety Authority (EFSA), FDA, and European standards EN 13432 and EN 14995 (Eranda *et al.*, 2024).

Conclusion and the Future Prospective

The use of polysaccharide-based biopolymers in food packaging represents a significant advancement toward sustainable, biodegradable, and functional packaging solutions. Derived from natural materials, these biopolymers offer inherent advantages, such as biocompatibility and biodegradability, effectively addressing growing environmental concerns and meeting consumer demand for eco-friendly products. Polysaccharide-based films enhance packaging properties through the incorporation of active ingredients, while robust fabrication methods are essential to ensure their durability. Interactions between polysaccharides and active ingredients are crucial for designing effective food packaging films for improving the quality of food products. By leveraging diverse fabrication techniques and understanding molecular interactions, these biopolymers are tailored to meet specific packaging requirements, contributing to a more sustainable and efficient food packaging industry. Most studies on polysaccharide-based biopolymers are conducted under controlled laboratory conditions, leaving a significant gap in understanding their long-term performance, stability, and interactions with food matrices in real-world environments characterized by varying humidity, temperature, and storage conditions. Key challenges that must be addressed for the widespread adoption of these biopolymers in food packaging include scalability and cost-effectiveness. The development of efficient manufacturing processes for biopolymers is crucial. Streamlining the extraction and purification of polysaccharides from agro-industrial waste presents economic hurdles. Complex extraction methods and film-forming techniques can further increase costs, which may hinder broader adoption. Therefore, achieving cost-effectiveness and scalability requires simplifying and optimizing these manufacturing processes. Many polysaccharides (e.g., chitosan and alginate) are derived from specific natural resources that often face availability limitations or raise environmental concerns. Research into developing alternative sustainable resources of polysaccharides or enhancing waste valorization for biopolymer production remains incomplete. In addition, the regulatory landscape is crucial for the commercial viability of biopolymer films. Strict regulations on non-biodegradable packaging materials, enforced by agencies, such as the FDA and EFSA, could bolster the market for biopolymer films if they comply with safety and efficacy standards. The development of hybrid biopolymer systems that integrate polysaccharides with other biopolymers (such as proteins and lipids) for improved functionality is still in its initial stages. Understanding synergy among these components is essential for advancing food applications. Despite the existing challenges, the future of polysaccharide-based food packaging appears promising. Several strategies such as molecular engineering, composite and hybrid structures, integration of multifunctional capabilities, biorefinery approaches, and efficient recycling and composting systems can enhance their functionality and marketability to overcome current limitations and drive the widespread adoption of sustainable packaging solutions.

AI Declaration

During the preparation of this work, the authors used ChatGPT (OpenAI) for the clarity of language. The authors reviewed and edited the content after using the tool and take full responsibility for the final content of the manuscript.

Acknowledgments

Authors are thankful to their respective universities and institutes for support.

Authors Contribution

All authors contributed equally to this article.

Conflict of Interest

The authors declared no conflict of interest or competing financial interests affecting this paper.

Funding

None.

References

Abedini, A.A., Pircheraghi, G. and Kaviani, A. 2022. The role of calcium crosslinking and glycerol plasticizing on the physical and mechanical properties of superabsorbent. Journal of Polymer Research 30(1): 20. https://doi.org/10.1007/s10965-022-03397-5

Afoakwah, N.A., Komla, M.G., Ali, A. and Ahmed, S. 2023. Extraction, structural properties, and applications of carrageenan gum. In: Ahmed, S. and Ali, A. (eds.). Natural Gums: Extraction, Properties, and Applications, Chap. 24. Elsevier, Amsterdam, the Netherlands, pp. 647–668. https://doi.org/10.1016/B978-0-323-99468-2.00024-3.

Akman, P.K., Bozkurt, F., Dogan, K., Tornuk, F. and Tamturk, F. 2021. Fabrication and characterization of probiotic lactobacillus plantarum loaded sodium alginate edible films. Journal of Food Measurement and Characterization 15(1): 84–92. https://doi.org/10.1007/s11694-020-00619-6

Albadran, H.A, Monteagudo-Mera, A., Khutoryanskiy, V.V. and Charalampopoulos, D. 2020. Development of chitosan-coated agar-gelatin particles for probiotic delivery and targeted release in the gastrointestinal tract. Applied Microbiology and Biotechnology 104(13): 5749–5757. https://doi.org/10.1007/s00253-020-10632-w

Aloui, H., Deshmukh, A.R., Khomlaem, C. and Kim, B.S. 2021. Novel composite films based on sodium alginate and gallnut extract with enhanced antioxidant, antimicrobial, barrier and mechanical properties. Food Hydrocolloids 113(April): 106508. https://doi.org/10.1016/j.foodhyd.2020.106508

Amin, U., Khan, M.U., Majeed, Y. Rebezov, M., Khayrullin, M., Bobkova, E., Shariati, M.A., Chung, I.M. and Thiruvengadam, M. 2021. Potentials of polysaccharides, lipids and proteins in biodegradable food packaging applications. International Journal of Biological Macromolecules 183: 2184–2198. https://doi.org/10.1016/j.ijbiomac.2021.05.182

Ardebilchi M.S., Almasi, H. and Marand, N.A. 2021. Chitosan-based nanocomposite films incorporated with NiO nanoparticles: physicochemical, photocatalytic and antimicrobial properties. International Journal of Biological Macromolecules 190: 667–678. https://doi.org/10.1016/j.ijbiomac.2021.09.024

Arfat, Y.A., Ejaz, M., Jacob, H. and Ahmed, J. 2017. Deciphering the potential of guar gum/Ag-Cu nanocomposite films as an active food packaging material. Carbohydrate Polymers 157: 65–71. https://doi.org/10.1016/j.carbpol.2016.09.069

Athanasopoulou, E., Bigi, F., Maurizzi, E., Iris, E., Karellou, E., Pappas, C.S., Quartieri, A. and Tsironi, T. 2024. Synthesis and characterization of polysaccharide-and protein-based edible films and application as packaging materials for fresh fish fillets. Scientific Reports 14(1): 517.

Awasthi, S.K., Kumar, M., Kumar, V., Sarsaiya, S., Anerao, P., Ghosh, P., Singh, L., Liu, H., Zhang, Z. and Awasthi, M.K. 2022. A comprehensive review on recent advancements in biodegradation and sustainable management of biopolymers. Environmental Pollution 307: 119600. https://doi.org/10.1016/j.envpol.2022.119600

Azucena Castro-Yobal, M., Contreras-Oliva, A., Saucedo-Rivalcoba, V., Rivera-Armenta, J.L., Hernández-Ramírez, G., Salinas-Ruiz, J. and Herrera-Corredor, A. 2021. Evaluation of physicochemical properties of film-based alginate for food packing applications. E-Polymers 21(1): 82–95. https://doi.org/10.1515/epoly-2021-0011

Bajić, M., Ročnik, T., Oberlintner, A., Scognamiglio, F., Novak, U. and Likozar, B. 2019. Natural plant extracts as active components in chitosan-based films: a comparative study. Food Packaging and Shelf Life 21: 100365.

Bashir, T., Islam, R.U., Junaid, P.M., Naseem, S., Khan, T., Naseem, S., Andrabi, S.H. and Azad, A.A. 2025. Cross-linked carrageenan/alginate bio-nanocomposite film with citrus limetta peel extract and copper oxide nanoparticles: fabrication, characterization and application. Food Hydrocolloids 168: 111537. https://doi.org/10.1016/j.foodhyd.2025.111537

Benalaya, I., Alves, G., Lopes, J. and Silva, L.R. 2024. A review of natural polysaccharides: sources, characteristics, properties, food, and pharmaceutical applications. International Journal of Molecular Sciences 25(2): 1322. https://doi.org/10.3390/ijms25021322

Beukelaer, H de, Chu, S., Esposito, C., Hilhorst, M. and Chacon, F.A. 2024. Replacing fossil-based foams with (potato) carbohydrate based foams. Wageningen Environmental Research 2562: 4.

Bhatia, S., Shah, Y.A., Al-Harrasi, A., Jawad, M., Koca, E. and Aydemir, L.Y. 2024. Enhancing tensile strength, thermal stability, and antioxidant characteristics of transparent kappa carrageenan films using grapefruit essential oil for food packaging applications. ACS Omega 9(8): 9003–9012. https://doi.org/10.1021/acsomega.3c07366

Biehl, P. and Zhang, K. 2024. Introduction to advances in bio-based polymers: chemical structures and functional properties at the interface. In K. Zhang & P. Biehl (Eds.), Green by design: Harnessing the power of bio-based polymers at interfaces (pp. 1–1). IOP Publishing. https://doi.org/10.1088/978-0-7503-6184-2ch1

Bravin, B, Peressini, D. and Sensidoni, A. 2004. Influence of emulsifier type and content on functional properties of polysaccharide lipid-based edible films. Journal of Agricultural and Food Chemistry 52(21): 6448–6455. https://doi.org/10.1021/jf040065b

Chaudhary, S., Jain, V.P. and Jaiswar, G. 2022. The composition of polysaccharides: monosaccharides and binding, group decorating, polysaccharides chains. In: Singh, P., Manzoor, K., Ikram, S. and Kumar, P. (eds.) Innovation in Nano-Polysaccharides for Eco-sustainability: From Science to Industrial Applications, Chap. 4. Elsevier, Amsterdam, The Netherlands, pp. 83–118. https://doi.org/10.1016/B978-0-12-823439-6.00005-2

Ciriminna, R., Ghahremani, M., Karimi, B. and Pagliaro, M. 2023. Emerging green routes to nanocellulose. Biofuels, Bioproducts and Biorefining 17(1): 10–17. https://doi.org/10.1002/bbb.2423

Cruz, Rui MS, Krauter, V., Krauter, S., Agriopoulou, S., Weinrich, R., Herbes, C., Scholten, Philip BV, Uysal-Unalan, I., Sogut, E. and Kopacic, S. 2022. Bioplastics for food packaging: environmental impact, trends and regulatory aspects. Foods 11(19): 3087. https://doi.org/10.3390/foods11193087

Das, A., Ringu, T., Ghosh, S. and Pramanik, N. 2023. A comprehensive review on recent advances in preparation, physicochemical characterization, and bioengineering applications of biopolymers. Polymer Bulletin 80(7): 7247–7312. https://doi.org/10.1007/s00289-022-04443-4.

Dashipour, A., Razavilar, V., Hosseini, H., Shojaee-Aliabadi, S., German, J.B., Ghanati, K., Khakpour, M. and Khaksar, R.

2015. Antioxidant and antimicrobial carboxymethyl cellulose films containing zataria multiflora essential oil. International Journal of Biological Macromolecules 72: 606–613. https://doi.org/10.1016/j.ijbiomac.2014.09.006.

Derkach, S.R., Voron'ko, N.G. and Kuchina, Y.A. 2022. Intermolecular interactions in the formation of polysaccharide-gelatin complexes: a spectroscopic study. Polymers 14(14): 2777.

Díaz-Montes, E and Castro-Muñoz, R. 2021. Edible films and coatings as food-quality preservers: an overview. Foods 10(2): 249. https://doi.org/10.3390/foods10020249

Díaz-Visurraga, J., Meléndrez, M.F., García, A., Paulraj, M. and Cárdenas, G. 2010. Semitransparent chitosan-TiO_2 nanotubes composite film for food package applications. Journal of Applied Polymer Science 116(6): 3503–3515. https://doi.org/10.1002/app.31881

Dong, Y., Rao, Z., Liu, Y., Zheng, X., Tang, K. and Liu, J. 2023. Soluble soybean polysaccharide/gelatin active edible films incorporated with curcumin for oil packaging. Food Packaging and Shelf Life 35: 101039. https://doi.org/10.1016/j.fpsl.2023.101039

Dong, W., Su, J., Chen, Y., Xu, D., Cheng, L., Mao, L., Gao, Y. and Yuan, F. 2022. Characterization and antioxidant properties of chitosan film incorporated with modified silica nanoparticles as an active food packaging. Food Chemistry 373: 131414. https://doi.org/10.1016/j.foodchem.2021.131414

Dutta, D. and Sit, N. 2024. Comprehensive review on developments in starch-based films along with active ingredients for sustainable food packaging. Sustainable Chemistry and Pharmacy 39: 101534. https://doi.org/10.1016/j.scp.2024.101534

Ellen McArthur Foundation. 2018. Closing the Loop on Single-Use Food Packaging: BioPak. Ellen McArthur Foundation, Sydney, Australia.

Eltabakh, M., Kassab, H., Badawy, W., Abdin, M. and Abdelhady, S. 2021. Active bio-composite sodium alginate/maltodextrin packaging films for food containing azolla pinnata leaves extract as natural antioxidant. Journal of Polymers and the Environment 30: 1355–1365. https://doi.org/10.1007/s10924-021-02287-z

Eranda, D.H.U., Chaijan, M., Uysal-Unalan, I., Panpipat, W., Naik, A.S., Dib, A.L., Karnjanapratum, S. and Gagaoua, M. 2024. Biopreservation of pre-processed fresh fish by bio-based coatings: a single strategy with multiple benefits towards waste prevention. Food Bioscience 58: 103696. https://doi.org/10.1016/j.fbio.2024.103696

Estevez-Areco, S., Guz, L., Famá, L., Candal, R. and Goyanes, S. 2019. Bioactive starch nanocomposite films with antioxidant activity and enhanced mechanical properties obtained by extrusion followed by thermo-compression. Food Hydrocolloids 96: 518–528. https://doi.org10.1016/j.foodhyd.2019.05.054

Ezati, P. and Rhim, J-W. 2020. Ph-responsive pectin-based multifunctional films incorporated with curcumin and sulfur nanoparticles. Carbohydrate Polymers 230: 115638. https://doi.org/10.1016/j.carbpol.2019.115638

Ezati, P. and Rhim, J-W. 2022. Pectin/carbon quantum dots fluorescent film with ultraviolet blocking property through light conversion. Colloids and Surfaces B: Biointerfaces 219(August): 112804. https://doi.org/10.1016/j.colsurfb.2022.112804

Feng, S., Tang, Q., Xu, Z., Huang, K., Li, H. and Zou, Z. 2023. Development of novel Co-MOF loaded sodium alginate-based packaging films with antimicrobial and ammonia-sensitive functions for shrimp freshness monitoring. Food Hydrocolloids 135: 108193. https://doi.org/10.1016/j.foodhyd.2022.108193.

Flórez, M., Vázquez, M. and Cazón, P. 2023. Enhancing the quality of Havarti cheese: chitosan films with nettle Urtica Dioica L. extract as slice separators to retard lipid oxidation. Lebensmittel-Wissenschaft & Technologie 189: 115504. https://doi.org/10.1016/j.lwt.2023.115504

Gao, L., Yuan, R., Qiao, L., Tu, C., Tan, R. and Xu, S. 2025. Comparative analysis of bio-based plasticizers: biocompatibility, plasticizing mechanisms, and molecular dynamics insights. RSC Advances 15(6): 4487–4495. https://doi.org/10.1039/d4ra07258h

Gupta, V., Yadav, R., Tanwar, R. and Gaikwad, K.K. 2023. Ƙ-Carrageenan-based bio-nanocomposite film reinforced with cellulose nanocrystals derived from amla pomace for food packaging. Biomass Conversion and Biorefinery 13(18): 16899–16908. https://doi.org/10.1007/s13399-021-02028-1

Gutiérrez, T.J, Toro-Márquez, L.A., Merino, D. and Mendieta, J.R. 2019. Hydrogen-bonding interactions and compostability of bionanocomposite films prepared from corn starch and nano-fillers with and without added Jamaica flower extract. Food Hydrocolloids 89: 283–293. https://doi.org/10.1016/j.foodhyd.2018.10.058

Gutiérrez-Jara, C., Bilbao-Sainz, C., McHugh, T., Chiou, B-S, Williams, T. and Villalobos-Carvajal, R. 2020. Physical, mechanical and transport properties of emulsified films based on alginate with soybean oil: effects of soybean oil concentration, number of passes and degree of surface crosslinking. Food Hydrocolloids 109: 106133. https://doi.org/10.1016/j.foodhyd.2020.106133

Guzmán-Pincheira, C., Moeini, A., Oliveira, P.E., Abril, D., Paredes-Padilla, Y.A. and Benavides-Valenzuela,S. 2025. Development of alginate-chitosan bioactive films containing essential oils for use in food packaging. Foods 14(2): 256. https://doi.org/10.3390/foods14020256

Hadi, A., Nawab, A., Alam, F. and Naqvi, S. 2023. Development of sodium alginate–aloe vera hydrogel films enriched with organic fibers: study of the physical, mechanical, and barrier properties for food-packaging applications. Sustainable Food Technology 1(6): 863–873. https://doi.org/10.1039/d3fb00122a

Hamdi, M. 2024. Sustainable Packaging Trends in the Consumer Packaged Goods Market. Harvard University, Extension School. https://www.researchgate.net/publication/383608198_Sustainable_Packaging_Trends_in_the_Consumer_Packaged_Goods_Market.

Hamed, I., Özogul, F. and Regenstein, J.M. 2016. Industrial applications of crustacean by-products (chitin, chitosan, and chitooligo saccharides): a review. Trends in Food Science & Technology 48: 40–50. https://doi.org/10.1016/j.tifs.2015.11.007

Hammoudi, N., Cherif, H.Z., Borsali, F., Benmansour, K. and Meghezzi, A. 2020. Preparation of active antimicrobial and antifungal alginate-montmorillonite/lemon essential oil nanocomposite films. Materials Technology 35(7): 383–394. https://doi.org/10.1080/10667857.2019.1685292

Han, Y., Weng, Y. and Zhang, C. 2024. Development of biobased plasticizers with synergistic effects of plasticization, thermal stabilization, and migration resistance: a review. Journal of Vinyl and Additive Technology 30(1): 26–43. https://doi.org/10.1002/vnl.22048

Hari, K.D., Garcia, C.V., Shin, G.-H. and Kim, J.-T. 2021. Improvement of the UV barrier and antibacterial properties of crosslinked pectin/zinc oxide bionanocomposite films. Polymers. 13(15): 2403. https://doi.org/10.3390/polym13152403

Hassani, D., Sani, I.K. and Pirsa, S. 2024. Nanocomposite film of potato starch and gum arabic containing boron oxide nanoparticles and Anise Hyssop (*Agastache foeniculum*) essential oil: investigation of physicochemical and antimicrobial properties. Journal of Polymers and the Environment 32(4): 1972–1983. https://doi.org/10.1007/s10924-023-03114-3

Hassanloofard, Z., Gharekhani, M., Zandi, M., Ganjloo, A. and Roufegarinejad, L. 2023. Fabrication and characterization of cellulose acetate film containing *Falcaria vulgaris* extract. Cellulose 30(11): 6833–6853. https://doi.org/10.1007/s10570-023-05337-y

Islam, M., Saini, P., Das, R., Shekhar, S., Sinha, A. and Prasad, K. 2023. Rice straw as a source of nanocellulose for sustainable food packaging materials: a review. BioResources 18(1): 2351–2385. https://doi.org/10.15376/biores.18.1.Islam

Islam, M., Sanjay, A. and Sinha, K. 2024. Organosolv delignification of rice straw cellulose fiber for functional food packaging.Cellulose31:9191–9214.https://doi.org/10.1007/s10570-024-06125-y

Jeya Jeevahan, J., Chandrasekaran, M., Venkatesan, S.P., Sriram, V., Britto Joseph, G., Mageshwaran, G. and Durairaj, R.B. 2020. Scaling up difficulties and commercial aspects of edible films for food packaging: a review. Trends in Food Science & Technology 100: 210–222. https://doi.org/10.1016/j.tifs.2020.04.014

Jiang, S., Lin, K. and Cai, M. 2020. ZnO nanomaterials: current advancements in antibacterial mechanisms and applications. Frontiers in Chemistry 8: 580. https://doi.org/10.3389/fchem.2020.00580

Junaid, Pir M., Ahmad, F., Dar, I.H., Bhat, A.H., Manzoor, S., Pandith, J.A. and Khan, F. 2023. Preservation strategies for fruits and vegetables: past, present, and future scope. In M. R. Goyal & F. Ahmad (Eds.), Quality control in fruit and vegetable processing: Methods and strategies (pp. 143. Apple Academic Press, New York, USA. https://doi.org/10.1201/9781003304999.

Junaid, Pir M. and Zaidi, S. 2024. Enhancing the properties of starch-based edible films through rice bran oil incorporation: a comprehensive investigation of development and characterization. Food Biophysics 19(4): 1114–1124. https://doi.org/10.1007/s11483-024-09883-1

Kang, S., Xiao, Y., Wang, K., Cui, M., Chen, D., Guan, D., Luan, G. and Xu, H. 2021. Development and evaluation of gum arabic-based antioxidant nanocomposite films incorporated with cellulose nanocrystals and fruit peel extracts. Food Packaging and Shelf Life 30: 100768. https://doi.org/10.1016/j.fpsl.2021.100768

Kapila, K., Kirtania, S., Monika Devi, L., Saikumar, A., Badwaik, L.S. and Rather, M.A. 2024. Potential perspectives on the use of poly (vinyl alcohol)/graphene oxide nanocomposite films and its characterization. Journal of Food Measurement and Characterization 18(2): 1012–1025. https://doi.org/10.1007/s11694-023-02264-1

Khanzada, B., Mirza, B. and Ullah, A. 2023. Chitosan-based bio-nanocomposites packaging films with unique mechanical and barrier properties. Food Packaging and Shelf Life 35: 101016. https://doi.org/10.1016/j.fpsl.2022.101016

Khoirunnisa, A.R., Joni, I., Panatarani, C., Rochima, E. and Praseptiangga, D. 2018. UV-screening, transparency and water barrier properties of semi refined iota carrageenan packaging film incorporated with zno nanoparticles. In A. R. Khoirunnisa, I. M. Joni, C. Panatarani, E. Rochima, & D. Praseptiangga (Eds.), AIP Conference Proceedings. Vol. 1927. No. 1, p. 030041 AIP Publishing.

Khoshkalampour, A., Ahmadi, S., Ghasempour, Z., Tak, L. and Marjan, L. 2024. Development of a novel film based on casein/modified tragacanth gum enriched by carbon quantum dots for shelf—life extension of butter. Food and Bioprocess Technology 17(5): 1–18. https://doi.org/10.1007/s11947-023-03187-x

Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E. and Hortyńska, P. 2021. Polysaccharides as edible films and coatings: characteristics and influence on fruit and vegetable quality—a review. Agronomy 11(5): 813. https://doi.org/10.3390/agronomy11050813

Kong, M., Guang Chen, X., Xing, K. and Park, H.J. 2010. Antimicrobial properties of chitosan and mode of action: a state of the art review. International Journal of Food Microbiology 144(1): 51–63. https://doi.org/10.1016/j.ijfoodmicro.2010.09.012

Kouser, S., Sheik, S., Prabhu, A., Nagaraja, G.K., Prashantha, K., D'souza, J.N., Navada, M.K. and Manasa, D.J. 2021. Effects of reinforcement of sodium alginate functionalized halloysite clay nanotubes on thermo-mechanical properties and biocompatibility of polyvinyl alcohol nanocomposites. Journal of the Mechanical Behavior of Biomedical Materials 118: 104441. https://doi.org/10.1016/j.jmbbm.2021.104441

Kurek, M., Hlupić, L., Garofulić, I.E., Descours, E., Ščetar, M. and Galić, K. 2019. Comparison of protective supports and antioxidative capacity of two bio-based films with revalorised fruit pomaces extracted from blueberry and red grape skin. Food Packaging and Shelf Life 20: 100315. https://doi.org/10.1016/j.fpsl.2019.100315

Law, K.L. and Narayan, R. 2022. Reducing environmental plastic pollution by designing polymer materials for managed end-of-life. Nature Reviews Materials 7(2): 104–116. https://doi.org/10.1038/s41578-021-00382-0

Leaw, Z.E., Kong, I. and Pui, L.P. 2021. 3D printed corn starch–gelatin film with glycerol and hawthorn berry (*Crataegus pinnatifida*) extract. Journal of Food Processing and Preservation 45(9): e15752. https://doi.org/10.1111/jfpp.15752

Lee, H., Rukmanikrishnan, B. and Lee, J. 2019. Rheological, morphological, mechanical, and water-barrier properties of agar/gellan gum/montmorillonite clay composite films. International Journal of Biological Macromolecules 141: 538–544. https://doi.org/10.1016/j.ijbiomac.2019.09.021

Li, Q., Cai, P., Xiao, H. and Pan, Y. 2023c. PH-responsive color indicator films based on chitosan and purple yam extract for in situ monitoring food freshness. Food Bioscience 56: 103373. https://doi.org/10.1016/j.fbio.2023.103373

Li, Y., Duan, Q., Yue, S., Alee, M. and Liu, H. 2024. Enhancing mechanical and water barrier properties of starch film using Chia mucilage. International Journal of Biological Macromolecules 274: 133288.

Li, C., Liu, J., Li, W., Liu, Z., Yang, X., Liang, B., Huang, Z., Qiu, X., Li, X. and Huang, K. 2023a. Biobased intelligent food-packaging materials with sustained-release antibacterial and real-time monitoring ability. ACS Applied Materials & Interfaces 15(31): 37966–37975.

Li, C., Zheng, C, Huang, H, Su, H. and Huang, C. 2023b. Preparation and plasticizing mechanism of deep eutectic solvent/lignin plasticized chitosan films. International Journal of Biological Macromolecules 240: 124473. https://doi.org/10.1016/j.ijbiomac.2023.124473

Liao, Y., Wang, C., Dong, Y. and Yu, H.-Y. 2023. Robust and versatile superhydrophobic cellulose-based composite film with superior UV shielding and heat-barrier performances for sustainable packaging. International Journal of Biological Macromolecules 253: 127178. https://doi.org/10.1016/j.ijbiomac.2023.127178

Lim, J.W., Lim, W.S. Lee, M.H. and Park, H.J. 2021. Barrier and structural properties of polyethylene terephthalate film coated with poly(acrylic acid)/montmorillonite nanocomposites. Packaging Technology and Science 34(3): 141–150. https://doi.org/10.1002/pts.2547

Lima, G.G.de, Zakaluk, I.C.B., Artner, M.A., Gonzalez de Cademartori, A.C.P.P.H., Muniz, G.I.B.de and Magalhães, W.L.E. 2025. Enhancing barrier and antioxidant properties of nanocellulose films for coatings and active packaging: a review. ACS Applied Nano Materials 8(9): 4421–4397. https://doi.org/10.1021/acsanm.4c04805

Lin, N., Huang, J. and Dufresne, A. 2012. Preparation, properties and applications of polysaccharide nanocrystals in advanced functional nanomaterials: a review. Nanoscale 4(11): 3274–3294. https://doi.org/10.1039/C2NR30260H

Liu, Y., Liu, R., Shi, J., Zhang, R., Tang, H., Xie, C., Wang, F., Han, J. and Jiang, L. 2023. Chitosan/esterified chitin nanofibers nanocomposite films incorporated with rose essential oil: structure, physicochemical characterization, antioxidant and antibacterial properties. Food Chemistry: X 18: 100714. https://doi.org/10.1016/j.fochx.2023.100714

Ma, X., Chang, P.R. and Yu, J. 2008. Properties of biodegradable thermoplastic pea starch/carboxymethyl cellulose and pea starch/microcrystalline cellulose composites. Carbohydrate Polymers 72(3): 369–375. https://doi.org/10.1016/j.carbpol.2007.09.002

Madhu, G., Saha, N. and Kadu, D. 2019. Evaluation of biodegradability characteristics of cellulose-based film as per IS/ISO 14855-1. Journal of Applied Packaging Research 11(3): Art. 2. https://repository.rit.edu/japr/vol11/iss3/2

Magri, A., Rega, P., Capriolo, G. and Petriccione, M. 2023. Impact of novel active layer-by-layer edible coating on the qualitative and biochemical traits of minimally processed 'Annurca Rossa Del Sud' apple fruit. International Journal of Molecular Sciences 24(9): 8315.

Mahmood, M.K., Nyamupangedengu, C., Gomes, C. and Smith, A. 2022. Reducing hydrophilic characteristics of kraft paper insulation by reinforcing with surface modified rutile-TiO_2 nanoparticles. IEEE Access 10: 102237–102246. https://doi.org/10.1109/ACCESS.2022.3208596

Mamatha, G., Sowmya, P., Madhuri, D., Mohan Babu, N., Suresh Kumar, D., Vijaya Charan, G., Varaprasad, K. and Madhukar, K. 2021. Antimicrobial cellulose nanocomposite films with in situ generations of bimetallic (Ag and Cu) nanoparticles using vitex negundo leaves extract. Journal of Inorganic and Organometallic Polymers and Materials 31(2): 802–815. https://doi.org/10.1007/s10904-020-01819-9

Manivasagan, P. and Oh, J. 2016. Marine polysaccharide-based nanomaterials as a novel source of nanobiotechnological applications. International Journal of Biological Macromolecules 82: 315–327. https://doi.org/10.1016/j.ijbiomac.2015.10.081

Mao, S., Li, F., Zhou, X., Lu, C. and Zhang, T. 2023. Characterization and sustained release study of starch-based films loaded with carvacrol: a promising UV-shielding and bioactive nanocomposite film. Lebensmittel-Wissenschaft & Technologie (Food Science and Technology) 180: 114719. https://doi.org/10.1016/j.lwt.2023.114719

Marimuthu, S., Saikumar, A. and Badwaik, L.S. 2024a. Development and characterization of biodegradable foam plates from corn starch and banana bunch stalks coated with beeswax. Biomass Conversion and Biorefinery 15: 7763–7777. https://doi.org/10.1007/s13399-024-05782-0

Marimuthu, S., Saikumar, A. and Badwaik, L.S. 2024b. Food losses and wastage within food supply chain: a critical review of its generation, impact, and conversion techniques. Waste Disposal & Sustainable Energy 6(4): 661–676. https://doi.org/10.1007/s42768-024-00200-7

Martins, J.T., Cerqueira, M.A. and Vicente, A.A. 2012. Influence of α-tocopherol on physicochemical properties of chitosan-based films. Food Hydrocolloids 27(1): 220–227. https://doi.org/10.1016/j.foodhyd.2011.06.011

Megashah, L.N., Ariffin, H., Zakaria, M.R., Hassan, M.A., Andou, Y. and Padzil, F.N.M. 2020. Modification of cellulose degree of polymerization by superheated steam treatment for versatile properties of cellulose nanofibril film. Cellulose 27(13): 7417–7429. https://doi.org/10.1007/s10570-020-03296-2

Min, S., Priyadarshi, R., Ezati, P., Rhim, J.-W. and Kim, J.T. 2023. Chitosan-based multifunctional coating combined with sulfur quantum dots to prevent listeria contamination of enoki mushrooms. Food Packaging and Shelf Life 35: 101014. https://doi.org/10.1016/j.fpsl.2022.101014

Monasterio, A., Natalia Brossard, E.N., Vega, R. and Osorio, F.A. 2023. Mechanical and surface properties of edible coatings elaborated with nanoliposomes encapsulating grape seed tannins and polysaccharides. Polymers 15(18): 3774. https://doi.org/10.3390/polym15183774

Morais Lima, M.de, Carneiro, L.C., Bianchini, D., Dias, A.R.G., Zavareze, E.da R., Prentice, C. and Moreira, A.d.S. 2017. Structural, thermal, physical, mechanical, and barrier properties of chitosan films with the addition of xanthan gum. Journal of Food Science 82 (3): 698–705. https://doi.org/10.1111/1750-3841.13653

Mortazavi, S.M., Sayed-Tabatabaei, L., Tabatabaei, M.S. and Moghaddam, A.V. 2025. Intraoral novel drug delivery systems.

In M. Hamidi & M. S. Tabatabaei (Eds.), Novel drug delivery systems: Fundamentals and applications (pp. 67–102). Wiley–Scrivener Publishing, Beverly, MA, USA. https://doi.org/10.1002/9781119852476.ch3

Niranjana Prabhu, T. and Prashantha, K. 2018. A review on present status and future challenges of starch based polymer films and their composites in food packaging applications. Polymer Composites 39(7): 2499–2522.

Nisar, T., Alim, A., Iqbal, T., Iqbal, M., Tehseen, S., Zi-Chao, W. and Guo, Y. 2022. Functionality of different probiotic strains embedded in citrus pectin based edible films. International Journal of Food Science & Technology 57(2): 1005–1015. https://doi.org/10.1111/ijfs.15460

Noshirvani, N., Ghanbarzadeh, B., Mokarram, R.R., Hashemi, M. and Coma, V. 2017. Preparation and characterization of active emulsified films based on chitosan-carboxymethyl cellulose containing zinc oxide nano particles. International Journal of Biological Macromolecules 99: 530–538. https://doi.org/10.1016/j.ijbiomac.2017.03.007

Nouri, A., Yaraki, M.T., Ghorbanpour, M. and Wang, S. 2018. Biodegradable κ-carrageenan/nanoclay nanocomposite films containing *Rosmarinus officinalis* L. extract for improved strength and antibacterial performance. International Journal of Biological Macromolecules 115: 227–235. https://doi.org/10.1016/j.ijbiomac.2018.04.051

Ortega, F., Arce, V.B. and Garcia, M.A. 2021. Nanocomposite starch-based films containing silver nanoparticles synthesized with lemon juice as reducing and stabilizing agent. Carbohydrate Polymers 252: 117208.

Othman, S.H., Kahar, N.S., Nordin, N. and Shapi'i, R.A. 2023. Properties and food packaging applications of solvent casting-made starch-based films incorporated with essential oils: a review. Starch (Stärke) 75(5–6): 2200152. https://doi.org/10.1002/star.202200152

Pan, J., Li, C., Liu, J., Jiao, Z., Zhang, Q., Lv, Z., Yang, W., Chen, D. and Liu, H. 2024. Polysaccharide-based packaging coatings and films with phenolic compounds in preservation of fruits and vegetables—a review. Foods 13(23): 3896. https://doi.org/10.3390/foods13233896

Panneerselvam, N., Sundaramurthy, D. and Maruthapillai, A. 2023. Pectin/xylitol incorporated with various metal oxide based nanocomposite films for its antibacterial and antioxidant activity. Journal of Polymers and Environment 31(4): 1598–1609. https://doi.org/10.1007/s10924-022-02652-6

Papagiannopoulos, A., Nikolakis, S.-P., Pamvouxoglou, A. and Koutsopoulou, E. 2023. Physicochemical properties of electrostatically crosslinked carrageenan/chitosan hydrogels and carrageenan/chitosan/laponite nanocomposite hydrogels. International Journal of Biological Macromolecules 225: 565–573. https://doi.org/10.1016/j.ijbiomac.2022.11.113

Patrocinio, D., Galván-Chacón, V., Gómez-Blanco, J.C., Miguel, S.P., Loureiro, J., Ribeiro, M.P., Coutinho, P., Pagador, J.B. and Sanchez-Margallo, F.M. 2023. Biopolymers for tissue engineering: crosslinking, printing techniques, and applications. Gels 9(11): 890. https://doi.org/10.3390/gels9110890

Priyadarshi, R., Riahi, Z. and Rhim, J.-W. 2024. Alginate-coated functional wrapping paper incorporated with sulfur quantum dots and grapefruit seed extract for preservation of potato hash browns. Sustainable Materials and Technologies 40(February): e00942. https://doi.org/10.1016/j.susmat.2024.e00942

Priyadarshi, R., Riahi, Z., Rhim, J.-W., Han, S. and Lee, S.-G. 2021. Sulfur quantum dots as fillers in gelatin/agar-based functional food packaging films. ACS Applied Nano Materials 4(12): 14292–14302.

Ramos, Ó.L., Pereira, R.N., Cerqueira, M.A., Martins, J.R., Teixeira, J.A., Xavier Malcata, F. and Vicente, A.A. 2018. Bio-based nanocomposites for food packaging and their effect in food quality and safety. In Food Packaging and Preservation (pp. 271–306). Elsevier. https://doi.org/10.1016/B978-0-12-811516-9.00008-7

Reddy S., Prakasham, Batchu, U.R., Buddana, S.K., Sambasiva Rao, K.R.S. and Penna, S. 2021. A comprehensive review on α-D-glucans: Structural and functional diversity, derivatization and bioapplications. Carbohydrate Research 503: 108297. https://doi.org/https://doi.org/10.1016/j.carres.2021.108297

Rhim, J.W., Wang, L.F. and Hong, S.I. 2013. Preparation and characterization of agar/silver nanoparticles composite films with antimicrobial activity. Food Hydrocolloids 33(2): 327–335.

Rodov, V., Sabag, A. and Porat, R. 2021. Performance of compostable bio-based packaging for preservation of bunch tomatoes. In: XIII International Controlled and Modified Atmosphere Research Conference – CAMA 2021. Acta Horticulturae (Vol. 1386, pp. 191–198). International Society for Horticultural Science. https://doi.org/10.17660/ActaHortic.2024.1386.26

Rodríguez-Varillas, S., Murru, C., Díaz-García, M.E. and Badía-Laíño, R. 2022. Green carbon dots as additives of biopolymer films for preserving from oxidation of oil-based products. Antioxidants 11(11): 2193. https://doi.org/10.3390/antiox11112193

Rostamabadi, H., Demirkesen, I, Colussi, R., Roy, S., Tabassum, N., Filho, J.G.d.O., Bist, Y., Kumar, Y., Nowacka, M. and Galus, S. 2024. Recent trends in the application of films and coatings based on starch, cellulose, chitin, chitosan, xanthan, gellan, pullulan, arabic gum, alginate, pectin, and carrageenan in food packaging. Food Frontiers 5(2): 350–391. https://doi.org/10.1002/fft2.342

Roy, S. and Rhim, J.-W. 2019. Agar-based antioxidant composite films incorporated with melanin nanoparticles. Food Hydrocolloids 94: 391–98. https://doi.org/10.1016/j.foodhyd.2019.03.038

Rukmanikrishnan, B., Ramalingam, S., Rajasekharan, S.K., Lee, J. and Lee, J. 2020. binary and ternary sustainable composites of gellan gum, hydroxyethyl cellulose and lignin for food packaging applications: biocompatibility, antioxidant activity, UV and water barrier properties. International Journal of Biological Macromolecules 153: 55–62. https://doi.org/10.1016/j.ijbiomac.2020.03.016

Saikumar, A., Singh, A., Dobhal, A., Arora, S., Junaid, P.M., Badwaik, L.S. and Kumar, S. 2024. A review on the impact of physical, chemical, and novel treatments on the quality and microbial safety of fruits and vegetables. Systems Microbiology and Biomanufacturing 4(2): 575–597. https://doi.org/10.1007/s43393-023-00217-9

Salimiraad, S., Safaeian, S., Basti, A.A., Khanjari, A. and Nadoushan, R.M. 2022. Characterization of novel probiotic nanocomposite films based on nano chitosan/nano cellulose/gelatin for the preservation of fresh chicken fillets. Lebensmittel-Wissenschaft & Technologie (Food Science and Technology) 162: 113429. https://doi.org/10.1016/j.lwt.2022.113429

Sanyang, M.L., Sapuan, S.M., Jawaid, M., Ishak, M.R. and Sahari, J. 2015. Effect of plasticizer type and concentration on tensile, thermal and barrier properties of biodegradable films based on sugar palm (Arenga pinnata) starch. Polymers 7(6): 1106–1124. https://doi.org/10.3390/polym7061106

Sarfraz, M.H., Hayat, S., Siddique, M.H., Aslam, B., Ashraf, A., Saqalein, M., Khurshid, M., Sarfraz, M.F., Afzal, M. and Muzammil, S. 2024. Chitosan-based coatings and films: a perspective on antimicrobial, antioxidant, and intelligent food packaging. Progress in Organic Coatings 188(January): 108235. https://doi.org/10.1016/j.porgcoat.2024.108235

Satriaji, K.P., Garcia, C.V., Kim, G.H., Shin, G.H. and Kim, J.T. 2020. Antibacterial bionanocomposite films based on $CaSO_4$-crosslinked alginate and zinc oxide nanoparticles. Food Packaging and Shelf Life 24: 100510. https://doi.org/10.1016/j.fpsl.2020.100510

Saurabh, Chaturbhuj K, Gupta, S., Bahadur, J., Mazumder, S., Variyar, P.S. and Sharma, A. 2015. Mechanical and barrier properties of guar gum based nano-composite films. Carbohydrate Polymers 124:77–84. https://doi.org/10.1016/j.carbpol.2015.02.004

Silva, S.P.M., Ribeiro, S.C., Teixeira, J.A. and Silva, C.C.G. 2022. Application of an alginate-based edible coating with bacteriocin-producing lactococcus strains in fresh cheese preservation. Food Science and Technology 153: 112486. https://doi.org/10.1016/j.lwt.2021.112486

Singh, A.K., Itkor, P., Lee, M., Saenjaiban, A. and Lee, Y.S. 2024. Synergistic integration of carbon quantum dots in biopolymer matrices : an overview of current advancements in antioxidant and antimicrobial active packaging. Molecules 29(21): 5138. https://doi.org/10.3390/molecules29215138

Singh, P., Magalhães, S., Alves, L., Antunes, F., Miguel, M., Lindman, B. and Medronho, B. 2019. Cellulose-based edible films for probiotic entrapment. Food Hydrocolloids 88:68–74. https://doi.org/10.1016/j.foodhyd.2018.08.057

Sogut, E., Filiz, B.E. and Seydim, A.C. 2022. Whey protein isolate- and carrageenan-based edible films as carriers of different probiotic bacteria. Journal of Dairy Science 105(6): 4829–4842. https://doi.org/10.3168/jds.2021-21245

Song, Z., Ma, T., Zhi, X. and Du, B. 2021. Cellulosic films reinforced by chitosan-citric complex for meat preservation: influence of nonenzymatic browning. Carbohydrate Polymers 272: 118476. https://doi.org/10.1016/j.carbpol.2021.118476

Song, Z., Wu, Y., Wang, H. and Han, H. 2019. Synergistic antibacterial effects of curcumin modified silver nanoparticles through ROS-mediated pathways. Materials Science and Engineering C99: 255–263. https://doi.org/10.1016/j.msec.2018.12.053

Souza, V.G., Mello, I.P., Khalid, O., Pires, J.R., Rodrigues, C., Alves, M.M., Santos, C., Fernando, A.L. and Coelhoso, I. 2022. Strategies to improve the barrier and mechanical properties of pectin films for food packaging: comparing nanocomposites with bilayers. Coatings 12(2): 108. https://doi.org/10.3390/coatings12020108

Stoica, M., Bichescu, C.I., Crețu, C.-M., Dragomir, M., Ivan, A.S., Podaru, G.M., Stoica, D. and Stuparu-Crețu, M. 2024. Review of bio-based biodegradable polymers: smart solutions for sustainable food packaging. Foods 13(9): 3027. https://doi.org/10.3390/foods13193027

Sun, S., Weng, Y., Han, Y. and Zhang, C. 2024. Plasticization mechanism of biobased plasticizers comprising polyethylene glycol diglycidyl ether-butyl citrate with both long and short chains on poly(lactic acid). International Journal of Biological Macromolecules 276: 133948. https://doi.org/10.1016/j.ijbiomac.2024.133948

Szefer, E., Leszczyńska, A., Hebda, E. and Pielichowski, K. 2021. The application of cellulose nanocrystals modified with succinic anhydride under the microwave irradiation for preparation of polylactic acid nanocomposites. Journal of Renewable Materials 9(6): 1127–1142. https://doi.org/10.32604/jrm.2021.014584

Tang, T., Zhang, M. and Mujumdar, A.S. 2024. Film forming properties of 3D printed polysaccharide based gels and development of CO_2 monitoring labels. Food Packaging and Shelf Life 46(August): 101401. https://doi.org/10.1016/j.fpsl.2024.101401

Tanpichai, S., Thongdonson, K. and Boonmahitthisud, A. 2023. Enhancement of the mechanical properties and water barrier properties of thermoplastic starch nanocomposite films by chitin nanofibers: biodegradable coating for extending banana shelf life. Journal of Materials Research and Technology 26: 5617–5625. https://doi.org/10.1016/j.jmrt.2023.08.244

Tao, L., Shi, C., Zi, Y., Zhang, H., Wang, X. and Zhong, J. 2024. A review on the chemical modification of alginates for food research: chemical nature, modification methods, product types, and application. Food Hydrocolloids 147: 109338. https://doi.org/10.1016/j.foodhyd.2023.109338

Teramoto, Y. 2015. Functional thermoplastic materials from derivatives of cellulose and related structural polysaccharides. Molecules 20(4): 5487–5527. https://doi.org/10.3390/molecules20045487

Titone, V., Rapisarda, M., Pulvirenti, L., Napoli, E., Impallomeni, G., Botta, L., Mistretta, M.C. and Rizzarelli, P. 2025. Sustainable biocomposites based on mater-bi and grape pomace for a circular economy: performance evaluation and degradation in soil. Polymer Degradation and Stability 231: 111091. https://doi.org/10.1016/j.polymdegradstab.2024.111091

Tønnesen, H.H. and Karlsen, J. 2002. Alginate in drug delivery systems. Drug Development and Industrial Pharmacy 28(6): 621–630. https://doi.org/10.1081/DDC-120003853

Uchida, K., Masuda, T., Hara, S., Matsuo, Y., Liu, Y., Aoki, H., Asano, Y., Miyata, K., Fukuma, T., Ono, T. and Isoyama, T., 2024. Stability enhancement by hydrophobic anchoring and a cross-linked structure of a phospholipid copolymer film for medical devices. ACS Applied Materials & Interfaces 16(30): 39104–39116. https://doi.org/10.1021/acsami.4c07752

Udayakumar, G.P., Muthusamy, S., Selvaganesh, B., Sivarajasekar, N., Rambabu, K., Banat, F., Sivamani, S., Sivakumar, N., Hosseini-Bandegharaei, A. and 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. https://doi.org/10.1016/j.jece.2021.105322

Vedove, T.M.A.R.D., Maniglia, B.C. and Tadini, C.C. 2021. Production of sustainable smart packaging based on cassava starch and anthocyanin by an extrusion process. Journal of Food Engineering 289: 110274. https://doi.org/10.1016/j.jfoodeng.2020.110274

Vijayanand, S., Ravi, A., Soundararajan, A., Sudha, P.N. and Hemapriya, J. 2020. Pullulan. In: Ahmed, S. and Soundararajan, A. (eds.) Pullulan: Processing, properties, and applications (pp. 1–34).. Jenny Stanford Publishing. https://doi.org/10.1201/9781003056942

Wang, Y., Su, J., Li, T., Ma, P., Bai, H., Xie, Y., Chen, M. and Dong, W. 2017. A novel UV-shielding and transparent polymer film: when bioinspired dopamine–melanin hollow nanoparticles join polymers. ACS Applied Materials & Interfaces 9(41): 36281–3689. https://doi.org/10.1021/acsami.7b08763

Wilpiszewska, K., Antosik, A.K., Schmidt, B., Janik, J. and Rokicka, J. 2020. Hydrophilic films based on carboxymethylated derivatives of starch and cellulose. Polymers 12(11): 2447. https://doi.org/10.3390/polym12112447

Wongphan, P. and Harnkarnsujarit, N. 2020. Characterization of starch, agar and maltodextrin blends for controlled dissolution of edible films. International Journal of Biological Macromolecules 156(August): 80–93. https://doi.org/10.1016/j.ijbiomac.2020.04.056

Xiong, J., Li, Q., Shi, Z. and Ye, J. 2017. Interactions between wheat starch and cellulose derivatives in short-term retrogradation: rheology and FTIR study. Food Research International 100: 858–863. https://doi.org/10.1016/j.foodres.2017.07.061

Xu, T., Gao, C.C., Feng, X., Yang, Y., Shen, X. and Tang, X. 2019. Structure, physical and antioxidant properties of chitosan-gum arabic edible films incorporated with cinnamon essential oil. International Journal of Biological Macromolecules 134: 230–236. https://doi.org/10.1016/j.ijbiomac.2019.04.189

Xu, Y. Wu, Z., Li, A., Chen, N., Rao, J. and Zeng, Q. 2024. Nanocellulose composite films in food packaging materials: a review. Polymers 16(3): 423. https://doi.org/10.3390/polym16030423

Yang, Z., Li, C., Wang, T., Li, Z., Zou, X., Huang, X., Zhai, X., Shi, J., Shen, T., Gong, Y. and Holmes. M.,. 2023. Novel gellan gum-based probiotic film with enhanced biological activity and probiotic viability: application for fresh-cut apples and potatoes. International Journal of Biological Macromolecules 239: 124128. https://doi.org/10.1016/j.ijbiomac.2023.124128

Zhai, X., Zhou, S., Zhang, R., Wang, W. and Hou, H. 2022. Antimicrobial starch/poly(butylene adipate-co-terephthalate) nanocomposite films loaded with a combination of silver and zinc oxide nanoparticles for food packaging. International Journal of Biological Macromolecules 206: 298–305. https://doi.org/10.1016/j.ijbiomac.2022.02.158

Zhang, K., Chen, Q., Xiao, J., You, L., Zhu, S., Li, C. and Fu, X. 2023. Physicochemical and functional properties of chitosan-based edible film incorporated with *Sargassum pallidum* polysaccharide nanoparticles. Food Hydrocolloids 138: 108476. https://doi.org/10.1016/j.foodhyd.2023.108476

Zhao, Y., Li, B., Zhang, W., Zhang, L., Zhao, H., Wang, S. and Huang, C. 2023. Recent advances in sustainable antimicrobial food packaging: insights into release mechanisms, design strategies, and applications in the food industry. Journal of Agricultural and Food Chemistry 71(31): 11806–11833. https://doi.org/10.1021/acs.jafc.3c02608

Zhu, H., Cheng, J.H. and Han, Z. 2024. Construction of a sustainable and hydrophobic high-performance all-green pineapple peel cellulose nanocomposite film for food packaging. International Journal of Biological Macromolecules 256(January): 128396. https://doi.org/10.1016/j.ijbiomac.2023.128396