# Starch based for intelligent food packaging: A review

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**Abstract.** Biodegradable materials are gaining attention as sustainable alternatives, particularly for food packaging, as they provide similar protection without environmental harm. Starch, an abundant, renewable, and affordable polymer, is promising for biodegradable films. However, its limitations, such as low solubility, weak mechanical properties, and high sensitivity to moisture, restrict its use in packaging. Thus, enhancing the mechanical and barrier properties of starch-based materials is critical. This review explores recent advances in starch-based films, focusing on their degradability, functional improvements, and applications in active and intelligent packaging. Although processing techniques have evolved, further research is needed to optimize film formulation, scale production, and reduce costs for commercial feasibility. Starch-based films can incorporate antimicrobial and antioxidant agents, offering active and intelligent packaging solutions that maintain food quality and extend shelf life. This review underscores the potential of starch-based materials as eco-friendly alternatives for future food packaging.

## 1 Introduction

Food products are highly vulnerable to external damage and contamination from production to consumption. The factors that affect it are often due to pathogenic bacteria and oxidation, leading to significant quality degradation. Effective food packaging is essential to address these concerns, as it helps preserve quality, prevent spoilage, extend shelf life, and minimize waste [1]. Traditionally, plastics have been the dominant material in food packaging due to their affordability, excellent mechanical properties, and reasonable barrier functions. The global production shows approximately 300 million tons of plastic annually, with 40% dedicated to packaging [2]. Data from Making Oceans Plastic Free (2017) states that an average of 182.7 billion plastic bags are used annually in Indonesia. The Central Statistics Agency (BPS) shows that plastic waste in Indonesia reaches 64 million tons per year. This causes serious environmental problems due to the non-decomposition of most plastic packaging.

Developing environmentally friendly and biodegradable food packaging materials has attracted increasing attention in response to environmental issues. Among various options, biodegradable materials are particularly suitable for food packaging, as they fulfill the same protective roles as conventional packaging while being environmentally benign. Over recent decades, research has shifted towards completely degradable biofilms, with polysaccharides like starch, chitosan, and cellulose emerging as critical components [3]. Despite this progress, biodegradable materials' high production costs and functional limitations have hindered their widespread adoption in the food packaging industry.

Starch, a naturally abundant and cost-effective polymer, is a promising candidate for biodegradable food packaging [4]. Starch is composed of amylose and amylopectin, contributing to its structural properties [5]. Commonly used starch sources come mainly from corn, potatoes, cassava, and cereals. However, using natural starch in packaging is limited by its low solubility, weak mechanical properties, and high hydrophilicity, which causes its inadequate performance in wet conditions [6]. Therefore, improving the mechanical strength and barrier properties of starch-based packaging materials is important.

Starch's biodegradability, renewability, and widespread availability hold significant potential for various industrial applications, especially in the food sector [7]. Recent studies have focused on improving the processing methods and addressing the challenges associated with starch-based biodegradable films. However, a comprehensive review of their use in active and intelligent food packaging remains lacking. This review aims to fill that gap by discussing the degradability, mechanical enhancements, and functional applications of starch-based materials in food preservation. By exploring these aspects, this review highlights the importance of developing green, safe, and functional starch-based packaging materials for future use.

## 2 Methods

This systematic review adheres to the guidelines outlined in the Preferred Reporting Items for Systematic

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Reviews and Meta-Analyses (PRISMA). This review aims to examine scientific articles on the use of polysaccharides based for intelligent food packaging. Strategic keyword selection was employed to search leading research databases, including Science Direct, Springer, Web of Science, PubMed, Taylor and Francis, and common platforms such as ResearchGate and Google Scholar. The study conducted searches using quotation marks and Boolean moderators (i.e., "AND" and "OR") to identify relevant articles. The keywords used in each database were "food packaging" OR "intelligent packaging" AND "starch based." The initial selection of the articles was based on criteria, as follows: (1) articles published after they were peer-reviewed; (2) articles report the application of starch based for intelligent food packaging; and (3) articles written consistently in English.

## 3 Result and discussion

### 3.1 Properties of starch based film

#### *3.1.1 Optical properties*

The optical qualities of starch-based materials are critical for their use in intelligent packaging because they impact product visibility and consumer appeal. Starch-based films are often highly transparent [8], allowing consumers to examine the packed food's quality visually. However, the transparency and glossiness of these films might vary depending on the botanical origin of the starch, processing processes, and the addition of fillers or plasticizers [9]. Native starch films are slightly opaque due to the crystalline structure of starch granules [10]. However, modifications such as blending with other biopolymers (e.g., chitosan or cellulose) or introducing nanoparticles might improve clarity [4]. Furthermore, adding pigments or intelligent indicators enables the packaging to provide visual cues regarding product freshness or quality, making starch-based films suitable for intelligent food packaging that requires both visibility and responsiveness to environmental changes [11].

#### *3.1.2 Organoleptic properties*

The organoleptic properties of starch-based films play a vital role in determining their application in intelligent food packaging. Typically, starch-based films provide good transparency, enabling clear visibility of the packaged product, which can enhance consumer appeal. However, due to the inherent brittleness of starch, the texture of these films can be rigid unless modified with plasticizers or other biopolymers [12]. Moisture sensitivity is another critical factor, as starch has a high water absorption capacity, which can cause the film to become tacky or lose structural integrity [13]. This affects the texture and barrier properties of the packaging, potentially compromising food quality. Starch-based films are generally neutral regarding odor and taste, but they may absorb surrounding odors under specific conditions [14]. Recent advances in crosslinking techniques, incorporating nanomaterials, and blending with other polysaccharides have improved mechanical properties and moisture resistance, making them more suitable for intelligent packaging applications [15].

#### *3.1.3 Mechanical properties*

The mechanical properties of starch-based films are important for their use in intelligent packaging because they affect strength, flexibility, and durability. Native starch films are often brittle and complex due to their semi-crystalline structure and strong hydrogen bonding, limiting their mechanical performance [16]. Plasticizers like glycerol or sorbitol are frequently used to minimize intermolecular tensions, increasing flexibility but often at the expense of tensile strength and water sensitivity [17]. Blending starch with other biopolymers, such as chitosan or cellulose, or reinforcing it with nanomaterials like cellulose nanofibers or clay nanoparticles has improved tensile strength, elongation at break, and flexibility [18]. Additionally, crosslinking techniques further stabilize the starch matrix, resulting in more durable films that are resistant to tearing and punctures [19]. These enhancements are essential for ensuring that starch-based films meet the mechanical demands of intelligent packaging, where strength, flexibility, and adaptability to different food products are key requirements.

#### *3.1.4 Barier properties*

The barrier qualities of starch-based films are critical to their success in intelligent packaging because they influence the material's ability to protect food from environmental variables such as moisture, oxygen, and gases. Because of their hydrophilic nature, native starch films often have poor water vapor barrier characteristics, resulting in excessive moisture absorption that can impair the quality of humidity-sensitive food products [20]. Several ways have been investigated to improve moisture barrier efficacy, including combining starch and hydrophobic materials and applying lipid or wax coatings [21]. Furthermore, using plasticizers can improve flexibility, but it may also increase water vapor permeability. Because of their rich polymer matrix, starch-based films perform well regarding oxygen barrier qualities when exposed to dry environments [22].

Nonetheless, their barrier performance significantly declines in humid environments due to swelling of the starch matrix [23]. Researchers have employed various approaches to mitigate this issue, including chemical crosslinking, reinforcement with nanomaterials such as clay or cellulose, and blending with other biopolymers like chitosan [24]. These modifications enhance water vapor and oxygen barrier properties, thereby improving the overall protective function of starch-based films. Such advancements render these materials more effective for intelligent packaging applications, where the maintenance of food freshness and the extension of shelf life are critical objectives.

## 3.2 Starch based intelligent packaging

In addition to extending the shelf life of food through active substances, innovative intelligent food packaging can enhance the functionality of starch-based materials. This intelligent packaging is capable of monitoring the quality of the food contained within and detecting environmental conditions surrounding the product. Typically, natural active substances incorporated into intelligent films possess antibacterial and antioxidant properties, allowing these packaging solutions to function actively. However, studies evaluating both active and monitoring functions concurrently are rare. A notable advantage of starch-based films compared to other biodegradable polymers is their colorless and transparent nature, which ensures that the visual changes in the packaging do not interfere with the sample matrix. Starch-based intelligent food packaging primarily utilizes indicators to provide intuitive, quantitative, or semi-quantitative information about the packaged food through observable color changes. These indicators include freshness indicators, which react with characteristic gases produced during storage to signal the remaining shelf life, and time-temperature indicators, which demonstrate shelf life based on accumulated time-temperature effects.

### *3.2.1 Freshness indicator*

The ability of starch to form films makes it an ideal biopolymer for producing intelligent colorimetric films. Recently, there has been increasing interest in developing pH-sensitive films using starch for intelligent packaging. Changes in pH are key indicators of food freshness and quality, as the pH level near food varies with microbial spoilage. Thus, the link between food freshness and pH can be effectively monitored. Organic pH indicators, which are safe for humans and the environment, can be sourced from various natural compounds. This has led to growing research interest in intelligent packaging that incorporates pH-sensitive materials such as anthocyanins, curcumin, and carotenoids. Among these, anthocyanins are particularly favored due to their broad color range and strong color differentiation in response to pH changes [25].

Starch-based films, combined with these pH indicators, can respond to food spoilage by detecting gas emissions like ammonia and dimethylamine, which alter the surrounding pH. The natural pigments in these films then exhibit color changes, signaling freshness levels. For instance, anthocyanins in bok choy show visible shifts from mauve to blue-purple to blue-green as pH rises, allowing consumers to assess food freshness visually. Choi and Lee developed a colorimetric pH indicator film using agar, potato starch, and sweet potato anthocyanins, which turned from red to green as pork quality deteriorated [26]. Similarly, Mayra and José examined a pH-sensitive film made from chitosan, corn starch, and purple cabbage extract to visually indicate fish spoilage.

In addition to colorimetric methods, electrochemical techniques in pH sensors can transform chemical data into electrical signals for analysis. These sensors detect chemical byproducts from spoiled food that interact with electrodes, leading to measurable chemical shifts. However, colorimetric sensors, which rely on visible color intensity and sensitivity, are often more sensitive than electrochemical alternatives. The color intensity and sensitivity of these sensors improve with higher anthocyanin content and increased porosity of the starch matrix. Additionally, a higher cellulose binder content enhances the sensor's mechanical strength.

An ideal freshness indicator in food packaging would signal spoilage or lack of freshness due to temperature abuse or package leakage. Some patented freshness indicators track volatile compounds from food aging, such as $CO_2$, diacetyl, amines, ammonia, and hydrogen sulfide. Currently, the FreshTag® label, developed by Cox Recorders in the USA, is one of the few commercial freshness indicators available. It detects volatile amines in fish, changing color to signal freshness [27]. Future developments in this field may include advanced electronic tags that can provide product details, manufacturing dates, prices, and function as indicators for freshness, temperature, and packaging integrity.

### *3.2.2 Time-temperature indicator*

Perishable foods are highly sensitive to temperature fluctuations, and maintaining low-temperature storage can significantly extend their shelf life. Conversely, high temperatures speed up the deterioration process, causing food to spoil more quickly. Both time and temperature are crucial factors influencing the quality of most foods. Time–temperature indicators (TTIs) provide a way to track and display temperature changes throughout the product's storage and distribution, showing the remaining shelf life by indicating any deviations in the temperature conditionsng detailed time and temperature data, TTIs allow monitoring of temperature variations at each stage in the food supply chain, helping to ensure food quality and safety [28]. TTIs work through visible, irreversible color changes triggered by temperature changes, which may result from chemical, microbial, enzymatic, or physical processes. Thesehe end of the product's shelf life, visually represent the food's freshness.

Research into TTIs has emerged relatively recently, still limited investigation in this field. For instance, Carolina and Pricila developed a biodegradable thermochromic sensor film using cassava myoglobin extract and nitrite as alternatives to traditional electronic sensors. Their natural, non-toxic sensor leverages the thermochromic properties of these proteins to track temperature changes by observing color shifts, demonstrating its potential for use in packaging or labeling. Additionally, Nogueira and Fakhouri tested starch-based edible films containing freeze-dried blackberry particleen sterilized at 127°C for 15 minutes, showed a notable color shift from red to brown, indicating temperature exposure.

Starch films have shown substantial improvement in mechanical and barrier properties, and extensive research highlights their promise as sustainable alternatives to petroleum-based packaging materials.

Modified starches and additives have been successfully incorporated to produce films with properties akin to conventional materials. Furthermore, starch-based films can carry functional ingredients, enabling them to be used in active and intelligent packaging by incorporating antibacterial, antioxidant, and indicator agents. This approach helps maintain food quality and shelf life while providing visual indicators of spoilage.

A time–temperature indicator is essentially a small measurement device that registers an irreversible, easily measurable change driven by time and temperature exposure, paralleling the degradation of a targeted attribute [29]. Temperature-sensitive indicators rely on the principle that food quality deteriorates faster at higher temperatures due to intensified biochemical reactions and microbial growth. It is essential that the activation energy of the indicator reaction is closely aligned with that of food spoilage, and that the indicator's time to "run out" aligns with the food's shelf life. TTI systems generally operate through mechanisms like enzymatic reactions, corrosion, polymerization, melting, or chemical diffusion. Only a few methods—such as color change or movement (diffusion)—are currently available for directly measuring these indicators.

### 3.3 Starch-based intelligent packaging application in the food industry

In response to consumer demand, there is a need to extend the shelf life of food products in the food industry. In the overall food circulation link, it is essential to maintain the high level of food quality. Certain starch-based biodegradable films have been used in food packaging. In addition to applied research on intelligent packaging film materials based on starch. At present, they are primarily focus on indicator intelligent packaging materials. Indicative intelligent packaging combines intelligent functions with standard packaging technology and provides consumers information through external color changes.

Based on the existing studies, intelligent packaging materials are mainly prepared using the color principle of CR and ATH, which has a good indicator effect on food with a significant change in pH value during food spoilage [30]. Still, the precise relationship between pH value change and quality change remains to be further studied. In addition, the film material with antibacterial function has been prepared based on intelligent packaging, so developing intelligent, active packaging material is a research direction in the future.

## 4 Conclusion

Starch has attracted significant interest in developing biodegradable films because it is both environmentally friendly and edible, inexpensive, easy to process, and suitable for thermal processing. Starch-based films and coatings are seen as viable alternatives to traditional packaging, helping to enhance food quality and safety. Moreover, these starch-based films can serve as carriers for functional ingredients, allowing them to be used in active, antioxidant, and intelligent packaging by incorporating agents with antimicrobial, antibrowning, or nutraceutical benefits to extend shelf life and maintain quality. However, more research is needed to advance technologies that enhance the effectiveness of these films and coatings. To date, most applications for food packaging have been explored only at the laboratory scale, underscoring the need for research focused on cost reduction, larger-scale production, stability, and safety to support the commercialization of biodegradable packaging. Further studies should also seek to optimize film composition and processing techniques to improve resistance to humidity and to tailor film properties for specific uses.

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