Chapter 6

Biodegradable Films for Mitigating Food Contaminants Through Sustainable Packaging

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ABSTRACT

Preserving food flavor, freshness, and nutritional content is possible through careful packaging, which accounts for physical, mechanical, and epidemiological aspects. Unfortunately, the accumulation of non-biodegradable waste is a direct result of the conventional packaging's use of non-renewable fossil fuels, which harms the environment. Therefore, biodegradable films for food packaging are in high demand; they provide a cost-effective solution that meets industry standards while maintaining food safety, and consumers are becoming more conscious of the importance of purchasing sustainably sourced, high-quality food. Learn why biodegradable films are crucial for food safety and how they function in packaging. Biodegradable

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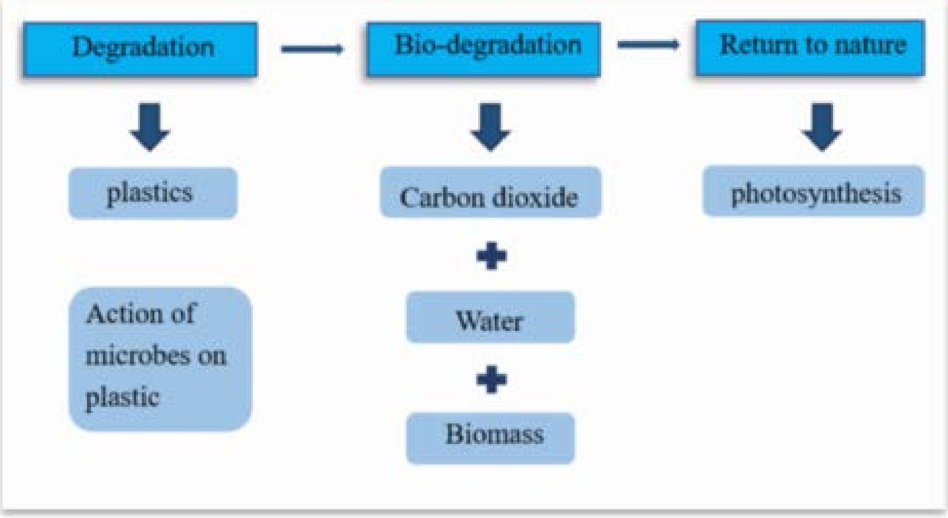
polymers derived from polysaccharides are the focus of this research, along with their application in multi-criteria food packaging and the success or failure of developing smart biodegradable films.

1. INTRODUCTION

Packaging is a significant challenge for the food industry. It protects food goods from physical, mechanical, and epidemiological factors that affect their taste, safety, and nutritional value of food items (Peelman et al., 2013). Metal, glass, and plastic are the most frequently used materials in food packaging (Díaz-Montes, 2022). The use of plastics for food packaging has increased at an average rate of 5% per year and is currently the second dominant material used in food packaging in recent decades (Adeghizadeh Yazdi et al., 2019). However, there are some restrictions on the use of plastics because they degrade more slowly than other materials, thereby polluting the environment (Sorrentino et al., 2007; Xu et al., 2005). Some of the adverse effects of plastics on ecosystems involve the contamination of animals on land and in the sea, as they decompose. Plastic waste is also believed to adversely affect or kill aquatic organisms, causing concern for the food chain and possibly resulting in extinction. Consequently, packaging made from the synthesized materials was used only once, before being discarded. Surveys show that, despite the adverse effects of plastic disposal, the use of petroleum-derived packaging drives about 37% of total plastic usage (Briassoulis, 2004; Europe, 2015;). Research is also underway to identify rapidly biodegradable materials suitable for food packaging to solve the problem of plastic elongated degradation (Jimenez et al., 2012).

Cellulose, pectin, chitosan, and starch are naturally biodegradable polymers that can be used as alternatives to plastics in food packaging. Based on these biodegradable polymers, these biodegradable films are seen as substitutes for conventional food packaging since they can prolong the storage lifetime of unprocessed food and maintain its quality. (Acevedo-Fani et al., 2017). To facilitate disintegration, biodegradable films are bio-assimilated using a process that reduces the polymer chains into smaller subunits or dimer units (Zoungranan et al., 2020). The degradation process of biodegradable films is much more straightforward than that of plastics, as illustrated in the flowchart below (Figure 1). Moreover, biodegradable materials outperform plastics in terms of their environmental friendliness. This is because biodegradable materials disintegrate after disposal, thereby producing new agricultural products (Xu et al., 2005).

Figure 1. The process of biodegradation



The incorporation of antimicrobial compounds and nanoparticles and the use of pH-indicating colors to assess food shelf life can increase customer preference for recyclable packaging. This article provides an overview of food packaging, including the attributes and requirements of biodegradable films to qualify as Packaging for food resources.

The food industry faces significant challenges in maintaining food safety and quality throughout the supply chain. Packaging plays a crucial role in protecting food from physical, chemical, and microbiological hazards that can compromise its nutritional value, taste, and safety (Peelman et al., 2013). However, conventional packaging materials, particularly petroleum-based plastics, present major limitations in ensuring long-term food safety and environmental protection (Díaz-Montes, 2022). Plastics have become dominant in food packaging due to their flexibility, durability, and low cost. Yet, their widespread use raises environmental and health concerns. One of the critical drawbacks of plastic packaging is its persistence in the environment. Plastics degrade extremely slowly, leading to accumulation in terrestrial and aquatic ecosystems. This waste can break down into microplastics, which infiltrate the food chain, posing risks to human and animal health (Sorrentino et al., 2007; Xu et al., 2005). Plastic waste harms marine life, disrupts aquatic ecosystems, and introduces bioaccumulative toxins into the food web. Additionally, plastics often contain additives such as plasticisers and stabilisers that can migrate into food, raising food safety concerns (Jimenez et al., 2012). Recycling rates for plastics remain critically low, with only about 10% being recycled, while the rest contributes to pollution through landfilling or incineration (Briassoulis, 2004; Europe, 2015).

The production of plastics, derived from non-renewable petroleum resources, is energy-intensive and environmentally damaging, exacerbating pollution and waste management issues, especially due to the prevalence of single-use plastics.

Biodegradable films are derived from renewable resources, are inherently biodegradable, and do not accumulate in ecosystems. Functionally, they serve as effective barriers against microbial contamination and oxidative damage, thereby extending the shelf life of fresh and minimally processed foods (Yadav et al., 2018). Moreover, incorporating active agents like antioxidants, antimicrobials, and pH-sensitive indicators can enhance their protective capabilities, transforming passive films into active and intelligent packaging systems (Díaz-Montes, 2022). These bio-based films degrade through enzymatic or microbial action into natural monomers, integrating harmlessly into ecological cycles and avoiding long-term environmental persistence (Zoungranan et al., 2020). As such, biodegradable films address both food safety and environmental sustainability challenges, presenting a promising solution to replace non-degradable plastics in food packaging. Ongoing research into active and intelligent biodegradable films could significantly advance the development of safer and more eco-friendly food packaging technologies (Xu et al., 2005; Díaz-Montes, 2022).

2. FOOD PACKAGING

Food packaging aims to preserve and safeguard all types of food and their constituents, particularly against aerobic and microbiological decomposition (Tharanathan, 2003). Food packaging is defined as any wrapping or coating that protects food from physical, mechanical, and epidemiological factors that affect the taste, safety, and nutritional value of food items. Physical contamination refers to any exterior material (such as lumps or bits of glass, plastic, or wood) that enters food and is usually connected with filthy circumstances throughout the processing, manufacture, transportation, and shipment of food goods. However, on the contrary, when food additives, such as flavorings, pigments, and sweeteners, or other chemicals, such as sterilizers and surfactants, are present, chemical contamination can occur during manufacturing, production, and preservation. Biological contamination is defined as the presence of microbes or harmful insects that produce toxins that can cause illness (Alexandre et al., 2019). The packaging of food products is classified into three types based on their protective abilities: passive, active, and intelligent packaging.

2.1. Passive Packaging

Standard food packaging must be safe for the food it holds, meaning it shouldn't change the food in any way. They are called passively protected baggage because their primary purpose is to offer physical protection from things like the climate, chemicals, and damage, along with blocking gases and moisture. (Díaz-Montes, 2022).

2.2. Active Packaging

Packaging food intentionally modifies the conditions inside the package or container to guarantee its quality of the food (Stoma et al., 2022). Active packaging comprises of absorbers and emitters. Absorbers absorb and release food-derived molecules such as moisture, the chemical ethylene, and carbon dioxide into their surroundings and emit biologically active compounds such as bacteria and anti-oxidants, both of which improve the longevity of food (Díaz-Montes et al., 2021).

2.3. Intelligent Packaging

This type of wrapping involves a system that monitors, generates, and displays information based on enzymatic properties, weather conditions, irradiation time, and physical responses to meals (Wilson, 2017). Chemical sensors or biosensors are used in intelligent packaging to maintain the factors that affect food condition, such as ripening, freshness, temperature, oxygen content, humidity, and various gases (Stoma, 2022).

2.4. Biodegradable Films in Food Packaging

The first bioplastic material to be produced was biodegradable alimentary packaging, which was successfully commercialized and verified as commercially biodegradable. The demand for bioplastics for food wrapping has rapidly increased. While strong packaging predominantly leads to recyclable packaging, soft packaging typically uses decomposed polymers. In addition, different fruits and vegetables are preserved under altered air conditions using recyclable polymers (Yadav et al., 2018). These films were originally intended to replace the plastic packaging. They have characteristics that are superior to those of nonbiodegradable polymers. .

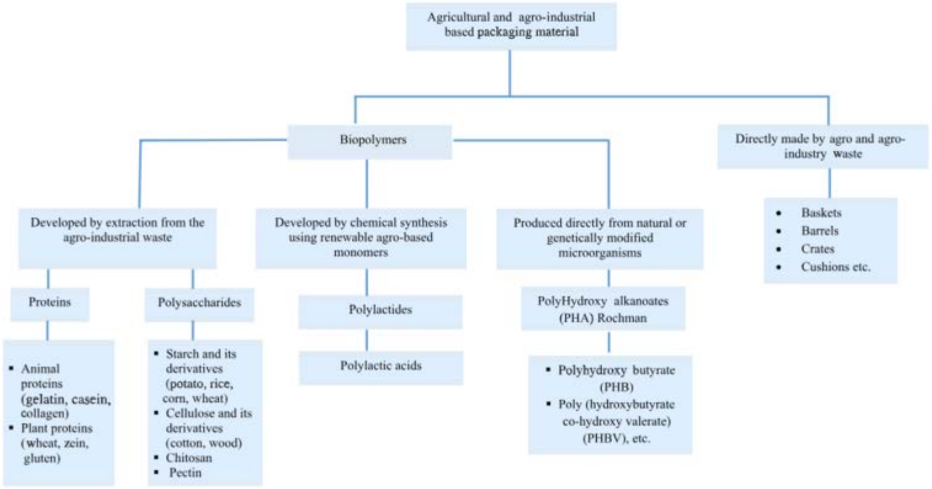
2.5. Essential Characteristics of a Good Packaging Film

Allowing regulated ventilation is a crucial feature of a good packaging film with excellent shielding qualities, which is beneficial in retaining the stability of the structure and halting or slowing the growth of pathogens.

3. NATURAL POLYMERS IN BIODEGRADABLE FILM FORMULATIONS

Biodegradable films can be formulated using different compositions of naturally degrading polymers, including starch, cellulose, chitosan, and pectin. All of these polymers can be obtained from agro-industrial wastes, which have been generated consecutively over the last few decades. By the end of 2050, the global population is expected to exceed 10 billion people. Countries worldwide are intensifying their efforts to boost food manufacturing to meet the world's constantly expanding population in the future. This could encourage the industrialization of agriculture and related areas, which would also increase waste generation (Duque-Acevedo et al. 2020). The management and disposal of these wastes are serious environmental concerns that must be addressed sustainably (Bharathiraja et al., 2017). Agricultural waste includes leaves, stalks, and pods of seeds, as well as processing waste, such as husks, grains, root systems, maple syrup, and vegetable and fruit skins. Although an immense amount of agricultural waste is generated worldwide, most of it remains unutilized. For example, many researchers have used various agricultural and industrial wastes to create biodegradable packaging materials. Cellulose (35-50%), hemicellulose (15-30%), and lignin (20-30%) are the major components of agricultural waste. The composition of these wastes is determined by the type of agricultural waste and the crop species. Hemicellulose derived from wheat straw is an excellent source for the development of organic alimentary packaging with low moisture content (Obi et al., 2016). Biodegradable packaging materials created using various agroindustrial trashes are classified into two types: (a) packaging materials created using current plastic production technology directly from agro-industrial waste and (b) biopolymers created using polymers derived from agricultural and industrial waste (Figure 3). Biopolymers are also divided into three types, as illustrated in figure 2 (Chiellini et al. 2008).

Figure 2. Classifications of biopolymers



3.1. Starch

Starch is a carbohydrate used for the preservation of vegetables originating from crop leaves and storage space tissues. Although it is also present in tuber roots, it can also be found in amyloplasts of grain endosperms, wheat, corn, potatoes, and other grains, which are some of the other good examples of starch sources (Tagliapietra et al., 2021). Among natural polymers, starch has great potential because of its natural ability to break down, its supply, and its yearly renewal. It is frequently recognized as an effective substitute for plastics in food packaging. Additionally, a biodegradable film made of starch can be utilised for wrapping a wide range of commodities, including fruits, vegetables, refreshments and dry goods using starches in sustainable packaging to their multiple benefits which include their contribution to Having no poisons, extraction from plant-based materials (renewable resources), biodegradable and biological compatibility, affordability and availability of starch, suitability for usage in edible food packaging, use as an environmentally acceptable disposal solution, and no net increase in CO_2 in the atmosphere are all advantages of starch. However, they have several disadvantages such as weak mechanical qualities, restricted water rigidity, porous permeability restriction, and brittleness at room temperature. To overcome these disadvantages, starch can be used as a matrix with other natural polymers, such as cellulose, pectin, and chitosan, to create compostable packaging with excellent mechanical properties and water stability to overcome these disadvantages (Adeghizadeh-Yazdi et al., 2019).

The two polysaccharides, amylopectin and amylose, which are both composed of α-d-glucose and are connected by (1–4) glycoside linkages, make up the majority of starch. Amylose, a linear polymer with a helicoidal shape, is one of these two components in starch granules and accounts for approximately 20-25% of the starch content. Amylose is a mildly water-soluble polysaccharide that occasionally has branches. Amylopectin, however, is a polysaccharide that has many branches with a reducing tail connected by α (1-6) glycosidic linkages and accounts for 70-80% of starch (Eliasson, 2004). Biodegradable bioplastics can be produced from starch in four ways. The initial approach was to increase the degradation ability of the final biopolymer by adding a small amount of starch to a standard petroleum-based polymer. The second method involves using more than half the quantity of starch to create a starch composite. The third is extrusion treatment of changeable granular starch to produce starch. The fourth method involves the creation of starch nanocomposites using nanoparticles is the fourth method (Birania et al., 2022).

3.2. Chitin/Chitosan

Crustacea, insects, and other species use naturally occurring mucopolysaccharide chitin as a support structure. Approximately six million tons of crabs are caught in both the inland and coastal oceans. Chitin usually appears in fungal cell partitions and differs only in the cellulose alcohol group. Saccharomyces and mushrooms are two other dietary sources of chitin in addition to crustaceans and insects. Chitin, a white, diligent, and inelastic nitrogenous polymer, is a significant contributor to atmospheric contamination of coastlines (Kumar 2020; Birania et al., 2022).

However, chitin cannot be effectively used as an early ingredient in bioplastics owing to its poor solubility. Crustaceans, insects, arthropods, and mollusks contain large amounts of chitin, which is a cationic polymer created upon chitin deacetylation (Klinger et al., 2019). As stated by Shaala et al. (2019) and Ehrlich et al. (2018), Deproteinisation, calcification, and decolorisation are steps used in naturally occurring extraction platforms to eliminate chitin from other substances. Chitin is deacetylated to produce chitosan. These polymers can also be processed using microbe-based biological extraction methods. Depending on their specific use, chitin and related compounds can be used as gel-like substances, beads, barriers, films, or sponges (Klinger et al., 2019; Wysokowski et al., 2013). Reuse of waste from the shipping industry is not recommended, and a sizable portion of the generated biomass is released into the untreated atmosphere (Wang et al., 2019).

The seafood industry generates about 104 tonnes of waste each year. Most of this waste is either turned into compost or made into low-value goods like animal feed and fertiliser. Around 2000 metric tonnes of chitin are produced each year, mostly from leftover shells of prawns and crabs. (Muñoz et al., 2018; Santos et al., 2020). To extend the shelf life of fruits and vegetables, chitin and chitosan have been used to create recyclable edible antimicrobial packaging. Chitosan can be used to prepare films without any additives and has excellent atmospheric carbon dioxide and oxygen permeability, outstanding physical capabilities, and antibacterial properties that are effective against molds, bacteria, and yeast. However, chitosan is incredibly sensitive to moisture (Kumar et al., 2017). Gram-positive and gram-negative bacteria, fungi (molds and yeasts), and other spoilage and pathogenic microorganisms are resistant to the antibacterial and antioxidant capabilities of chitosan (Kaur et al., 2021; Díaz-Montes et al., 2022).

3.3. Pectin

Plant cell walls contain pectin, a structural polysaccharide with High molecular weight materials can be changed into a hydrogel, which forms a stretchy web of polymer chains. It is a complex sugar that plays key roles in plant growth and development, helping plants stay strong and safe from their surroundings. The main and most valuable sources of pectin come from citrus fruits, apples, and the leftover materials from their processing, like citrus peels and apple pulp. Cocoa leaves, pumpkins, watermelons, pears, and potato pulp are other sources of pectin. Pectin can come in different forms based on where it comes from or how it is extracted. It is a type of polysaccharide that can be recycled and has natural organic qualities. (Freitas et al., 2021). When esterification was greater than 50%, pectin was classified as high-methoxyl or high-ester pectin; however, pectin was classified as low-ester or low-methoxyl when esterification was less than 50%. The degree of ester formation is defined as the proportion of d-galacturonic acid carboxyl groups esterified with ethyl alcohol (Wang et al., 2018). Rhamnogalacturonan I (RGI), Rhamnogalacturonan II (RGII), and xylogalacturonan (XG) are three subdomains constituting the complex structure of pectin. Pectin undergoes chemical, physiological, and/or enzymatic changes, and the numerous functional groups present in its structure can stimulate various functionalities and alterations that enable its use in food, farming, drugs, and biomedical research. Currently, pectin is used to create nanoparticles, antimicrobial bio-based films, therapeutic agents, and cancer treatments, as well as coated foods to protect food (Tharanathan et al., 2003). Pectin has poor mechanical properties and low thermal ability, which are drawbacks when used in biodegradable packaging. It can be combined with other plastics to make these qualities better. Hydrothermal treatment extraction is the most common way to remove pectin. The pectin in the solvent was dissolved when the dehydrated and pulverized crop residue was dispersed in acidulated water (hydrochloric or nitric acid). Pectin is precipitated by adding alcohol after pectin-containing water is separated (Valdés et al., 2015). Then, it was dried to separate the pectin. Other techniques for pectin extraction include enzyme-assisted, subcritical water, and ultrasound-assisted extraction.

3.4. Cellulose

One of the most common polymers on Earth is cellulose, which can be readily synthesized from plant cell partitions. Payene was the first cellulose to be identified. Cellulose is an inexpensive commodity with strong demand in the global market owing to its high durability, especially in the agricultural and clothing sectors. An enormous amount of agricultural waste, including fruits, vegetables, cotton twigs, and debris from forests, is being dumped into the environment. This waste must be subjected to several recycling processes. The derivation of cellulose from these waste products is one of the rarest and the most important methods. Cellulose and nanocellulose fibers (NC), as well as their derivatives, are becoming increasingly popular in the food packaging sector due to its unique characteristics, biodegradability, and enhanced structural and physiological capabilities (Liu et al., 2021). Cellulose functions as an armour against UV rays and possesses significant heat tolerance. Antioxidant benefits and antibiotics can be transported. They are also disposable and reusable, and because They are resistant to corrosion, combustible, and non-toxic, suitable for the fabrication of various composites of polymers.. Additionally, it is readily accessible and priced worldwide. However, the disadvantages of cellulose and its derivatives include substantial water absorption and inadequate surface adherence (David et al., 2019). These limitations have led to extensive scientific research on cellulose.

It is simple to encapsulate other artificial and organic polymers into cellulose. Traditionally, paper is made using cellulose. Additionally, cellulose can dissolve because of its composition, and this inflammatory activity results in hypersensitivity when it interacts with liquids (Dai et al., 2019). It prolongs the period of storage of food and maintains the high standards of unpackaged products. Furthermore, cellulose serves as a material for packaging with obstacle characteristics that restrict the movement and transmission of solutes, lipids, gases, and moisture.

Additionally, they help to retain the structure, enhance mechanical transportation, and delay the demise of chlorophyll, which maintains the color of the food. Additionally, they act as a means of incorporating various food additives, aiding in the avoidance and reduction of microbial deterioration during long-term food storage (Abdul Khalil et al., 2018). Wood is The main source of cellulose. Wood pulp can be used to make cellulose, which has many uses. A prevalent source is cotton, mostly utilised for the production of threads and garments. Cotton blossoms contain cellulose. The outer layers of various grains, maize kernels, wheat bran, and many other sources of bacterial cellulose, water crops, certain types of grasses, agricultural byproducts, factory trash, food wastes, food leftovers, peels of different fruits and vegetables, and many other materials contain cellulose (Zhao et al., 2019; Zhong et al., 2020). Cellulose can be extracted using a modified acid hydrolysis process. Anhydro glucose units (AGUs), which are (14)-linked d-glucose units, are comprised of cellulose molecules. Every second, the AGU along the chain plane twists by 180° because of -linkage. AGU is the recurring unit of cellulose. Strong intramolecular and intermolecular H-bonds were generated as a result of each AGU having three hydroxyl groups, and these H-bonds give rise to the semi-crystalline structure of cellulose, which includes crystalline cellulose (Heinze et al., 2018).

3.5. Additives in Biodegradable Films Formulations

Some of you can enhance the features of biofilms by adding substances like plasticisers, crosslinkers, or active biological components. (Shit et al., 2014). Crosslinking agents, including stimuli (such as pH and electrical changes) and biomolecules (such as ions and enzymes), can enhance the mechanical, biological, and chemical characteristics of polymers substances (Rouhi et al., 2017). According to Suderman et al. (2018), glycerol, sorbitol, xylitol, and fructose are the plasticizers most frequently used in biodegradable films because they alter the thickness of the film and enhance its mechanical (e.g., fragility and flexibility), physicochemical (e.g., solubility), Heat and obstruction properties (e.g., gas absorption). The communication between a plasticizer and a polymer is governed by one of them. For instance, according to Sanyang et al. (2016), adding plasticizing agents (glycerol and sorbitol) to the process of creating sugar palm starch films decreased the fragility and retention of water, while improving solubility and wetness. Further research by Kaewprachu et al. (2018) revealed that the addition of a plasticizer enhanced fish protein film stretching, humidity, and vaporized water permeability. This is because cross-linking cannot occur owing to the hydrophobicity of the lipids. Chitosan is an acetylated polymer that must have a substance that crosslinks to acidify its environment and encourage protonation (Díaz-Montes et al., 2021), allowing it to interact with other polymers and create biodegradable films (Deshmukh et al., 2021). As genipin triggers nucleophilic interactions between the peptide and carboxylic bonds in a neutral acid solution, which might result in films that degrade owing to intermolecular contacts, it is frequently used as an agent for crosslinking amino polymers or proteins (Roy et al., 2022). Additionally, biodegradable films can include molecules with potential health effects, known as bioactive chemicals, which come from biological sources and have antibacterial, antifungal, antioxidant, or probiotic capabilities. Polysaccharides (such as starch, cellulose, pectin, and chitosan) are some of the commonly utilised monomers for the fabrication of films that decompose because of their capacity to dissolve in water, manageability (i.e., sources and costs), and properties (i.e., nontoxicity, biodegradability, and bioactivity).

3.6. Standardisation and Safety Issues of Polysaccharide-Based Biodegradable Films

Various rules must be followed when packing food items or objects that come in contact with food. Depending on where they are manufactured, sold, or marketed. However, each country has its national regulatory entity with basic regulations that can be broadly enforced. The primary role and goal of these regulatory entities worldwide is to ensure food safety, and food packaging is generally recognized as safe (GRAS) (Galus et al., 2020). Films derived from polysaccharides such as starch, cellulose, chitosan, and pectin are inherently non-toxic and biodegradable; nevertheless, additions including plasticisers, crosslinkers, and antimicrobial agents must adhere to food-grade standards to mitigate contamination hazards. Films containing bioactive compounds must ensure that their functional doses do not jeopardise food safety. Moreover, structural integrity is essential to avert physical contamination resulting from film degradation or particulate emission. Inadequate mechanical qualities may result in ruptures or disintegration during manipulation, posing a risk of direct food contamination. The combination of various polymers and meticulous additive selection improves film strength and barrier characteristics, successfully obstructing microbiological, chemical, and physical pollutants.

The food-grade label can be obtained using a variety of methods, including (1) the list of items that fulfil food-grade standards and (2) the examination of compounds used in the manufacturing of food or food packages. (3) Experts outside the organisation evaluate the goods. and (4) publishing research on a novel food-grade substance or package (FDA, 2023; Alamri et al., 2021). All marketed food products must truly reveal that the consumption of food additives, such as colours and flavours, is controlled by government agencies. For example, the European Union and Mexico require that food products use only approved ingredients. If goods contain allergens, such as proteins, they must be listed. Films that degrade polysaccharides must be labelled GRAS chemicals. Additives in the mixture must meet the needed element standards.

While “bioactive” films decomposing need to ensure that extra substances like oils, antioxidants, or antimicrobials do not pose toxicity issues when employed in the dosage specified. Food or food packaging substances can reach the market with the consent of regulatory organizations once they meet all these requirements and pass the quality tests of the regulatory authorities.

4. NATURAL COLORANTS IN BIODEGRADABLE FOOD PACKAGING

The objective of food packaging is to maintain the nutritional value while safeguarding food goods throughout transit and storage. The four principal roles of packaging are containment, communication, convenience, and protection. (Brody et al., 2008). In addition to these essential functions, food packaging is also required to perform an increasing number of tasks. Therefore, the evolution of smart and clever packaging deserves special attention. Consequently, radio frequency identification, time-temperature indicators, and natural acid-base color pigments that serve as ripeness indicators have been added (Wanihsuksombat et al., 2010). Colorimetric indicators can be attached to the exterior of food packaging or inserted inside packages to detect and observe alterations in the condition of packed products via visible colour variations.

Singh et al. (2018) presented evidence about the possible application of anthocyanins. Additionally, roselle anthocyanins have been proposed as chromatic agents for assessing the freshness of pork in intelligent indicator films composed of starch, polyvinyl alcohol, and chitosan (Zhang et al., 2019). Furthermore, roselle anthocyanins have been suggested for use as coloured components in intelligent films made of starch, polyvinyl alcohol, and chitosan to evaluate pork freshness (Zhang et al., 2019). Consequently, a novel and emerging field is the Utilisation of food colouring in biodegradable plastics as a proactive indicator. The additives. Utilised are permissible for application in the food business; therefore, if they are transferred to packaged food goods, this will not be a problem. A new generation of sustainable, clever packaging components that change colour under regulated maturation (thermos oxidation, UV, weathering) affects the longevity of the packaging material and is made possible by the incorporation of renewable polymers and organic food colorants. Because they are both aesthetically pleasing and functionally beneficial to the container, natural colourants are an important component of biodegradable food packaging. These pigments add natural colour and help keep food safe and fresh for longer; they come from plants including turmeric, beetroot, carrots, leafy greens, and berries. The pH-sensitive colour shifts of anthocyanins (found in berries and roselle) and curcumin (found in turmeric) are used extensively as visual markers of food freshness and deterioration.(Zhong et al., 2020) Beetroot betalains and carrot carotenoids serve as antioxidants and light barriers, respectively, while chlorophyll shields against ultraviolet radiation and kills microbes. Complementing the packaging's antioxidant, antibacterial, and UV-shielding capabilities are chemicals such as flavonoids and anthraquinones.

By mixing these dyes with biodegradable polymers, we can make packaging solutions that are both smart and active, able to track the status of products and cut down on food waste. Aligning with sustainability aims and customer expectations for clean-label packaging solutions, these natural additives are non-toxic and authorised for food-contact applications.(Martău et al., 2019) Natural colourants have several benefits in modern packaging technologies, including the replacement of synthetic dyes and the addition of functional properties to biodegradable films. This helps with environmental conservation and allows for better food safety monitoring. The various natural pigments and their sources are shown in Fig. 11 and in table 1

Table 1. Natural Colorants Utilized in Biodegradable Food Packaging

Natural Colorant	**Source**	**Functionality**	**Reference**
Anthocyanins	Berries,grapes, roselle	pH-sensitive indicator for freshness; antioxidant	Singh et al., 2018; Zhang et al., 2019
Betalains	Beetroot	Color indicator; antioxidant	Zhong et al., 2020
Carotenoids	Carrots, tomatoes	Light barrier; antioxidant	Liu et al., 2021
Chlorophyll	Leafy vegetables	UV-protective barrier; visual appeal	Abdul Khalil et al., 2018
Curcumin	Turmeric	pH-sensitive indicator; antimicrobial	Díaz-Montes, 2022
Anthraquinones	Aloevera, rhubarb	Color stability; antimicrobial	Freitas et al., 2021
Flavonoids	Tea, citrus peels	Antioxidant; UV protection	Martău et al., 2019
Roselle anthocyanins	*Hibiscus sabdariffa*	Intelligent indicator film component	Zhang et al., 2019

5. BIOSENSORS DEVELOPED IN FOOD PACKAGING SENSORS

A sensor detects changes around it and responds based on information from another machine. A sensor turns an actual occurrence into a measurable voltage or sometimes a digital signal. This information is then sent for reading, further processing, or shown on a display that people can understand. Most sensors have two parts: a receptor, which acts as the sensor. This method can identify certain chemicals or physical substances by looking for their presence, activity, make-up, or amount. The sensor, the second part, measures the energy that the receptor changes from physical or chemical information (Mlalila et al., 2016). A transducer was employed to convert the recorded signal into a valuable analytical value. There may be thermal, visual, substance, or electrical indicators. (Kerry et al., 2006).

The majority of detectors have two main parts: one that acts as the sensor and another that is the receiver. This helps identify specific chemicals or physical substances for different reasons, like checking if they are present, how active they are, what they are made of, and how much is there. In the second part, the sensor measures the energy the receptor gets from the chemical or physical data. A transducer converts the recorded signal into an analyzable format. This can be a warning based on light, heat, chemicals, or electricity. O2 was found using a mix of electrochemical, ultrasonic, laser, and infrared instruments (Park et al., 2015). Biosensors are a kind of sensor. They have receptors made of organic parts like enzymes, antigens, hormones, and nucleic acids, instead of chemical sensors. You can use different types of sensors, like electrochemical, optical, or acoustic ones, based on the monitoring needs. The Toxin Guard by Toxin Alert is a device that can identify infections like Salmonella, E. coli, Campylobacter, and Listeria. It uses a special system based on antibodies and is built into packaging that breaks down naturally. Visual cues show that results are successful (Bodenhamer et al., 2004).

5.1. Polymer-Based Biosensors for Bacterial Detection

Bacterial infections are a significant global problem, posing a serious threat to people's health and food safety. Many harmful germs, such as Staphylococcus aureus, Mycobacterium tuberculosis, and Escherichia coli, are present (Zhang et al., 2023) (Table 2). Despite using methods like pasteurisation and ultra-high-temperature sterilisation to kill germs in food, foodborne bacteria are still the leading cause of illness in both rich and poor countries. It's essential to create effective biosensors to detect dangerous germs in food (Kang et al., 2022). Salmonella species, particularly *Salmonella typhimurium*, are prominent foodborne pathogens. Researchers have created optical biosensors for detection utilising polymers like poly-L-lysine and poly(styrene/acrylamide). Poly-L-lysine, renowned for its superior adhesion characteristics, enhances optical biosensors such as those created by Sheikhzadeh et al. (2016). Ding et al. (2022) employed poly(styrene/acrylamide) in optical biosensing systems for the detection of *Salmonella* sp. *Staphylococcus aureus*, a significant pathogen, has been detected utilising poly(3-thiopheneacetic acid) in electrochemical biosensors (Hu et al., 2020), providing improved sensitivity and specificity. Biosensors for Escherichia coli Detection: A primary emphasis in biosensor innovation is the identification of Escherichia coli due to its common occurrence in foodborne epidemics. Optical biosensors employing poly(carboxybetaine acrylamide) were developed for this purpose (Vaisocherová-Lísalová et al., 2016). To augment electrochemical sensing capabilities, alternative polymers including poly pyrrole, polyvinyl pyrrolidone, and graphene-polymer composites have been employed (Ren et al., 2021; Jo et al., 2021). The remarkable conductivity of graphene, when integrated with polymers, enhances electrochemical responsiveness and biosensor stability. Electrochemical detection with nitrogen-doped carbonised polymers, as investigated by Shi et al. (2022), signifies an innovative method aimed at E. coli, exhibiting enhanced detection limits attributable to the nanostructured polymer interface. Detection of Pseudomonas and Campylobacter: The identification of Pseudomonas species is facilitated by advanced optical biosensors, including photonic crystal fibres (Fatema et al., 2020), which allow for accurate optical signal modulations in response to pathogen presence. Surface imprinted polymers offer mechanical sensing methods for Campylobacter jejuni, utilising molecular recognition through imprinting technologies (Ali et al., 2020; Soni et al., 2018). This approach provides structural complementarity to the pathogen surface, hence enhancing specificity. *Enterobacter vibrio* pathogen in infant formula contamination, is identified utilising chitosan-based optical biosensors, which exploit chitosan's biocompatibility and film-forming characteristics. Polydimethylsiloxane is utilised in electrochemical chemiluminescence biosensors for the detection of *Vibrio parahaemolyticus*, providing a dual detection method with enhanced sensitivity (Ali et al., 2020; Soni et al., 2018). Innovative material combinations, including polydopamine-polyethyleneimine and polydopamine composites, are utilised in biosensors aimed at detecting Pseudomonas aeruginosa. Both optical and electrochemical biosensing modalities are examined, as evidenced by research conducted by Ali et al. (2020) and Fu et al. (2020). These materials enable adaptable sensor architectures that exhibit swift responsiveness and strong pathogen affinity. Microfluidic and Paper-Based Platforms: Microfluidic paper-based analytical devices (μPADs) integrated with polyvinyl carbon have been devised for optical detection of Cronobacter sakazakii (Zhong et al., 2020). This method represents advancement in the development of portable, economical diagnostic instruments appropriate for real-time food safety assessment.

Table 2. Polymer-based biosensors for detection of pathogenic bacteria

Category	Polymeric material	Biosensor type	References
Staphylococcus typhimurium	Poly-L-lysine	Optical	Sheikhzadeh et al. 2016
	Poly(styrene/acrylamide)	Optical	Ding et al. 2022
S*taphylococcus aureus*	Poly(3-thiopheneacetic acid)	Electrochemical	Hu et al. 2020
Salmonella sp.	Poly(carboxybetaine acrylamide)	Optical	Wang et al. 2021

continued on following page

Table 2. Continued

Category	Polymeric material	Biosensor type	References
Escherichia coli	poly(carboxybetaine acrylamide)	Optical	Vaisocherová-Lísalová et al. 2016
	N-methyl-2-pyrrolidonecarbonized polymer	Electrochemical	Vaisocherová-Lísalová et al. 2016
	Polypyrrole	Electrochemical	Shi et al. 2022
	Poly(polyvinyl pyrrolidone)	Electrochemical	Ren et al. 2021
	Graphene-polymer	Electrochemical	Jo et al. 2021
Pseudomonas sp.	Photonic crystal fiber	Optical	Fatema et al. 2020
Campylobacter jejuni	Surface imprinted polymers	Mechanical	Ali et al. 2020; Soni et al. 2018
Enterobacter sakazakii	Chitosan	Optical	Ali et al. 2020; Soni et al. 2018
Vibrio parahaemolyticus	Polydimethylsiloxane	Electrochemical Chemiluminesence (ELC)	Ali et al. 2020; Soni et al. 2018
Pseudomonas aeruginosa	Polydopamine-polyethyleneimine	Optical	Ali et al. 2020; Zhu et al. 2016
	Poly-dopamine	Electrochemical	Ali et al. 2020; Fu et al. 2020
Cronobacter sakazakii	µPADs +Polyvinyl carbon	Optical	Zhong et al. 2020

5.2. Polymer-Based Biosensor for the Detection of Food Allergens

Allergens found in foods may cause the immune system to react abnormally. Food allergies are complicated disorders with substantial individual variability, and are strongly correlated with the function of a person's immune system (Kalita et al., 2023). While minor food allergies may cause symptoms such as lip or facial swelling, Rashes, tightness in the throat, shaking, vomiting, stomach pain, or diarrhea, severe reactions can be life-threatening. Certain foods possess allergies, and among those that do, only a small number cause most allergy reactions. Similar meals, especially those made from plants, often contain the same allergens. For instance, people allergic to peanuts may behave differently to other legumes. The most common allergies have been identified in crustaceans, eggs, milk, dairy products, and peanuts (Sarabaegi et al., 2021). So, it's important to identify food issues. Table 3 summarises how polymer-based biosensors are used to detect allergens. According to Mohamad et al. (2020), electrochemical biosensors based on polyaniline may detect tropomyosin, a significant allergen present in seafood. Because of its biocompatibility and high electrical conductivity, polyaniline is a good choice for this purpose. Mohamad et al. (2019) also created optical biosensors with poly-dopamine polymers, which boost detection by taking advantage of dopamine's chemical stability and sticky characteristics.

Electrochemical biosensors using poly-dopamine were introduced by Jiang et al. (2024) to detect parvalbumins, which are abundant in fish. One of the main milk allergens, casein (Bos d 8), has been detected by electrochemical biosensors made of gelatin and carbon nanofiber composites (Jiang et al., 2019). The carbon nanofibers' increased surface area and conductivity allow for very sensitive detection.The presence of β-lactoglobulin, a typical milk allergy, can be detected using a variety of biosensors. In order to achieve efficient binding, Wang et al. (2021) used polyethyleneimine, which is polycationic, for electrochemical sensing. Amor-Gutiérrez et al. (2020) also found that electrochemical biosensors based on poly-lysine allowed for sensitive detection because of the high surface functionalisation of these sensors. The biocompatibility and film-forming capabilities of chitosan have led to its use in electrochemical biosensors for the detection of β-lactoglobulin.A fluorescence polarisation biosensor was created by Chen et al. (2017) to detect lactoferrin and lysozyme. This biosensor makes use of a bivalent aptamer-functionalized fluorescein isothiocyanate dye, enabling quick and accurate identification. Graphene oxide and gold nanoparticles are used in electrochemical biosensors for lysozyme detection (Erdoğan et al., 2023), which improves electron transfer and signal sensitivity due to their synergistic effects. Using chitosan and poly-dopamine in electrochemical biosensors, ovaalbumin can be detected. Ovalbumin is a prominent egg white protein allergy. The film-forming process is made easier by chitosan's inherent characteristics, and the detection capabilities are improved by poly-dopamine's stable film adhesion and chemical reactivity. Electrochemical biosensors based on polydimethylsiloxane are used for the detection of lectins and other allergens. Two types of peanut allergens, Ara h2 and Ara h1, are detected by different methods: one uses chitosan-based electrochemical biosensors, while the other uses poly-vinyl alcohol (Wang et al., 2022). Lastly, sophisticated electrochemical biosensors employ Cd quantum dot tags to detect complex allergens such as immunoglobulin G and casein.

Table 3. Polymer-based biosensors for the detection of food allergens

Category	Polymeric material	Biosensor type	References
Tropomyosin	Polyaniline	Electrochemical	Mohamad et al. (2020
	Poly-dopamine	Optical	Mohamad et al. (2019)
Parvalbumins	Poly-dopamine	Electrochemical	Chen et al. (2017)

continued on following page

Table 3. Continued

Category	Polymeric material	Biosensor type	References
Casein (Bos d 8)	Gelatin/carbon nanofiber	Electrochemical	Jiang et al. (2019)
ß-lactoglobulin	Chitosan	Electrochemical	Jiang et al. (2019)
	Polyethyleneimine	Electrochemical	Wang et al. (2021)
	Poly-lysine	Electrochemical	Amor-Gutiérrez et al. (2020)
Lactoferrin	Bivalent aptamer fluorescein isothiocyanate dye	Fluorescence polarization	Chen et al. (2017)
Lysozyme	Graphene oxide+ AuNPs	Electrochemical	Erdoğan et al. (2023)
Ovalbumin	Chitosan	Electrochemical	Jiang et al. (2020)
	Poly-dopamine	Electrochemical	Fu et al. (2023)
lectins	polydimethylsiloxane	Electrochemical	Kalita et al. (2023)
Ara h2	Poly-vinyl alcohol	Electrochemical	Wang et al. (2022)
Ara h1	Chitosan	Electrochemical	Sun et al. (2015)
Casein and Immunoglobulin G	Cd quantum dot tags	Electrochemical	Jiang et al. (2020)

6. CHALLENGES AND PERSPECTIVES

As evident in the preceding sections, manufacturing components have a significant impact on the behavior of natural polymer-based degradable films. However, despite experiments showing that they can reduce infections, deliver biologically active elements, and extend shelf life, their commercial application in food wrappers is still in its infancy, because most food studies have been restricted to plastic products and other artificial substances. The main drawback of biodegradable films is their poor mechanical characteristics. Poor mechanical characteristics, including tear strength, pressure at break, and flexibility modulus, were measured using tensile tests. The hydrophilic properties are also important because they may result in increased liquid permeability. To improve the tensile strength of the film, more polymers can be combined with it, and additives can be added. The natural polymer extraction method determines water absorption and barrier attributes. To improve the film, adequate extraction and addition of suitable additives and monomers may be helpful. Further investigation is required to compare various polymer resources, such as conventional ones, to advance the discussion and to make it easier to correlate these aspects. Food technology and science continue to investigate alternative polymers for producing edible films. In addition to investigating natural polymers, further studies are required to scale up for industrial applications, better understand various film-forming technologies, and boost the mechanical characteristics and water tolerance to values closer to those of synthetic plastics. Sustainable packaging will be crucial if all of these problems are resolved because it will hasten the decomposition of plastics owing to their biodegradable nature.

7. CONCLUSION

This study evaluated current status of research on biodegradable films and their uses in food packaging. In addition to their recognised environmental benefits, biodegradable films enhance food safety by reducing microbiological, chemical, and physical pollutants during storage and transport. Their capacity to prolong shelf life, mitigate contamination risks, and offer visual cues of food freshness underscores their multifaceted purpose in contemporary food packaging. Despite constraints including mechanical vulnerabilities and moisture susceptibility, the integration of antimicrobial agents, nanoparticles, and functional additives might augment their protective effectiveness against various pollutants.

To facilitate the transfer of biodegradable films from specialised uses to widespread industrial implementation, effective commercial strategies and supporting policy frameworks are needed. This encompasses governmental incentives, standardisation regulations, and industry-wide cooperation designed to enhance manufacturing scalability, guarantee safety standards, and bolster customer trust. Chemists, materials scientists, and microbiologists need to work together to tackle these issues and expedite the creation of durable, commercially viable biodegradable packaging solutions.

Declaration of interests

The authors declare no competing financial interests or personal relationships that could influence the work reported in this study.

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