Biodegradable Packaging Materials

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Food packaging is used to protect food products from physical, chemical, or biological stresses in their environment, thereby improving their quality and extending their shelf life. A variety of packaging materials have traditionally been used for this purpose, including plastic, glass, metal, paper, wood, and textiles. Some of these materials, particularly plastics, cause considerable environmental damage during their manufacture and after their disposal. For0 this reason, there has been great interest in developing biodegradable forms of packaging materials that are more sustainable to produce, that rapidly decompose after disposal, and that do not cause as much environmental pollution. These packaging materials can be constructed from biodegradable film-forming materials such as proteins, polysaccharides, and lipids. Moreover, their functional performance can be enhanced by incorporating organic or inorganic nanoparticles or nanofibers. For instance, nano-forms of clay, iron oxide (Fe2O3), titanium dioxide (TiO2), silver (Ag) and zinc oxide (ZnO) can be used (inorganic nanoparticles), as well as nano-forms of chitin and cellulose and their derivatives (organic nanoparticles). The resulting nanocomposites often have enhanced technofunctional characteristics such as improved optical, mechanical and barrier properties, as well as some novel functional attributes, such as antimicrobial and antioxidant activities, that can prolong the shelf life of packaged foods. Moreover, it is possible to incorporate sensing materials into biodegradable films to provide information about the quality, freshness, or safety of packaged foods.

Keywords: smart materials ; active packaging ; colorimetric indicators ; biodegradability ; biocomposite films

1. Introduction

Biodegradable materials for constructing packaging materials can be obtained from plant, animal, or microbial sources. It is important that these materials can be produced economically and sustainably, and that they quickly degrade when disposed of in the environment, usually as the result of natural chemical or biochemical processes [1]. In this section, we provide a few examples of edible materials that can be used to fabricate biodegradable packaging materials.

2. Proteins

2.1.1. Dairy Proteins

Dairy proteins, such as casein and whey protein, have been shown to be capable of forming biodegradable packaging materials. Caseins, which come in various types (including α_{S1}, α_{S2}, β, and κ caseins), make up around 80% of the proteins in milk [2][3]. These proteins are fairly flexible proteins that tend to aggregate around their isoelectric point (pH 4.6), which is important for many of their functional attributes. In the food industry, these proteins are usually available in the form of powdered calcium or sodium caseinate ingredients, which are formed by adding $Ca(OH)_2$ or NaOH to casein solutions, respectively [4]. Edible films have been formed from caseinate that has favorable mechanical and optical characteristics [5]. Whey proteins, which also come in various types (including β-lactoglobulin, α-lactalbumin, bovine serum albumin, and immunoglobins), make up around 20% of the proteins in milk [4]. They are globular proteins that have also been shown to be effective at forming films due to their good gelling properties. For instance, films made from whey protein isolate (WPI) have been reported to have good mechanical and oxygen barrier properties under low and intermediate relative humidity (RH) conditions [6]. However, these films exhibited poor water vapor barrier properties, which limits their application as packaging materials for many foods. The formation of films with appropriate functional attributes requires careful control of the denaturation, association, and crosslinking of the whey proteins [7][8]. Typically, films made from milk proteins tend to be relatively soft, smooth, tasteless, and clear, which is desirable for many applications. Moreover, they can also be made to have antimicrobial and antioxidant activity by encapsulating functional additives within them [9]. One of the main challenges of this kind of packaging material is their poor resistance to moisture transport and their fragility.

2.1.2. Meat Proteins

Gelatin is one of the most commonly used meat proteins for forming biodegradable films. It is isolated from waste products of the meat industry, such as the collagen-rich bones, skin, tendons, and hooves of animals [10]. Typically, collagen is converted to gelatin by heating in a strong acid or alkaline solution at high temperatures (e.g., 80 °C) [11]. The gelatin obtained from this process is purified and then converted into a powdered form that is used as a functional ingredient in food and other industries. Gelatin exists as a random coil molecule at high temperatures but undergoes a coil-to-helix transition when it is cooled below a critical transition temperature. The helices formed may then act as crosslinking points between different gelatin molecules due to hydrogen bonding. At sufficiently high concentrations, the gelatin molecules form a 3D network that leads to solid-like properties. Gelatin gels are typically formed by heating a gelatin solution above the coil-to-helix transition temperature (typically around 20–30 °C for terrestrial animals and lower for fish), and then cooling and drying the solution, which increases the protein concentration and promotes crosslink formation [12][13]. Gelatin films can be formed with thicknesses and mechanical properties suitable for use as food packaging materials, but they often have poor barrier properties, especially against water vapor transport [14][15], which limits their practical applications.

2.1.3. Plant Proteins

Many different kinds of plant protein are available to produce biodegradable films, including those isolated from zein, gluten, soybeans, nuts, peas, and sunflower [16]. Zein is a hydrophobic corn protein that is insoluble in water but soluble in concentrated alcohol solutions, which is important for the formation of edible films [17]. Previously, zein has been used as a constituent of packaging materials for various foods [18][19]. The proteins isolated from soybeans have also been shown to be suitable for forming edible films [20], which is often carried out using film casting or baking methods [21]. Smooth and stretchable edible films can be formed from soy proteins that have good mechanical properties, but again their water barrier properties tend to be poor [22]. The water barrier properties of soy films can be improved by incorporating hydrophobic additives into them, such as stearic acid, but this also modulates their optical and mechanical properties [23]. Other additives, such as glycerol, gellan gum, or κ-carrageenan, have also been shown to improve the functional performance of soy films [24].

2.2. Polysaccharides

Polysaccharides such as starch, cellulose, chitin, chitosan, and hydrocolloid gums, have also been used as components to construct biodegradable films [25][26]. These polysaccharides differ in their molecular characteristics, which alters the physicochemical and functional attributes of the packaging materials constructed from them

2.2.1. Starch

Starch is widely used because of its relative cheapness, abundance, biodegradability, and renewability [27]. In nature, starch molecules are packed into small granules (around 1 to 20 μm) that consist of amylose and amylopectin molecules organized into concentric amorphous and crystalline rings [28]. Edible films made entirely from starch have high water vapor permeability and weak mechanical properties, which limits their usage [29]. For this reason, researchers have examined the impact of incorporating other additives to improve their functional performance. For instance, starch has been combined with polyvinyl alcohol to produce a film with good barrier properties against water, thereby extending its potential for commercial applications as a food packaging material [30].

2.2.2. Cellulose

Cellulose is the most abundant source of functional polysaccharides in nature, which is usually obtained from wood or cotton using acid hydrolysis processes [31]. Cellulose and its derivatives, such as methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), and carboxymethyl cellulose (CMC), have been widely explored for their potential in forming biodegradable films [32][33]. For instance, films with good mechanical and water solubility characteristics have been produced using CMC [34]. However, other studies have reported that cellulose-based films act as poor water vapor barriers, which limits their application in foods [35].

2.2.3. Chitin and Chitosan

Chitin is the second most abundant polysaccharide found in nature, while chitosan is produced from chitin using controlled de-acetylation reactions [1]. Chitin and chitosan have both been shown to be capable of forming biodegradable films that can be used to increase the shelf life of food products [36]. Typically, the films formed by chitin are mechanically weaker and have worse barrier properties than those formed by chitosan. As with other biopolymers, the functional performance of chitin and chitosan films can be improved by combining them with proteins or other polysaccharides, or by incorporating other functional additives [37][38]. The fact that both chitin and chitosan naturally exhibit antimicrobial activity is useful for the development of active biodegradable films that can increase the shelf life of foods [38][1].

2.2.4. Hydrocolloid Gums

A variety of edible hydrocolloid gums can be used to form biodegradable packaging materials. Pectin is an anionic polysaccharide consisting of a linear anionic chain with neutral side chains attached to certain regions [39][40]. Commercial pectin ingredients are typically isolated from apple, citrus fruit, or sugar beet. Pectin is widely used in the food industry as a stabilizer, thickening agent, gelling agent, and film former [41]. Studies have shown that pectin can form films that are relatively strong and have good resistance to oxygen diffusion, but are fragile and have poor resistance to water diffusion [42]. Pectin films have been shown to be able to protect foods with relatively low water activities [43]. They have also been reported to increase the shelf life of a wide range of fruits and vegetables, including apple, apricot, avocado, berries, guava, chestnuts, melon, peach, walnuts, papaya, tomato, and carrot [44]. Pectin is often preferred for these applications because it can be naturally derived from fruits and vegetables. Nevertheless, numerous other kinds of hydrocolloid gums can also be utilized to create biodegradable films because of their ability to form crosslinks with each other, including agar, alginate, carrageenan, and gum arabic [45][46].

2.3. Lipids

A number of lipids can be used to assemble biodegradable films, either in isolation or in combination with other components, including monoacylglycerols, diacylglycerols, triacylglycerols, phospholipids, free fatty acids, and waxes [47][48][49]. Lipid-based films have advantages for creating a glossy surface appearance, retaining moisture in foods, and reducing water permeability [50][51]. For instance, films produced from palm fruit oil have been reported to be transparent and have good water barrier properties [52]. Sunflower oil-based films have been used to coat hamburgers, which were shown to improve their quality by controlling oxygen and water vapor permeability [53]. Essential oils (EOs) isolated from the peels of citrus fruit (such as lemon, mandarin, and orange) have been incorporated as functional ingredients into methylcellulose and chitosan films to enhance their functionality [54]. Antimicrobial essential oils from cinnamon, allspice, and clove bud have also been incorporated into edible films to protect apples during storage [55]. In many cases, lipids are converted into an oil-in-water emulsion by homogenizing them with an aqueous solution containing an emulsifier prior to incorporating them into biopolymer-based films. The composition, size, concentration, and interfacial properties of the lipid droplets used to impact the mechanical, optical, barrier and other functional attributes of the films formed, and should therefore be optimized for each application [52].

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