

# Bio-based Active and Smart Packaging Materials: Applications in Extending Food Shelf-Life and Quality Monitoring

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## ABSTRACT

Food packaging is crucial in the protection of food from physical damage, contamination, moisture, oxygen, and other environmental factors that may affect quality and shorten the shelf-life. Traditional petroleum-based plastic packaging materials offer adequate protection, but are problematic due to their long persistence in the environment and utilization of non-renewable resources. Bio-packaging materials are thus emerging as increasingly attractive packaging solutions. They are materials that can be made from renewable biological resources like polysaccharides, proteins, lipids, and by-products of agriculture. Bio-materials not only have environmental potential, but they can be engineered to have an active and smart packaging role. Active packaging is designed to react with the contents of the package or the environment in order to preserve the quality and/or to slow the deterioration of the packaged food. Packaging can contain antimicrobial and antioxidant agents which can help to prevent microbial growth and oxidation reactions in the product, and moisture and oxygen barriers can keep the product stable. Smart packaging, on the other hand, offers information regarding the packaged food by means of indicators and sensors that react to changes in the food, including temperature, gases, pH, and microbial activity. Potential applications for these technologies include: meat, dairy products, fruits, vegetables, bakery products, and other perishable foods. This article reviews some of the most important bio-based materials employed for active and smart packaging, their mechanisms, applications in food shelf-life extension and monitoring of food quality and benefits, limitations, and future perspectives. Safe, economical, biodegradable, and effective packaging systems might help to enhance food preservation and decrease food waste.

**Keywords:** Bio-based packaging; food shelf-life; antimicrobial packaging; freshness indicators; food quality monitoring

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## Introduction

Food packaging plays a crucial role in the food system by helping to safeguard food products during the processing, transportation, storage, and distribution stages. A good package can minimize oxygen, moisture, light, and microorganism exposure and also limit physical damage to the food, which can enhance food safety and quality. It can also contain valuable information for consumers such as product identification, storage information, expiration dates, and handling instructions [1]. Despite this, common plastic packaging has caused environmental issues due to the fact that many plastics that are made from petroleum are not biodegradable and can be found in terrestrial and aquatic environments. The problems of plastic pollution, resource depletion, and sustainability have prompted researchers and food industries to seek alternative materials for packaging that can be sourced from renewable biological resources [2].

Bio-based Packaging means packaging which are made from biological and renewable resources in part or in full. They include starch, cellulose, chitosan, proteins, alginate, pectin, gelatin, etc., and other naturally occurring polymers [3]. By-products of agriculture and food processing can also be used as raw materials, which provides opportunities to add value to by-products that could be regarded as waste. Bio-based materials can be formed into films, coatings, trays, containers, etc. for use in packaging. They can be treated with blending, cross-linking, or functional compounds or nanomaterials [4].

Bio-based packaging is not limited to plastic replacement, but has developed to a more complex level. Development of active packaging and smart packaging systems is increasingly taking place. Active packaging aims to engage with the packaged food or its environment to preserve or enhance food quality. For instance, antimicrobials can be released from packaging to fight microorganisms, and antioxidants can help prevent the oxidation of sensitive food components. The packaging materials can also be engineered to control moisture or oxygen [5].

Smart packaging serves various purposes. It is not used to preserve food, but to provide data on the food's condition or its surroundings. Smart systems can have indicators/sensors that sense changes in pH, gases, microbial activity, and temperature. For instance, freshness indicators can change colour as a result of the build-up of compounds originating from deterioration within a package. Time-temperature indicators can give information on the temperature exposure during storage and transportation [6].

The use of bio-based materials and the development of active and smart technologies is a promising approach to creating a more sustainable

packaging system while keeping it functional. These systems can include helping to ensure longer food shelf-life, better quality monitoring, better food safety, and food waste reductions [7]. However, there are issues to overcome in terms of mechanical strength, barrier protection, production costs, stability, scalability, regulatory approval, and consumer acceptance. The article, therefore, focuses on the description of bio-based active and smart packaging materials and their prospective utilization in food preservation and quality monitoring.

## 1. Bio-based Packaging Materials

Bio-packaging materials are packaging materials that are made from renewable biological resources and can be categorized broadly based on their chemical composition. Polysaccharides, proteins, lipids, and biopolymers are the most frequently studied materials. They can be made into food packaging materials with the help of their properties like mechanical strength, flexibility, transparency, biodegradability, and resistance to moisture and gases [3].

The use of polysaccharide-based materials is widely studied due to their availability and film-forming properties. Maize, potato, wheat, and cassava are sources of starch, which is one of the most abundant and inexpensive natural polymers. Transparency and biodegradability are potential properties of starch-based films, but moisture sensitivity can be a barrier to their performance [8]. Cellulose and its derivatives are also significant as cellulose is readily available, renewable, and can be used to build strong structures. In addition, nanocellulose has been of special interest due to its mechanical properties and potential barrier properties [9].

Another prominent bio-based material developed from chitin is chitosan. It has film-forming properties, and it is naturally endowed with antimicrobial properties, which is why it is very appealing for active food packaging. Chitosan films can also be used to incorporate other antimicrobial or antioxidant agents [10].

Protein-based materials are gelatin, whey protein, casein, soy protein, zein, and other plant or animal proteins. Proteins have functional groups capable of interacting with active compounds, and they can also be used to form films with desired oxygen barrier properties. Protein-based films, however, might present some drawbacks in terms of moisture sensitivity and mechanical properties [11].

Bio-based packaging can also include lipids, including waxes, fatty acids, and other lipophilic compounds. The hydrophobic nature can provide better water vapour resistance. The mixing of various materials can offer some combination of performance in practice [12]. Polysaccharides or proteins

can be crosslinked with lipids for enhanced moisture resistance and active compounds can be added for antimicrobial or antioxidant properties [13]. Agricultural residues and food processing by-products can also be used to make bio-based materials. This method can offer an extra environmental advantage by turning low-value biomass into valuable packaging resources. The properties of such materials may, however, differ depending on their source and processing [14]. Thus, formulation and processing should be rigorously managed to ensure consistent packaging.

## 2. Active Packaging Systems

Active packaging is intended to serve a specified function in addition to separating the food from the external environment. It reacts with the food or package atmosphere to create and sustain a desirable atmosphere and food quality in the package. Functional components such as antimicrobial agents, antioxidants, oxygen scavengers, moisture regulators, or others can be added to active packaging [5].

### 2.1. Antimicrobial Packaging

Another cause of food spoilage, and a food-safety risk, is microbial growth. The goal of antimicrobial packaging is to minimally inhibit or control the microbial growth on or about the packaged food. Another option for bio-based films and coatings is to be loaded with a bioactive compound that is kept in proximity to the food surface [15].

Among the interesting properties of chitosan is its intrinsic antimicrobial activity. Essential oils, organic acids, plant extracts, bacteriocins, and some enzymes are other natural antimicrobial compounds. Some essential oils derived from plants, like oregano, thyme, cinnamon, and clove, have antimicrobial properties and can be used in packaging films [16].

### 2.2. Antioxidant Packaging

Oxidation may have adverse impacts on the quality of food, leading to undesirable flavors, loss of nutrients, colour changes and rancidity. Unsaturated fatty acids are especially prone to lipid oxidation in foods. One way to lessen these reactions is to add antioxidant compounds to films, coatings or other packaging structures, which is called antioxidant packaging [17].

Bio-based packaging can be made with natural antioxidants, such as plant phenolic compounds, flavonoid extracts, and some vitamins. Packaging material can serve as a carrier and can permit the slow migration of antioxidant materials to the surface of the food. This can be helpful in situations in which food oxidation is mainly at the food–package boundary [18].

### 2.3. Moisture and Oxygen Control

Moisture and oxygen transfer are important factors affecting food stability. Too much moisture can lead to changes in texture, mould growth and loss of crispness, while too little moisture can result in dehydration. Oxygen can be a source of oxidation and encourage aerobic microorganism growth [19]. For barrier properties, the bio-based packaging materials can be modified. The lipid components may contribute to hydrophobicity and decrease water vapour transmission, and dense polysaccharide and protein structures can offer the desired oxygen barrier properties under the correct conditions. Different bio-based components can then be combined to offer complementary properties [20].

Active packaging can also contain oxygen-scavenging systems. These systems remove oxygen from the package and may contribute to a reduced rate of oxidative deterioration inside the package. Such systems are effective when the packaging structure, amount of oxygen, food respiration, storage temperature, and desired shelf-life are considered [21].

## 3. Smart Packaging Systems

The main interest of smart packaging is monitoring and communicating information about food quality, safety, storage conditions, and/or packaging condition. Smart packaging does not play an active role in preserving the product, but it can help manufacturers, retailers, and consumers determine the condition of the product [22].

### 3.1. Freshness Indicators

Freshness indicators are one of the most promising technologies for smart packaging for perishable foods. They react to changes in food's chemistry or biology which are linked to the deterioration of food. In the case of the spoilage of meat and fish, for instance, microbial metabolism can yield volatile products like ammonia and other basic products. These changes may affect the pH of the package [23].

Packaging can be equipped with colour-changing indicators which can react to these changes. Natural pigments such as anthocyanins, which are extracted from plants, are of particular interest as their colour varies with pH. These can be used to give a simple visual indication of changes taking place within the package [24].

### 3.2. Time–Temperature Indicators

One of the major factors affecting the rate of deterioration of food is temperature. Time–temperature indicators (TTIs) are indicators that are

used to get information on the product's history of temperature exposure, but not just at one moment in time.

TTIs may be useful for foods that are transported and stored under controlled temperature. If a product changes colour or other measurable characteristic, it may have been exposed to too high a temperature. This could be useful in determining possible cold chain violations [25].

### 3.3. Gas and pH indicators

The quality of food packed in a container can be indicated by changes in the gases and pH. Fresh fruits and vegetables change the concentration of oxygen and carbon dioxide during respiration, and microbial growth can produce gases and volatiles.

Gas-sensitive indicators can then be utilized to check the package atmosphere. Likewise, chemical changes of spoilage can be determined using pH-sensitive indicators. Bio-based smart packaging can be made from films or labels that contain natural pigments or other compounds that are capable of sensing [26].

## 4. Applications in Extending Food Shelf-Life

The use of bio-based active packaging in foods could be expanded to various food categories. Packaging for meat and poultry can cause microbial growth and oxidative deterioration to be reduced through the use of antimicrobial and antioxidant packaging. It is especially important to consider these systems, as meat products are very perishable and can experience significant quality changes during storage [13].

In fish and seafood products, active packaging can be used for the control of microbial growth and oxidation of highly unsaturated lipids. Antioxidants can also help to prevent rancidity, and antimicrobials could help to keep up the microbiological quality of the product [5].

Packaging is particularly important for fruits and vegetables because it needs to protect the product, while also allowing for the natural respiration of fresh produce. Bio-based films/coatings can be used to control gas and moisture transfer. Functional edible coatings with antimicrobial and/or antioxidant agents could provide an extra barrier and keep the product's appearance and quality intact [19].

Active packaging technologies can also be used to advantage in the dairy industry. Antimicrobial packaging can be used to control microorganisms, and oxygen-control systems can help to limit oxidation. Different package systems can be developed based on the product properties of cheese, yoghurt, and other refrigerated products [15].

Moisture migration and microbial spoilage are significant quality problems in bakery products. Bio-based packaging can be used to control moisture transfer, and antimicrobials can help to reduce mould growth. The formulation should have desired texture and sensory properties [27].

Techniques employed in active packaging are effective depending on the mitigation of the deterioration mechanisms of the food in the packaging system. Materials that are good for a dry product may not be suitable for a high-moisture product. Hence, food composition, storage temperature, packaging environment, and the targeted shelf-life need to be taken into consideration when designing the packaging [28].

## 5. Applications in Food Quality Monitoring

Smart packaging gives opportunities for enhanced food quality monitoring during the food supply chain. Typical expiration dates do not imply specific storage conditions, and may not indicate exposure to temperatures higher than intended or deterioration that has occurred at a rate faster than usual. Smart indicators can give other details when the actual conditions are known [29, 33].

Freshness indicators can be especially helpful for seafood and meat, where there may be measurable changes to the pH and volatile compounds due to microbial activity. There should be a visible indicator that can give a quick indication that quality is changing. This could aid in making better decisions by retailers and consumers [30].

Time–temperature indicators can be used to assist in the monitoring of the cold chain. This is especially true for foods that need to be refrigerated all the time, like seafood, dairy, meats, and some prepared foods. Deterioration could be faster than anticipated if temperature conditions are not being maintained [25].

Smart packaging can also help to reduce food waste. Consumers can refuse to use products due to date labels alone when products are still acceptable, and improper storage practices can lead to earlier than expected deterioration. Better informative packaging can be used to enable consumers to make better choices. However, the use of smart indicators should be carefully validated and should not supersede existing food-safety control measures. Quality monitoring can still be further enhanced through the integration of smart packaging and digital technologies. Future systems may include sensors with data storage, wireless communications, or mobile applications. The technologies might enable information to be fed to various parties along the food chain and enable more transparent monitoring of the conditions of the product [29, 31, 32].

## Conclusion

Research on bio-based materials for active and smart packaging is an important area that contributes to the preservation of food and the use of more sustainable packaging. Films, coatings and packaging structures with functional properties can be made from polysaccharides, proteins, lipids and other renewable resources. Active packaging can play a role in preserving food by having antimicrobial and antioxidant properties, and by controlling moisture and oxygen. These can be complemented with smart packaging, which gives information on freshness, temperature history, gases, and pH changes.

These technologies can be applied to meat, seafood, dairy, fruits/vegetables, bakery and other perishable products. They can give an extension in shelf-life, ensure quality, enhance the monitoring of the supply chain and prevent the unnecessary loss of food. However, issues with mechanical properties, moisture sensitivity, cost, stability of active compounds, migration, regulatory requirements, and industrial scale production must be overcome. The interdisciplinary research field involving food science, nutrition, materials science, biotechnology, and environmental assessment will be the basis for future improvement. Bio-based active and smart packaging can be a key part of sustainable and intelligent food packaging systems provided it is appropriately validated for safety and commercial development.

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