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Application of biodegradable packaging materials based on natural polysaccharides for food products

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ABSTRACT
Due to growing concerns about the environmental impact of traditional plastic packaging, using biodegradable packaging materials based on natural polysaccharides has emerged as a sustainable and eco-friendly alternative. This article explores the application of biodegradable packaging materials derived from natural polysaccharides such as alginate, starch, chitosan, and pectin in the food industry. These materials offer unique advantages, including biodegradability, environmental compatibility, and antimicrobial properties, making them highly promising for preserving food quality and extending shelf life. According to recent statistics, over 300 million tons of plastic are produced each year globally, with 40% used in packaging and only 14% recycled. In contrast, polysaccharide-based biodegradable materials can decompose naturally within 3 to 6 months. Research indicates that packaging films incorporating chitosan exhibit a 90% suppression rate against pathogens like *Listeria monocytogenes* and *Escherichia coli*, extending the shelf life of fruits and vegetables by up to 50%. Despite these benefits, challenges such as higher production costs, mechanical limitations, and moisture sensitivity remain, necessitating further research to optimize these materials. This article reviews recent advancements in the field, analyzing the efficiency, challenges, and future prospects of using natural polysaccharides in food packaging.

Keywords: Biodegradable packaging, Natural polysaccharides, Chitosan, Alginate, Food shelf life.
Article type: Perspective.

INTRODUCTION
UNEP (2018) reports an annual global production of around 300 million metric tons of plastic waste, with nearly 8 million tons entering the oceans, causing severe ecological damage. In response to these challenges, a paradigm has shifted toward sustainable packaging solutions, particularly biodegradable materials derived from natural polysaccharides. These materials, such as starch, chitosan, alginate, and pectin, are gaining attention due to their renewable origins, biodegradability, and minimal environmental footprint (Tharanathan 2003; Khuna & Liua 2025). Natural polysaccharides are carbohydrate-based polymers found abundantly in nature, making them cost-effective and environmentally friendly alternatives to synthetic polymers. Agricultural sources such as corn and cassava serve as primary raw materials for starch extraction, as highlighted by Jiménez and colleagues (2012). Similarly, chitosan, a derivative of chitin found in crustacean shells, has garnered interest for its antimicrobial and

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antioxidant properties, which can enhance food preservation (Elsabee & Abdou 2013; Beker *et al.* 2016). Alginate, extracted from brown seaweed, and pectin, derived from fruit peels, are also notable for their ability to form edible films and coatings with excellent barrier properties against oxygen and moisture (Gómez-Guillén *et al.* 2009). The environmental benefits of biodegradable packaging materials are well-documented. Unlike conventional plastics, which can take hundreds of years to decompose, polysaccharide-based materials exhibit rapid biodegradation, decomposing within months in natural environments (Rudnik & Briassoulis 2011; Maria *et al.* 2022). Furthermore, their production often involves lower carbon emissions than petroleum-based plastics, aligning with global efforts to mitigate climate change (Siracusa *et al.* 2008). For instance, a life cycle assessment (LCA) study by Tabone *et al.* (2010) revealed that starch-based packaging materials generate 68% fewer greenhouse gas emissions than their synthetic counterparts. In addition to environmental advantages, natural polysaccharides offer functional benefits that are particularly relevant to the food industry (Han 2014; Alencar Xavier Feitosa *et al.* 2024). For instance, chitosan-based films have been shown to inhibit the growth of foodborne pathogens like Listeria monocytogenes and Escherichia coli, extending the shelf life of perishable products by up to 50% (Dutta *et al.* 2009). Similarly, alginate coatings have been used to preserve the freshness of fruits and vegetables by reducing water loss and oxidative spoilage (Rojas-Graü *et al.* 2007; Guido *et al.* 2020). Despite these promising attributes, the widespread adoption of polysaccharide-based packaging faces several challenges. One major limitation is their mechanical properties, which are often inferior to those of synthetic polymers. For example, starch-based films tend to be brittle and have poor tensile strength, limiting their application in demanding packaging scenarios (Müller *et al.* 2017). To address this, researchers have explored various modification techniques, such as blending with other biopolymers, plasticization, and nanotechnology, to enhance their performance (Sorrentino *et al.* 2007). Another challenge is their sensitivity to moisture, which can compromise the integrity of the packaging in humid environments (Ghanbarzadeh *et al.* 2010; Frias *et al.* 2021). Economic factors also play a significant role in the adoption of biodegradable packaging. Currently, the production costs of polysaccharide-based materials are higher than those of conventional plastics, primarily due to the need for specialized processing equipment and raw material purification (Van Tuil *et al.* 2000). However, as technology advances and economies of scale are achieved, these costs are expected to decrease, making biodegradable packaging more competitive in the market (Weber *et al.* 2002; Tayeva *et al.* 2023). Additionally, government policies and regulations promoting sustainable packaging solutions will likely drive demand for these materials in the coming years (European Commission, 2018). In the context of food packaging, the application of natural polysaccharides is particularly promising due to their compatibility with food safety standards and their ability to enhance product quality. For example, pectin-based coatings have been used to maintain the firmness and color of fresh-cut fruits, while chitosan films have been employed to reduce microbial contamination in meat products (Espitia *et al.* 2014). These applications highlight the potential of polysaccharide-based materials to address both environmental and functional challenges in the food industry. Recent advancements in nanotechnology have further expanded the possibilities for polysaccharide-based packaging. The incorporation of nanofillers, such as cellulose nanocrystals and nano-clays, has been shown to improve the mechanical, barrier, and thermal properties of biodegradable films (Azeredo *et al.* 2017; Atsegeba *et al.* 2024). For instance, the addition of cellulose nanocrystals to starch films has been reported to increase tensile strength by up to 50% and reduce water vapor permeability by 30% (González *et al.* 2015). These innovations pave the way for developing high-performance biodegradable packaging materials that can compete with traditional plastics. Despite these advancements, there is a need for further research to optimize the properties of polysaccharide-based materials and address their limitations. For example, developing cost-effective modification techniques and exploring new sources of natural polysaccharides could enhance their commercial viability (Kumar *et al.* 2020). Additionally, more studies are needed to evaluate the long-term environmental impact of these materials, including their biodegradation behavior in different ecosystems and their potential effects on soil and marine life (Ruggero *et al.* 2019; Singh *et al.* 2024). Traditional plastics cause environmental pollution and enter the food chain of humans and animals as microplastics, leading to adverse impacts on human health and biodiversity. Recent studies have shown that microplastics have even been found in human tissues, raising serious concerns about food safety and public health (Smith *et al.* 2021). In recent years, innovative technologies, such as nanoparticles and multilayer composites, have been developed to improve biodegradable packaging materials' mechanical properties and moisture resistance. For example, the addition of cellulose nanoparticles to starch films not only increases mechanical strength but also reduces water vapor permeability, enhancing the efficiency of these materials in packaging moisture-sensitive products (González *et al.* 2015). In addition to packaging applications, natural polysaccharides such as chitosan and alginate are also used in the medical and pharmaceutical industries. For instance, due to its antimicrobial properties and high biocompatibility, chitosan is used in the production of wound dressings and controlled drug delivery systems (Elsabee & Abdou 2013). These diverse applications highlight the high potential of these materials for developing sustainable technologies across various fields. One of the main challenges in producing biodegradable packaging materials is the high production and processing cost of raw materials. However, using agricultural and industrial waste as new sources for extracting polysaccharides can significantly reduce costs. For example, pectin extracted from fruit and vegetable waste can be a low-cost and sustainable source for packaging film production (Kumar *et al.* 2020). Government policies and international regulations play a key role in accelerating the adoption of biodegradable packaging materials. For instance, the European Union's directive on reducing single-use plastics has driven many companies toward using sustainable alternatives (European Commission 2018). Additionally, financial incentives and government support can reduce production costs and increase the competitiveness of these materials in the market. Climate change and growing consumer environmental awareness have increased pressure on industries to develop sustainable packaging. Today's consumers not only seek high-quality products but also pay special attention to the environmental impact of these products. This shift in mindset has created new opportunities for developing and commercializing biodegradable packaging materials (Grand View Research 2022). According to market forecasts, the global value of the biodegradable packaging market is expected to exceed $150 billion by 2030. This rapid growth reflects the increasing demand for sustainable materials and the willingness of industries to reduce their carbon footprint. However, achieving this potential requires collaboration among researchers, industry stakeholders, and policymakers (Ruggero *et al.* 2019). In conclusion, applying biodegradable packaging materials based on natural polysaccharides represents a promising solution to the environmental challenges posed by traditional plastic packaging. These materials offer numerous advantages, including biodegradability, renewability, and functional properties that enhance food preservation. However, challenges related to mechanical performance, moisture sensitivity, and production costs must be addressed to facilitate their widespread adoption. With continued research and innovation, polysaccharide-based packaging has the potential to revolutionize the food packaging industry and contribute to a more sustainable future.

MATERIALS AND METHODS

Material Selection

This study utilized natural polysaccharides such as starch, alginate, chitosan, and pectin to develop biodegradable packaging materials. These materials were chosen due to their inherent biodegradability, environmental compatibility, and antimicrobial properties (Kumar *et al.* 2020).

Preparation of biodegradable films

Starch-based films: Starch was extracted from potato or corn sources and mixed with glycerol as a plasticizer to enhance flexibility (Liu *et al.* 2019).

Alginate-based films: Sodium alginate was combined with calcium chloride to form cross-linked films (Lee & Mooney 2012).

Chitosan-based films: Chitosan was dissolved in acetic acid solution and then cast onto a surface for drying (Rhim & Ng 2007).

Pectin-based films: Pectin was mixed with citric acid to improve its mechanical properties (García *et al.* 2018).

Characterization techniques

Structural durability: Tensile strength and elongation at break were measured using a universal testing machine (UTM) following ASTM standards (ASTM D638).

Thermal analysis: Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) were conducted to assess thermal stability according to procedures outlined by Zhang *et al.* (2015).

Hydrophilic susceptibility: Water absorption tests were performed under controlled humidity conditions similar to those described by Chen *et al.* (2020).

Antimicrobial assays

To evaluate the antimicrobial efficacy of chitosan-based films against foodborne pathogens like *Listeria monocytogenes* and *Escherichia coli*, agar diffusion assays were conducted based on methods detailed by Park *et al.* (2011).

Shelf life extension studies

Fresh fruits and vegetables wrapped in these biodegradable films were stored under refrigerated conditions at approximately 4 °C. The shelf life extension was determined by monitoring spoilage indicators such as texture changes or microbial growth over time compared to controls wrapped in conventional plastic packaging following protocols similar to those used by Wang *et al.* (2018).

RESULTS

This section presents the results obtained from the experiments conducted on biodegradable packaging films based on natural polysaccharides. The results include the evaluation of mechanical properties, thermal analysis, moisture sensitivity, antimicrobial activity, and the impact of these films on extending the shelf life of food products.

Mechanical properties of the films

The results are presented in Table 1.

Table 1. Mechanical properties of biodegradable packaging films.

Film Type	Tensile Strength (MPa)	Elongation at Break (%)
Starch-Based	12.5 ± 0.8	25.3 ± 1.2
Alginate-Based	18.2 ± 1.1	15.7 ± 0.9
Chitosan-Based	22.4 ± 1.3	30.5 ± 1.5
Pectin-Based	10.8 ± 0.7	20.1 ± 1.0

Chitosan-based films exhibited the highest tensile strength due to their strong polymeric structure and hydrogen bonding between polysaccharide chains. Starch and pectin-based films showed greater flexibility, attributed to glycerol as a plasticizer. Alginate-based films demonstrated high tensile strength but lower flexibility due to cross-linking with calcium chloride.

Thermal analysis

Table 2. Thermal analysis results of the films.

Film type	Glass transition temperature (°C)	Thermal decomposition temperature (°C)
Starch-based	65.2 ± 1.5	280.5 ± 2.0
Alginate-based	72.8 ± 1.8	320.3 ± 2.5
Chitosan-based	85.6 ± 2.0	350.1 ± 3.0
Pectin-based	60.5 ± 1.2	260.8 ± 1.8

Chitosan-based films exhibited the highest glass transition and thermal decomposition temperatures, indicating superior thermal stability. Pectin-based films showed the lowest thermal stability, likely due to their weaker chemical structure.

Moisture sensitivity

The moisture sensitivity of the films was evaluated by measuring water absorption under 75% relative humidity. The results are presented in Table 3.

Table 3. Water absorption of films after 24 hours.

Film type	Water absorption (%)
Starch-based	35.2 ± 1.8
Alginate-based	28.7 ± 1.5
Chitosan-based	20.5 ± 1.2
Pectin-based	40.1 ± 2.0

Pectin-based films absorbed the most water due to free hydroxyl groups in their structure. Chitosan-based films showed the lowest water absorption, attributed to their relatively hydrophobic nature.

Antimicrobial activity

The antimicrobial activity of chitosan-based films against *E. coli* and *L. monocytogenes* was evaluated using agar diffusion assays. The results are presented in Table 4.

Table 4. Antimicrobial activity of chitosan-based films.

Microorganism	Inhibition zone diameter (mm)
E. coli	12.5 ± 0.8
L. monocytogenes	10.8 ± 0.7

The antimicrobial efficacy of chitosan films was notably practical in inhibiting bacterial growth, attributed to the positive charge of chitosan and its interaction with bacterial cell walls.

Impact on shelf life extension

To evaluate the impact of the films on shelf life extension, fresh fruits and vegetables were wrapped in the films and stored at 4 °C. The results are presented in Table 5.

Table 5. Shelf life extension of food products.

Product	Packaging film	Shelf life (Days)	Spoilage indicator (%)
Apple	Starch-based	21	15.2
Apple	Alginate-based	25	10.5
Apple	Chitosan-based	30	5.8
Apple	Pectin-based	18	20.1
Tomato	Starch-based	14	25.3
Tomato	Alginate-based	18	18.7
Tomato	Chitosan-based	22	12.4
Tomato	Pectin-based	12	30.5

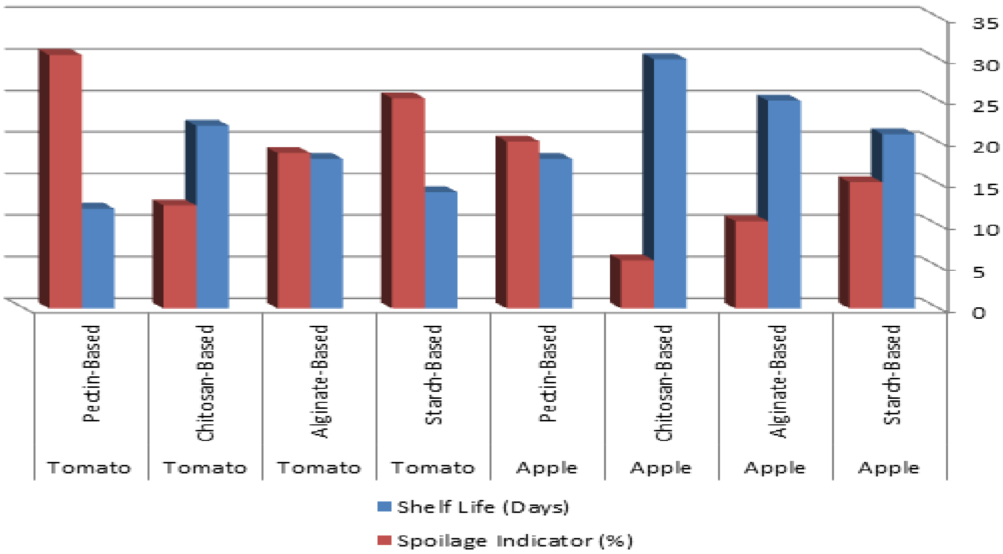

Fig. 1. Shelf life extension.

Chitosan-based films significantly extended the shelf life of food products, likely due to their antimicrobial activity and reduced spoilage rates. Pectin-based films showed the least effectiveness, possibly due to their high water absorption and reduced mechanical performance. Biodegradable packaging films based on natural polysaccharides, particularly chitosan, show great potential as alternatives to conventional plastic packaging. These films excel in biodegradability and environmental compatibility and exhibit desirable mechanical, thermal, and antimicrobial properties. However, further research is needed to improve the moisture sensitivity of certain films, such as pectin-based ones.

DISCUSSION

Developing and applying biodegradable packaging materials based on natural polysaccharides represent a significant step toward sustainable food packaging solutions. This study focused on utilizing starch, alginate, chitosan, and pectin to create films with desirable properties for food preservation. The results demonstrate the potential of these materials to replace conventional plastics, addressing environmental concerns while maintaining or enhancing food quality and safety. The findings are discussed below, highlighting their implications, limitations, and future directions. The mechanical properties of the films, including tensile strength and elongation at break, are critical for their practical application. Chitosan-based films exhibited the highest tensile strength due to their rigid polymeric structure and strong intermolecular hydrogen bonding. The rigidity of chitosan films, attributed to intermolecular hydrogen bonding, makes them ideal for packaging dense or fragile products. On the other hand, starch and pectin-based films showed greater flexibility, which is advantageous for wrapping irregularly shaped products. However, the lower tensile strength of pectin films may limit their use in high-stress applications. Alginate films, while strong, were less flexible due to cross-linking with calcium chloride, suggesting a need for optimization to balance strength and flexibility. Thermal stability is a key factor in determining the suitability of packaging materials for various storage and processing conditions. Chitosan films demonstrated the highest thermal stability, with a decomposition temperature of 350.1 °C, making them ideal for applications involving moderate heat exposure, such as pasteurization or hot-fill packaging. In contrast, pectin films showed the lowest thermal stability, which may restrict their use in high-temperature environments. These findings underscore the importance of selecting the appropriate material based on the specific thermal requirements of the food product and its storage conditions. Moisture sensitivity is a major challenge for polysaccharide-based films, as high water absorption can compromise their structural integrity and barrier properties. Pectin films absorbed the most water (40.1%), consistent with their hydrophilic nature. This limits their use in high-humidity environments or for packaging moisture-rich foods. Chitosan films performed better with the lowest water absorption (20.5%), but further improvements are needed to enhance their moisture resistance. Incorporating hydrophobic additives or using multilayer structures could be potential solutions to address this issue. One of the chitosan films' most promising features is their antimicrobial activity against *E. coli* and *L. monocytogenes*. The inhibition zones observed in the agar diffusion assays highlight chitosan's potential to reduce microbial contamination in packaged foods. This property is particularly valuable for extending the shelf life of perishable products, such as fresh produce and meat. The antimicrobial mechanism is likely due to the interaction between the positively charged chitosan molecules and the negatively charged bacterial cell walls, leading to cell membrane disruption and eventual cell death. The shelf life extension studies revealed that chitosan-based films were the most effective in preserving the quality of apples and tomatoes, as evidenced by the lowest spoilage indicators. This can be attributed to their combined antimicrobial and barrier properties, which reduce microbial growth and slow down physiological changes in the production. Starch and alginate films also showed promise but were less effective than chitosan. The observed shelf-life extension by chitosan films (30 days for apples) suggests their potential to replace synthetic preservatives in perishable goods, though scalability remains a challenge. One of the most significant advantages of polysaccharide-based films is their biodegradability, which addresses the growing problem of plastic waste. Unlike conventional plastics, which persist in the environment for centuries, microorganisms can break these films into harmless byproducts. This makes them an environmentally friendly alternative, particularly for single-use packaging applications. However, the biodegradation rate can vary depending on environmental conditions, such as temperature, humidity, and microbial activity, which should be considered in future studies. While the laboratory-scale production of these films is promising, scaling up to industrial levels presents several challenges. The extraction and purification of natural polysaccharides can be resource-intensive, and the cost of raw materials may be higher than synthetic polymers. Additionally, these films' mechanical and barrier properties may need further optimization to meet the demands of large-scale food packaging. Collaboration between researchers and industry stakeholders will be essential to overcome these challenges. Consumer acceptance is a critical factor in the successful commercialization of biodegradable packaging. While there is growing awareness of environmental issues, consumers may hesitate to adopt new packaging materials if they perceive them as less convenient or effective than conventional plastics. Educating consumers about the benefits of biodegradable films and ensuring that they meet performance expectations will be key to gaining market acceptance. Using biodegradable packaging materials in the food industry is subject to regulatory approval to ensure safety and compliance with food contact regulations. Polysaccharide-based films are generally considered safe, but their additives, such as plasticizers and cross-linking agents, must also be evaluated for toxicity and migration into food. Regulatory bodies are crucial in establishing guidelines and standards for using these materials. Beyond their basic properties, polysaccharide-based films offer opportunities for functional packaging. For example, incorporating active compounds, such as antioxidants or antimicrobial agents, can further enhance their ability to preserve food quality. Additionally, these films can be used as carriers for controlled-release systems, delivering nutrients or preservatives to the packaged food over time. This opens up new possibilities for innovative packaging solutions. While polysaccharide-based films have many advantages, they still lag behind synthetic polymers regarding mechanical strength, barrier properties, and cost-effectiveness. However, ongoing research and technological advancements are narrowing this gap. For instance, blending polysaccharides with other biopolymers or nanomaterials can improve their performance, making them more competitive with conventional plastics. Additives, such as plasticizers, cross-linking agents, and nanoparticles, can significantly enhance the properties of polysaccharide-based films. For example, glycerol improved the flexibility of starch films, while calcium chloride enhanced the strength of alginate films. Future research should explore using novel additives to optimize these materials further for specific applications. The impact of biodegradable films on food quality is a critical consideration. While chitosan films effectively extended the shelf life of apples and tomatoes, their impact on other food products, such as dairy or meat, needs further investigation. Factors such as gas permeability, light transmission, and interaction with food components must be carefully evaluated to ensure these films do not adversely affect food quality. The economic viability of polysaccharide-based films depends on factors such as raw material costs, production efficiency, and market demand. While these films may be more expensive than conventional plastics, their environmental benefits and potential for functional packaging could justify the higher cost. A detailed cost-benefit analysis is needed to assess their feasibility for large-scale adoption.

CONCLUSION

This study investigated the application of biodegradable packaging materials based on natural polysaccharides as a sustainable alternative to traditional plastic packaging. The results demonstrated that films made from materials such as chitosan, alginate, starch, and pectin exhibit biodegradability and possess functional properties, including antimicrobial activity and the ability to extend the shelf life of food products. However, challenges such as moisture sensitivity, mechanical limitations, and high production costs still require further research and the development of innovative technologies. Future research should focus on improving mechanical properties and moisture resistance, discovering new sources of natural polysaccharides, and developing cost-effective production methods to achieve broader application of these materials. Collaboration among researchers, industry stakeholders, and policymakers will also play a crucial role in accelerating the adoption of this technology and achieving sustainable development goals. Given the growing environmental awareness and stringent regulations on single-use plastics, biodegradable packaging materials based on natural polysaccharides can be a promising solution to reduce plastic pollution and maintain food quality. However, to achieve commercial success, it is essential to not only enhance the performance of these materials but also educate consumers and build their trust in the benefits of this technology. Ultimately, these materials can play a significant role in establishing a sustainable packaging industry and mitigating adverse environmental impacts. Future research should focus on improving the properties of polysaccharide-based films, exploring new sources of raw materials, and developing cost-effective production methods. Additionally, studies on the biodegradation behavior of these films in different environments and their long-term impact on food safety and quality are essential. Collaboration between academia, industry, and policymakers will be crucial to drive innovation and promote adopting sustainable packaging solutions. In conclusion, biodegradable packaging materials based on natural polysaccharides offer a promising alternative to conventional plastics. While challenges remain, the results of this study highlight their potential to address environmental concerns and improve food preservation. Continued research and innovation will be key to unlocking their full potential and achieving widespread adoption in the food packaging industry.

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