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A review on applications of cellulose and cellulose derivatives in food packaging

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Abstract

The development of biodegradable substitutes, especially those made from natural polymers like cellulose, has increased due to growing environmental concerns about traditional plastic packaging. The most prevalent renewable biopolymer on the planet, cellulose is a crucial component of environmentally friendly food packaging due to its promising qualities, which include mechanical strength, biodegradability, and compatibility with living systems. Because of their distinct solubility, film-forming, and barrier properties, a variety of cellulose derivatives, such as cellulose ether, methyl cellulose, carboxymethyl cellulose, ethyl cellulose, and cellulose acetate, are being investigated for packaging applications. Extrusion, solvent casting, and layer-by-layer assembly are techniques used to create cellulose-based food packaging. Paper coatings are improved by the use of microcrystalline cellulose (MCC) and nano-fibrillated cellulose (NFC). These coatings improve mechanical strength, water resistance, and barrier properties. Additionally, cellulose and its derivatives are widely utilized in active packaging systems that provide antimicrobial and antioxidant functions, as well as in intelligent packaging systems incorporating colorimetric sensors that indicate spoilage through visible pH-induced color changes. Innovations such as acetylated cellulose coatings with cinnamaldehyde, pH-responsive films with anthocyanins, and UV-protective films derived from lignin and cellulose nanocrystals demonstrate cellulose's versatility. These developments highlight cellulose's central role in advancing eco-friendly, functional, and smart food packaging technologies aimed at enhancing food safety, extending shelf life, and reducing environmental impact.

Keywords: Cellulose biopolymer, biodegradable packaging, food safety

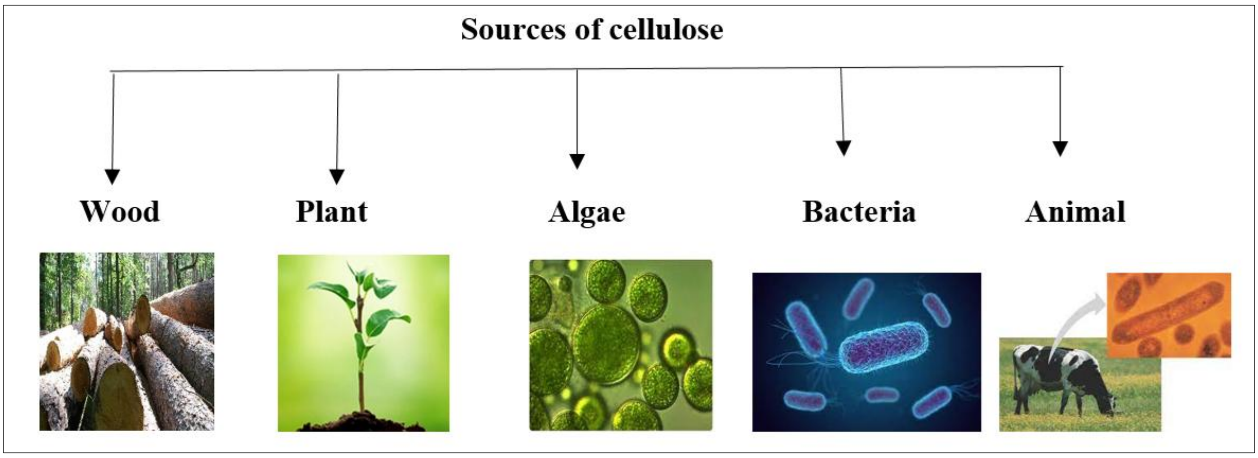
Introduction

The rise of biodegradable food packaging materials has gained significant attention due to the environmental damage caused by non-biodegradable plastic packaging (Moshood *et al.*, 2022) [22]. Natural biopolymers are interesting materials for food packaging. Recently, many studies have concentrated on biodegradable polymers, especially polysaccharides and proteins. These materials are notable for their good biodegradability, compatibility with living organisms, safety, and easy availability Natural polysaccharides like cellulose are increasingly in demand because of their strong mechanical properties, biodegradability, and accessibility (Cabanas-Romero *et al.*, 2020) [5].

Cellulose is one of the most abundant organic polymers on Earth. It is the primary structural component of plant and microbial cell walls. Cellulose provides the mechanical strength of plant cell walls. Anselme Payan, a French scientist, discovered cellulose in 1938. It is the most common renewable natural polymer. Cellulose is a polysaccharide with the chemical formula $(C_6H_{10}O_5)_n$. It consists of a long chain of several hundred to thousands of connected D-glucose units. Cellulose is mainly used to produce a wide range of products, such as paper, textiles, pharmaceuticals, and insulation. It is also known as cellulose ester, fiber, paper, and cellulosic fiber. In 1890, it was used to create the first thermoplastic, celluloid (Liu *et al.*, 2021) [19].

The most commonly used cellulose-based products are paper and paperboard. When smaller amounts of cellulose are treated under the right conditions, they can be changed into many different derivatives. These derivatives can be used to make some commercial items, such as cellophane and rayon (Rose & Palkovits, 2011) [30]. Cellulose also fulfills the dietary needs of certain animals, especially ruminants and termites.

These animals can digest cellulose thanks to symbiotic microorganisms in their gut. Some organisms produce a group of enzymes called cellulases to help break down cellulose molecules. Because humans lack cellulases, they cannot digest cellulose. As a result, cellulose serves as a hydrophilic bulking agent for feces and may help with defecation. People used cellulose in various metabolic transformations long before scientists identified and understood its polymeric nature. By identifying its polymeric structure, nitrocellulose was discovered, organosoluble cellulose acetate was created, and Schweizer's reagent—the first cellulose solvent—was created. Nanocellulose is another important subject that has shown promise in a number of different industries (Fernandes *et al.*, 2011) [10], (Chawla *et al.*, 2015) [6].



Cellulose and its derivatives

1. **Cellulose Ether (CE):** It is made by etherifying cellulose hydroxyl groups with compounds like epoxides or halogenoalkanes (Seddiqi *et al.*, 2021) [32].
2. **Methyl cellulose (MC):** MC is a basic cellulose ether produced from methyl chloride or dimethyl sulfate. Its structure contains H or CH_3 groups (Seddiqi *et al.*, 2021) [32].
3. **Carboxymethyl Cellulose (CMC):** CMC forms when cellulose reacts with monochloroacetic acid. And it is water-soluble, biodegradable, and safe. It contains H or CH_2COOH groups.
4. **Ethyl Cellulose (EC):** EC results from reacting alkali cellulose with ethyl chloride. It has H or CH_2CH_3 groups and is not soluble in water (Rekhi & Jambhekar, 1995) [29].
5. **Hydroxyethyl Cellulose (HEC):** HEC forms by reacting alkali cellulose with ethylene oxide. Its structure contains H or CH_2CH_2OH groups (Ursachi *et al.*, 2024) [36].
6. **Hydroxypropyl cellulose:** Secondary OH groups are formed when reacting with 1,2-propylene oxide. The chemical structure is H or CH2CH(OH)CH3 (Aneel Kumar, 2020) [2].
7. **Cellulose ester:** Cellulose ester is a thermoplastic biopolymer that is available for commercial use and is made from cellulose. In contrast to cellulose, cellulose esters dissolve easily in common solvents and melt before they break down (Furlan Sandrini *et al.*, 2024) [12].
8. **Cellulose acetate:** In order to produce CA, cellulose's hydroxyl groups are usually acetylated with acetic anhydride, acetic acid as a solvent, and sulfuric acid as a catalyst. Its chemical structure is H or (C=O) CH_3.
9. **Cellulose nitrate:** Cellulose nitrate is produced by reacting cellulose with nitric acid. This process replaces the hydroxyl groups with nitrate groups. The chemical structure is H or NO_2 (Nurazzi *et al.*, 2023) [25].
10. **Cellulose sulphate:** The reaction can take place directly on cellulose in a heterogeneous environment or on partially substituted cellulose ethers or esters, usually in a homogeneous environment. H or SO3H are present in the chemical structure.

Food packaging is central to today's food market, with very few products sold without packaging. Good packaging cuts down on waste and ensures that the product keeps its quality throughout its shelf life. Packaging has four key roles: confinement, protection, convenience, and communication (Farrell *et al.*, 2024) [9]. Protection is often seen as the most important role of packaging. It keeps the contents safe from outside factors like water, odours, water vapour, gases, dust, micro-organisms, vibrations, shocks, and pressure (Marsh & Bugusu, 2007) [20]. Most foods depend on their packaging for preservation. For instance, aseptically packed milk and fruit juices in paperboard cartons remain sterile only as long as the package protects them. As mentioned before, packaging needs to be strong, attractive, affordable, and safe (Singh & Singh, 2005) [35]. It improves the look of the products and makes them more appealing for marketing. Packaging also offers convenience for users. The labels provide important details, including production and expiry dates, nutritional information, and manufacturer details. Additionally, some packages may include special features like anti-theft devices. Proper packaging helps organize, group, and store products correctly.

Scope: Market distribution of packaging materials

The market distribution of various food packaging materials, according to (Muller *et al.*, 2017) [23] (2017) is depicted in figure 1. Paper and board hold the largest share at 34%, followed by stiff plastic at 27%, glass at 11%, and flexible plastic at 10%. The rest includes beverage cartons at 6%, various metals at 9%, and other materials at 3%. The high use of paper-based and plastic materials comes from their low cost, versatility, and suitability for food preservation. However, growing environmental concerns are leading to a move toward more sustainable options.

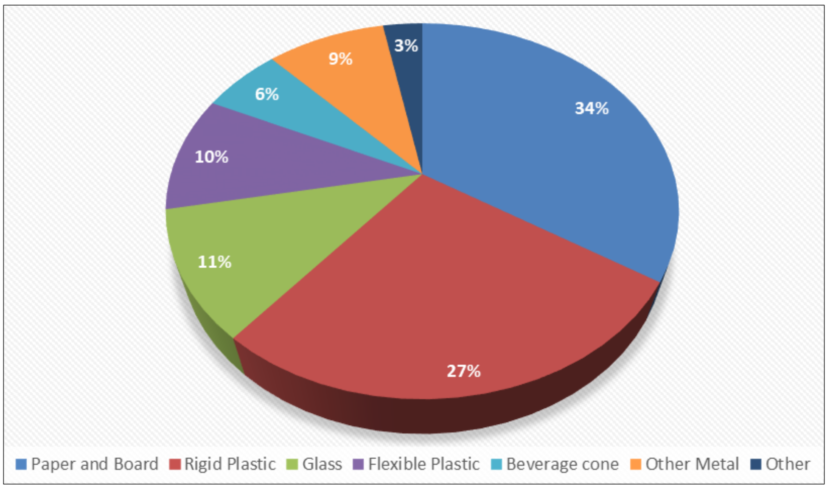


Fig 1: Schematic representation of commercial packaging materials used for food packaging (Muller *et al.*, 2017) [33].

Modern food packaging has many practical features that support safety, quality, and sustainability. Key traits include antibacterial and antioxidant properties that help prevent spoilage, moisture resistance, and effective barriers that protect against environmental factors. Probiotics and bioactive components also promote health, while biodegradable, non-toxic, and biocompatible materials tackle environmental issues. Longer shelf life, cost-effectiveness, easy product identification, and convenient transportation all enhance packing efficiency and marketability. Depicted in fig 2.

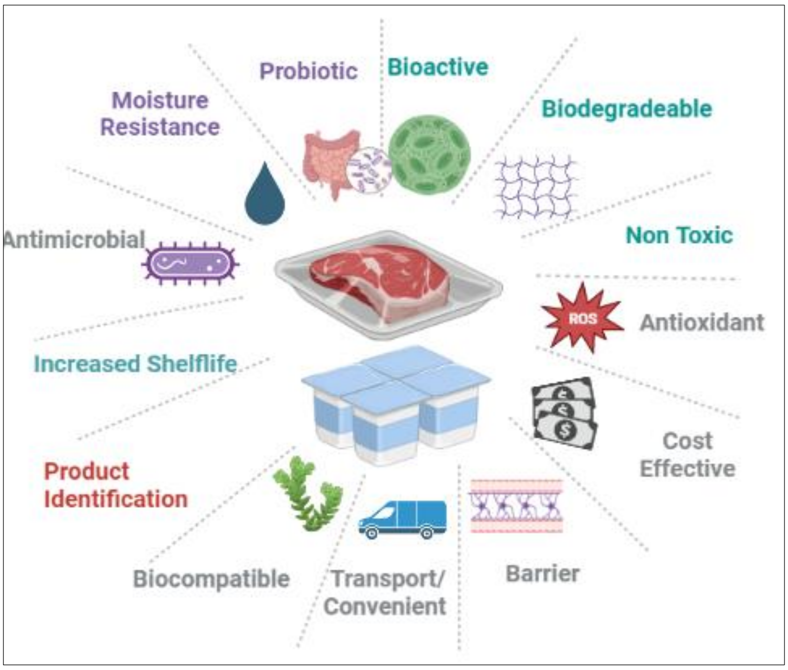


Fig 1: Schematic representation showing Demands for advanced food packaging (Phothisarattana & Harnkarnsujarit, 2022) [27]

Fabrication methods for cellulose-based food packaging

1. Solvent casting is a common method for making biopolymer films in labs and on pilot scales. The process includes three main steps: (i) dissolving the biopolymer in a suitable solvent, (ii) placing the solution into a mold or on a Teflon-coated glass plate, and (iii) drying the solution to help the solvent evaporate. Unlike melt-processing, this method relies on the solubility of the polymer instead of heat (Flórez *et al.*, 2023) [11]. Drying tools like hot air ovens, tray dryers, vacuum dryers, and microwave ovens help remove the solvent quickly and make it easier to take the film off the mold surface.
2. Layer-by-layer assembly (LBL) is a flexible way to make films and coatings that needs only a little equipment and space. This method lets you build multiple layers, each offering its own advantages and features. It shows good functional, barrier, and physicochemical properties. Several studies have been done on the LBL approach (S. Zhang *et al.*, 2021) [44].
3. Extrusion is a common industrial method for processing polymers, including biopolymers, due to its ability to alter material structure and improve physical and chemical properties. The process usually includes three main areas: (i) the feeding zone, (ii) the kneading zone, and (iii) the heating zone, which is located near the machine's exit (Hyvärinen *et al.*, 2020) [16]. First, film-forming components are placed in the feeding zone and compressed with air. This method is often called a dry process because it requires very little water or solvents.

Application of Cellulose as coating agent for food packaging

Paper is often used for food packaging because it has high mechanical strength and breaks down easily. However, paper's use is limited because it strongly attracts water and oil. Paper has a porous structure made of plant fibers, which creates capillary phenomena. This leads to poor greaseproofing, air permeability, and moisture resistance in paper products. Surface coating method has several benefits compared to wet-end forming, making it more suitable for commercial manufacturing. These benefits include better filler retention, reduced production costs, and a lower risk when scaling up. Consequently, it has become a popular option for enhancing the functional and mechanical properties of cellulosic paper. Paper packaging made of cellulose, including paper boards, paper bags, and paper cartons, has great potential in the packaging industry due to its biodegradability, flexibility, and renewability (Semple *et al.*, 2022) [33]. Polymers are commonly used to enhance the strength and barrier properties of the original paper in order to correct its flaws. To enhance the physical characteristics of paper coatings, certain synthetic polymers were used, including waxes, fluorocarbons, polyethylene, and polyvinyl chloride. However, this led to a loss in biodegradability and recyclability. A more eco-friendly approach to the problems related to porous cellulose-based materials is to coat them with bio-based resources like cellulose (Yadav *et al.*, 2024) [40].

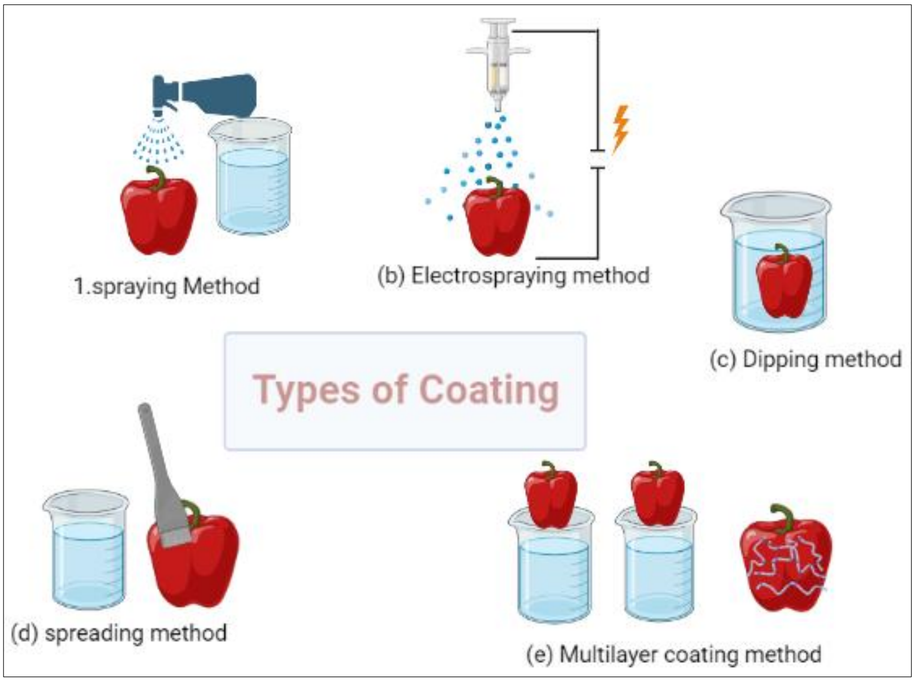


Fig 2: Schematic representation of active edible coating and their different types 1. Spraying method 2. Electrospraying method, 3. Dipping method, 4. Spreading method, 5. Multilayer coating method (Pirozzi *et al.*, 2021) [28].

The acetylation reaction significantly reduces the moisture-absorbing properties of cellulose. This makes acetylated cellulose suitable for paper coatings and food packaging. Researchers developed a strong, antibacterial paper by coating Kraft paper with acetylated cellulose solutions containing different amounts of cinnamaldehyde. When tested against Staphylococcus aureus and Escherichia coli, the coated paper showed excellent antibacterial and antioxidant properties. Cellulosic paper is a flexible, renewable, and biodegradable material made mainly from cellulose sourced from various natural materials. It is widely used in food packaging (Yang *et al.*, 2023) [41]. However, cellulosic paper has its limits. It has a porous structure, poor resistance to microorganisms, and low mechanical qualities. These factors make it hard to stop moisture and oxygen from getting in, which shortens the shelf life of food products. Nanofibrillated cellulose (NFC) is a bio-based nanomaterial that is gaining attention in coating preparation due to its unique properties (Jin *et al.*, 2021) [17]. Microcrystalline cellulose (MCC) is homogenized under high pressure to create NFC. After that, it is used as a coating agent to improve the properties of coated paper and paper coatings. The results revealed that the paper coatings had a significant dependence on NFC concentration regarding rheological behavior. Additionally, the water retention value decreased as more NFC was added. Meanwhile, adding NFC minimized the Cobb value, improved air resistance, and increased the tensile strength of coated paper. Nanofibrillated cellulose (NFC) is therefore regarded as an efficient coating agent for creating high-performance coated paper appropriate for use in food packaging. The mechanical, thermal, and barrier characteristics of porous paper substrates that were dip-coated with nanocellulose (NC) were assessed. To enhance toughness, sorbitol plasticizer was used along with a citric acid crosslinker to improve the coatings' moisture stability. Plasticized nanocellulose (NC) coatings significantly improved the barrier qualities, lowering water vapor permeability by as much as 60%. Cellulose acetate (CA) is a derivative of cellulose (Herrera *et al.*, 2017) [15]. Coating solutions were made with ethyl acetate/ethanol, cellulose acetate, and different amounts of gallic acid (GA). It was coated onto a paper substrate one layer at a time and then dried at room temperature. When it was exposed to higher alkaline pH levels in the presence of oxygen, the label changed colour from green to yellow. This change is shown in the UV-visible spectra and occurs because of a change in the structure of GA.

Active packaging

Labuza coined the term "active packaging" in 1987 to describe packaging systems that do more than merely act as a passive barrier to outside influences. Active packaging engages with the product or its surroundings to improve quality or prolong shelf life, in contrast to intelligent packaging, which offers details about the food's condition or history. Common examples include oxygen scavengers, carbon dioxide emitters and absorbers, moisture and ethylene absorbers, ethanol emitters, flavor-releasing or absorbing systems, time-temperature indicators, and antimicrobial coatings (Labuza & Breene, 1989) [18].

Table 1: Table representing earlier work on cellulose and its applications in food packaging, along with other biopolymers and Bioactives

SI. No	Product	Cellulose extracted	Biopolymers	Add on/matrix	Conclusion	Reference
1.	Cellulose nanocrystals	water hyacinth (CNC)	polyvinyl alcohol (PVA)	Gelatin	1. The strength of films is between 7 and 14 MPa. 2. Elongation at break between 45% and 81% 3. The film's thermal stability was raised to 385 °C. 4. Moisture uptake from 22.5% to 19.05% improved water barrier property	(Oyeoka *et al.*, 2021) [26]
2.	Cellulose nanofibers	birch kraft pulp		aloe juice carboxymethyl cellulose	1. Increased the tensile strength 21-fold 2. Antibacterial activities against E. coli and S. aureus 3. Shelf life of fresh pork 4. Increase the thermal stability and glass transition temperature	(C. Zhang *et al.*, 2021) [43]
3.	Bacterial nanocellulose (BNC	Gluconacetobacter sacchari	poly(sulfobetaine methacrylate)	poly(ethylene glycol)	Antimicrobial activity, moisture-scavenging capacity, and UV-barrier qualities	(Vilela *et al.*, 2019) [38]
4.	Cellulose nanocrystals cellulose nanofibrils	Rice straw poplar wood			Thermal stability	(Rostamabadi *et al.*, 2024) [31]
5.	Cellulose acetate			bacteriophage	Antimicrobial activity	(Rostamabadi *et al.*, 2024) [31]
6.	cellulose nanocrystals		polylactic acid (PLA	green tea extract	1. Reduction in of oxygen transmission ratio and water 2. Vapor permeability 3. Optimal macroscopic mechanical behaviour 4. Enhanced barrier properties.	(Vilarinho *et al.*, 2021) [37]
7.	cellulose nanofibrils		polyvinyl alcohol (PVA)	alizarin	Tensile strength ,thermal stability, water colour sensitivity and contact angle	(Chen *et al.*, 2021) [7]
8.	Bacterial cellulose		poly(3-hydroxybutyrate)	Clove essential oil (CLO)	1. No trace of oil permeation 2. Resistance to folding 3. Hydrophobicity 4. Microbial growth 5. Better mechanical 6. Thermal properties,	(Chen *et al.*, 2021) [7]
9.	cellulose nanocrystals			chitosan	1. improved thermal stability 2. oxygen barrier 3. water vapor permeability 4. mechanical properties 5. bactericidal effect 6. fungicidal activity 7. prolong its shelf-life	(Albuquerque *et al.*, 2021) [1]
10	Cellulose Nanocrystal			1. Hydroxypropyl guar 2. 1-butyl-3-methylimidazolium chloride 3. Anthocyanin	1. permeability to water vapor and oxygen, 2. Resistance to solvents 3. Durability 4. Resistance to low temperatures	(Meng *et al.*, 2020) [21]
11.	cellulose nanofiber			1. zinc oxide nanorods 2. grapefruit seed extract	1. Highly transparent 2. Improved ultraviolet blocking 3. Vapor barrier properties 4. Antimicrobial and antioxidant actions	(Meng *et al.*, 2020) [21]
12.	spray-dried carboxymethyl cellulose	bleached bagasse	polylactic acid (PLA)		1. Prolong mango shelf life about 3 weeks 2. Reduce the respiratory rate and physio-chemistry parameters	(Meng *et al.*, 2020) [21]
13.	cellulose nanoparticle			1. Propolis ethanolic extract 2. Ziziphora clinopodioides essential oil	1. Increased the minced beef's shelf life by roughly 11 days.	(Shavisi *et al.*, 2017) [34]
13	Carboxymethyl cellulose		Polyvinyl alcohol (PVOH) a	1. Clove oil	2. Increased tensile strength 3. Reduced water vapor transmission rate 4. Negligible oxygen transmission rate 5. Shelf life of 12 days	(Shavisi *et al.*, 2017) [34]

Intelligent packaging

There is growing interest in smart food packaging that provides information on food quality and safety during storage. It also offers features for real-time quality monitoring, such as sensing, detecting, and recording changes in food. Active packaging, which contains active compounds, can improve food shelf life. This type of packaging goes beyond the basic protective features of standard packaging. It enhances the quality, safety, durability, or sensory properties of food by changing packing conditions. The materials used in smart packaging monitor the food's status or the surrounding environment and communicate information to consumers in a clear way (Azeredo & Correa, 2021) [3]. Intelligent sensor-based packaging materials can be classified by the variables they control. These include time-temperature, gas, and freshness indicators. They monitor unwanted temperature changes along the supply chain, shifts in gas composition within the food package, especially in modified atmosphere packaging, and freshness decline through changes in metabolite concentration that indicate microbial growth (Heo & Lim, 2024) [14]. This leads to alterations in the packaging. Cellulose is an interesting and promising bio-based renewable polymer due to its availability and strong physical properties.

One of the most popular smart packaging technologies is pH-responsive colour indicator packaging film. This film can detect changes in food quality in real time with the naked eye. Food freshness indicator films contain colorants that change colour based on pH. Several recent studies have focused on creating and characterizing these colour indicator films. a biodegradable cellulose ether with a high viscosity, hydroxypropyl methylcellulose (HPMC), forms films. It is frequently added to synthetic films to improve their mechanical strength and flexibility. The mechanical limitations of konjac glucomannan (KGM) are compensated for by HPMC. The KGM-HPMC (KH) matrix's mechanical qualities and UV resistance are greatly enhanced by the addition of mangosteen peel extract (MBE). Interestingly, almost all UV light in the 200–600 nm range was blocked by the KHMBE-20% coating. According to Table 37, this 20% MBE formulation also showed the highest level of improved antibacterial and antioxidant activity. Parallel to this, berries' natural pigments called anthocyanins have drawn interest as potential pH-sensitive markers because of their striking colour shifts. In order to create a colorimetric pH indicator that can be used to detect spoilage in pasteurized milk, this study investigated the use of anthocyanins (ABC) extracted from black carrots as a chemoresponsive dye integrated into a cellulose–chitosan matrix (Ebrahimi Tirtashi *et al.*, 2019a) [8]. Cellulose paper was soaked with a sol-gel chitosan solution that included ABC, which has a total anthocyanin concentration of 10 mg per 100 mL. The results showed that ABC was trapped in the polymeric indicator matrix. This did not significantly affect the samples' chemical and supermolecular structure. In food testing, fresh pasteurized milk changed color from blue to violet rose after 48 hours of storage at 20 °C. This change was easy to see. The findings indicated that the indicator could be used to test the freshness and spoilage of milk with food-grade biomaterials. A sol-gel chitosan solution containing ABC, with a total anthocyanin concentration of 10 mg/100 mL, was used to soak cellulose paper. The analysis confirmed that ABC was successfully retained in the polymeric indicator matrix, and the samples' chemical and supermolecular structures remained unchanged. Fresh pasteurized milk showed a clear color shift from blue to violet rose during the food test after 48 hours at 20 °C. This change was obvious to the naked eye. The results suggested that the indicator could effectively check the freshness and spoilage of milk using food-grade materials (Ebrahimi Tirtashi *et al.*, 2019a) [8].

Table 2: Table depicting the cellulose along with other compounds in food packaging to measure the freshness of food from difference in PH and colour change

Combination	PH	Colour	Source/Reference
MBE+KGM+HPMC (KH)	pH 2 to 12	Purple to gray to yellow	Fish(You *et al.*, 2022a) [42]
Anthocyanin-rich pigment+Cellulose paper+chitosan solution	pH 2–11	Pink to khaki	Milk(Chen *et al.*, 2021) [7]
Anthocyanins of red cabbage+bacterial cellulose+polivinyl alcohol	pH 1–14	Red to purple blue-gray to yellow	Milk (Hailu *et al.*, 2025) [13] freshness
Cellulose nanofibrils + polyvinyl alcohol+ alizarin	pH 6–7 up to 8	Yellow to orange yellow to purple	Chicken (Boonsiriwit *et al.*, 2022) [4]
Hydroxypropyl methylcellulose+ butterflypea+ anthocyanin		Purple/violet to blue, green ocean	Scomber scombrus (fish)
Cellulose nanocrystal-silver nanoparticles		Yellowish to dark wine-red color to metallic grey	Chicken breast (You *et al.*, 2022b)
Cellulose nanocrystals (CNCs) and nano-fbrillated cellulose (NFC)+ Anthocyanins (red cabbage)	Acidic to neutral or alkaline range	Light purple to green	Shrimp (Ebrahimi Tirtashi *et al.*, 2019a) [8]
Cellulose Nanocrystal+1-butyl-3-methylimidazolium chloride+ anthocyanin +hydroxypropyl guar (HPG	2.0 to 12.0	Red to light purple to olive	Chicken breast (Ebrahimi Tirtashi *et al.*, 2019b)
cellulose nanocrystals+ Polyvinyl alcohol + purple cabbage anthocyanins	pH (2−13)	purple to gray blue upon deterioration	Shrimp (Zheng *et al.*, 2024) [45] freshness
bacterial cellulose+ pelargonidin	pH3− pH10	red to blue	Tilapia fillets freshness (Zheng *et al.*, 2024) [45]

UV-protection films made from renewable materials are among the most promising options for the packaging industry. The modified lignin and cellulose nanocrystals came from the Argania nutshell. The films showed maximum UV light absorption in the 450-200 nm range and performed well for food packaging. To detect and preserve shrimp in real time, researchers created a film using anthocyanin-rich purple potato extract (ANT), thymol (THY), and 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO)-oxidized bacterial cellulose (TOBC). The

TOBC/THY/ANT composite film showed strong antibacterial properties, antioxidant effects, and the ability to change color based on pH. To check the film's recyclability and performance consistency, these features were tested over three reuse cycles. The results indicate that TOBC/THY/ANT holds great promise for use in commercial shrimp packaging with real-time spoilage monitoring. (Wen *et al.*, 2021) [39].

Conclusion

This review discusses how cellulose and its derivatives contribute to smart and active food packaging systems. Cellulose is one of the most promising bio-based materials for making films. It is a naturally occurring, biodegradable, and readily available polymer. Cellulose films have several beneficial properties, such as probiotic, antioxidant, and antibacterial activity. These qualities make them great for food packaging. Despite these advantages, the widespread use of cellulose films in industry is still limited by their mechanical and barrier properties compared to more conventional plastic packaging materials.

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