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Review

Cactus Mucilage for Food Packaging Applications

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Abstract: Natural polymers have been widely investigated for the development of eco-friendly materials. Among these bio-polymers, cactus mucilage is attracting increasing interest regardless of the plant species or the plant organ used for extraction. Mucilage, which is a highly branched heteropolysaccharide, has been previously studied for its chemical composition, structural features, and biotechnological applications. This review highlights the mucilage application in the food packaging industry, by developing films and coatings. These cactus-based biomaterials will be discussed for their functional properties and their potential in preserving food quality and extending shelf life.

Keywords: films; coatings; mucilage; polysaccharide; cactus; packaging

1. Introduction

Currently, demand for minimally processed and ready-to-use foodstuffs is continuously increasing. However, these food products are subject to several physical deteriorations and microbial contaminations. Browning is one of the major problems occurring after physical damage by cutting or abrasion and is mostly attributed to the instability of phenolic compounds or to the activity of some enzymes, such as oxidase and peroxidase [1]. Browning can also be induced by light reflection on the food surface. Another serious problem is microbial contamination resulting from bacterial or fungal growth. In fact, moisture, oxygen, carbon sources, and high-water activity promote the growth of spoilage and pathogenic microorganisms. Since food products are highly subjected to many types of deteriorations, it is mandatory to search for sustainable, eco-friendly, and safe packaging solutions able to reduce quality loss and extend shelf life of food products. In this context, edible films and coatings have been proposed as an effective solution to prevent food deterioration. In fact, this approach is far from a novel one since it was used in the mid-20th century to minimize weight loss and enhance the shine and brilliance of fruit and vegetables. Cellulosic and waxy coatings are the oldest ones used for fresh and perishable foodstuffs [2]. Films are thin polymeric layers formed by a dry (e.g., extrusion) or a humid process (e.g., casting). They are stand-alone materials generally used as pushes or wraps. Coatings consist of a polymeric matrix directly applied on the foodstuff surface or between its constituents by dipping, spraying, or electro-spraying, which is followed by drying. For both films and coatings, the used polymers should be non-toxic and intended for human consumption. Hence, edible films and coatings are primary packaging materials generally used as a selective barrier to gas, moisture, and/or solute migration without affecting color, taste, or smell of the coated product [2,3]. Moreover, several edible films and coatings were developed from biopolymers and enriched with some additives such as essential oils, plant extracts, enzymes, and probiotics. These additives can provide biological and functional properties such as antioxidant and antimicrobial activities for edible films and coatings. In this context, Özvural et al. [4] studied the effect of chitosan and green tea essential oil applied on hamburger patties with three different techniques (direct addition, encapsulation, and coating). The authors confirmed that the coated patties were more resistant to lipid oxidation and had the lowest microbial load, during eight days of storage. Aloui et al. [5] developed an edible coating for okra (*Abelmoschusesculentus (L.)*), based on sodium alginate and essential oil of bergamot or bitter orange. This coating decreased weight and firmness losses by 36% and 18%, respectively, during 12 days of cold storage, while, at the same time, preserving the sensory attributes of okra pods. More recently, Feng et al. [6] dipped fresh cut apple pieces in coating solutions based on whey protein isolate nanofibrils and confirmed the retarding effect of this coating on browning and weight loss of apple pieces. The total phenolic content of coated apple pieces was maintained during 10 days of storage at 4 °C. In addition, the characterized whey protein isolate nanofibrils-based films were quite transparent (transparency between 27% and 48%)and come with a smooth, continuous, and hydrophilic surface (contact angle between 22° and 46°). Likewise, standalone films have received huge interest because of the new and promising trends revealed by the use of highly available and low-cost biopolymers with interesting properties. Biopolymer-based materials offer many advantages over conventional packaging materials due to their sustainability and safety for human health. Yellow passion fruit co-products and pectin were used to develop a new biodegradable composite material using a continuous casting method [7]. The developed films exhibited interesting mechanical properties comparable to polyvinyl chloride (PVC) cling film and were compostable and easily degraded by bacteria. In another study, polyvinyl alcohol (PVA) was mixed with chitosan nanoparticles and mulberry extracts for the development of visually responsive intelligent films [8]. Film with a 20% mulberry extract showed good tensile strength (TS) and a color response to pH variation from 1 to 13. This biomaterial was then tested to monitor fish spoilage by changing the color from red to green when the product is spoiled. Ferreira et al. [9] developed films and coating materials from fruit and vegetable residue as well as potato peels. The resulting films showed a solubility of 87% and an elongation at break (EB) of 33%. Even if the films exhibited poor mechanical properties, their application as a coating material on acerola fruit extended its shelf life by 50%. Hence, edible films and coatings from natural polymers are highly effective for food preservation during storage.

One of the trendy biopolymers used for this purpose is cactus mucilage. In literature, we found only five studies on films and coatings from cactus mucilage, between 2005 and 2015 (Figure 1). In the last four years (2016–2019), more than 15 papers dealing with the use of cactus mucilage for food packaging were published, which proves growing interest in this eco-friendly, available, and versatile biopolymer. The valorization of biomass extracted polymers, particularly polysaccharides, constitutes an eco-friendly and economically profitable alternative to petroleum-based materials. With more than 170 billion tons of biomass annual production, this low cost and widely available raw material constitutes an inexhaustible resource of functional biopolymers that could find effective and profit-making applications. Carbohydrates, which constitute 75% of the produced biomass, are a promising candidate for industrial and biotechnological applications [10]. Cactus mucilage, which is one of the most abundant carbohydrates in a cactus plant, could be of particular interest thanks to its low cost and wide availability. In fact, the cactus plant covers large areas over the world. The cactus-cultivated areas in Mexico, Tunisia, Brazil, and Ethiopia are estimated at 3,000,000, 600,000, 500,000, and 360,000 ha, respectively. All these plants are mainly cultivated for fruit consumption, forage, and dye production [11]. Today, cactus biomass is considered a valuable raw material for added-value biomolecules with various industrial applications.

Therefore, the present review deals with cactus mucilage as a functional and film-forming polysaccharide and discusses the efficiency of mucilage biomaterials in food packaging applications.

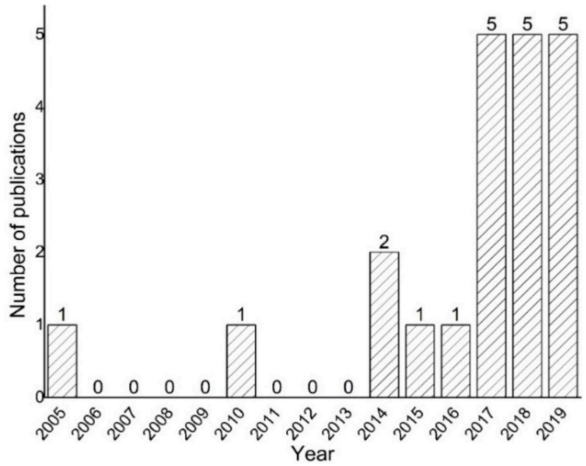

Figure 1. Publications on cactus mucilage for edible films and coatings.

2. Cactus Mucilage: Composition, Structure, Properties, and Applications

Biomass-derived polysaccharides such as mucilage (from different plants), cellulose, and pectin offer several advantages over synthetic polymers since they are renewable, biocompatible, completely biodegradable, and naturally available. In addition, polysaccharides display a wide range of physicochemical properties depending on their structural features and monosaccharides composition. Polysaccharides also have the ability to interact easily with other polymers under soft and environmentally-friendly conditions [10]. Consequently, polysaccharides can find effective and innovative applications in various industrial fields. In fact, they have been widely used as thickeners, gelling agents, stabilizers, and emulsifiers in pharmaceutical, cosmetic, and food industries [12]. More recently, current and trendy applications were investigated, such as tissue engineering, 3D printing, and the development of composite scaffolds [12–14]. Moreover, polysaccharides are very effective at developing green materials and can be used as promising alternatives to petroleum-based materials [12]. Polysaccharides have been used as polymeric matrices and reinforcing or blending agents for the development of bio-composite materials. The obtained green materials could be applied in biomedical, construction, furniture, and packaging industries [12,15].

Cactus, which is a natural source of polysaccharides, is a widespread plant growing under a wide range of climatic conditions, particularly in arid and semi-arid countries in Africa (Tunisia, Morocco, South Africa), America (Mexico, Chile, Brazil, United States), Europe (Italy, Spain), and Asia (Iran, India, and Israel). The decline in water resources and global desertification may increase the importance of a cactus as an effective system for fruit and vegetable production as well as biomass valorization [16]. The cactus belongs to the kingdom of Plantae, order of Caryophyllales and family of Cactaceae [17]. Thanks to its genetic variability, there are more than 300 species in the *Opuntia* genus and the most abundant one is *Opuntia ficus indica*. This species is known for its modified stems, called cladodes, and its fleshy sweet fruit sheltered in a thick colored peel. Cactus biomass is an inexhaustible source of active and functional molecules such as carbohydrates, fibers, polyphenols, dyes, and oils. Carbohydrates are likely the most abundant organic molecules on Earth, since they are present in the cells of all living organisms and represent the major form of photosynthetically-assimilated carbon in the biosphere. Among carbohydrates, which represent the main constituent of *Opuntia ficus* cladodes [18], mucilage is an heteropolysaccharide known particularly for its high molecular weight and branched structure. Mucilage has the ability to swell when dissolved in water and to form colloidal and viscous suspensions [19]. Mucilage is stored in mucilaginous cells present within the chlorenchyma (external green cells) and parenchyma (internal cylinder of white cells) but are more abundant in the parenchyma [19]. The hydrocolloid has great water-holding capacity, which plays a very important role in the physiology of the plant commonly growing under water-stress conditions [20]. Cactus mucilage can be extracted by different methods and the most common one uses water as a solvent for maceration, which is followed by the filtration process and precipitation. Table 1 summarizes some methods used for mucilage recovery. Sepulveda et al. [19] confirmed that extraction parameters deeply influenced the yield of extraction. In fact, mucilage extraction yields depend on the plant organ, the cactus species, and the extraction method. The mucilage is more abundant in cactus cladodes (24% of cladodes' dry weight for *Cereus Triangularis* variety [21] and 19.4% of cladodes' dry weight for the *Opuntia Ficus Indica* variety [19]) than the other parts of the plant, such as fruit peels (4.1%), fruit pulp (3.8%), and flowers (18.3%) [22–24]. In fact, the mucilage content in cladodes increases as a response to drought in order to preserve the plant. Mucilage content is also higher in the older cladodes than in the younger ones [20].

Mucilage from cladodes of *Opuntia ficus indica* is the most studied one and is well defined in literature as a complex polysaccharide of about 33 to 55 sugar residues [24,25]. Different studies agreed that arabinose, galactose, xylose, and rhamnose are the major neutral constituents of the mucilage with slight variation in the content (Table 1) while the presence of galacturonic acid was contested. However, Mc Garvie and Parolis [26] assumed that the presence or absence of galacturonic acid is possibly due to seasonal variation in sugar composition. Furthermore, Trachtenberg and Mayer [27] attributed these contradictions to the possible contamination of mucilage with other compounds from the cell wall or to purification methods that are not completely effective. Saenz et al. [20] compared mucilage composition of different cactus varieties. Mucilage of *Opuntia Fulgidas*, known as Cholla gum, has a complex structure with the main chain of galactose units having ramifications of D-galacturonic acid, D-galactose, D-xylose, and L-rhamnose. *Opuntia Dilleniis'* mucilage consists of a main chain of galactose with branched chains of arabinose units. Lastly, the mucilage of *O. ficus indica* (*Opuntia ficus indica*) is composed of acidic fractions containing arabinose, galactose, rhamnose, xylose, and galacturonic acid with neutral fractions of glucans and glycoproteins.

Cactus mucilage, which is a renewable and eco-friendly raw material, can be successfully used in biotechnological and industrial applications. In addition to its current use as gelling, stabilizing, or encapsulating agents, cactus mucilage has been employed as a flocculating agent for heavy metals in water [28], a coagulant-flocculant agent for the treatment of textile effluents [29], a wound-healing and skin-repairing agent [30], and a drug delivery system [31]. The development of eco-friendly materials is among the most unique applications of cactus mucilage. The latter was successfully used to develop edible films and coatings as well as form bio-composites when it is blended with other polymers [32–34]. Cactus mucilage has also been employed as a reinforcement agent in polymeric matrices [35,36].

Table 1. Method and properties of mucilage from different cactus species and plant organs.

Raw Material	Extraction	Yield of Extraction (% Dry Weight)	Composition and Structure	Properties and Applications	Reference
Cladodes *Opuntiaficusindica*	Homogenization in water with blender Filtration Centrifugation Lyophilization Resuspension in TCA solution Dialyze against water Addition of ethanol Centrifugation lyophilization	1.124 mg/mL of tissue	Arabinose 67% Galactose 6% Xylose 20% Rhamnose 5%	MW 4.3 × 10^6 g/mol Water holding capacity	[27]
Cladodes *Opuntia ficus indica*	Mechanical press	-	Two polysaccharidic entities: Linear β-(1-4)-galactose polymer and highly branched xyloarabinan	Moisturize and heal cutis favoring cutaneous reparative processes Wound healing properties	[30]
Cladodes *Opuntia ficus indica*	Mechanical press of cladodes inner part Precipitation with ethanol	14%	Galactose 40% Arabinose 30% Xylose, rhamnose, glucose: Minor sugars NMR specific signals of arabinogalactan polysaccharide	Film-forming properties	[33]
Cladodes *Opuntia ficus indica*	Maceration in water, assisted with a microwave Precipitation with ethanol	8%	Arabinose Galactose Rhamnose Xylose Acide galacturonique	Viscoelastic behavior MW 16.7–17.5 × 10^6 g/mol.	[37]

Table 1. *Cont.*

Raw Material	Extraction	Yield of Extraction (% Dry Weight)	Composition and Structure	Properties and Applications	Reference
Cladodes *Opuntia ficus indica*	Maceration Centrifugation Decantation Precipitation with acetone Washing with isopropyl alcohol	-	Arabinose 44% Galactose 20% Xylose 22% Rhamnose 7% Galacturonic acid 6%	MW 2.3×10^4 g/mol Non-Newtonian shear-thinning behavior High elastic properties similar to synthetic polymers like polyisobutylene At low concentrations (<3%): Typical behavior of dilute solution At high concentrations: Weak gel behavior	[38]
Cladodes *Opuntia dillenii haw*	Maceration in water, Precipitation with ethanol	6%	Arabinose 39% Galactose 33% Rhamnose 16% Xylose 5% Glucose 5%	Pseudo plastic behavior Good swelling index High water-holding capacity Anti-obesity property through lipase inhibition	[39]
Cladodes *Cereus triangularis*	Maceration in water Precipitation with ethanol	24%	Galactan backbone composed of (1→4) linked β-D-Galp residues substituted by L-arabinofuranosyl residues	MW 8.4×10^6 g/mol Antioxidant activity	[21]
Pulp *Cereus peruvianus*	The plant was manually pealed, and the pulp was recovered Solvent extraction in saline solution composed of NaCl, KCl, and $NaNO_3$ Filtration	-	Characteristic FTIR pics of complex polysaccharides	Partially crystalline structure Treatment of textile effluents by coagulation/flocculation	[29]
Fruit pulp *Opuntiaficusindica*	Blending with screw press Filtration, centrifugation Dialysis against water Precipitation with ethanol	3.8%	Uronic acid 23% Arabinose, rhamnose, xylose, galactose: 1.0:1.7:2.5:4.1 (ratio) complex mixture of polysaccharides	-	[23]

Table 1. *Cont.*

Raw Material	Extraction	Yield of Extraction (% Dry Weight)	Composition and Structure	Properties and Applications	Reference
Fruit pulp ***Opuntiaficusindica***	Mixing in water Microwave-assisted extraction Filtration Freeze drying	-	Glucose 78% Arabinose 13% Xylose 5% Galactose 2% Mannose 2% Arabinoglucan structure	MW 3.67×10^6 g/mol Shear-thinning behavior Thickening, stabilizing, and antioxidant properties Anti-DPPH radical scavenging activity comparable to that of BHT	[40]
Fruit peels ***Opuntiaficusindica***	Maceration in water Precipitation with ethanol	4%	Arabinose 33% Galactose 23% Galacturonic acid 14% Arabinogalactan structure	-	[22]
Fruit peels ***Opuntia ficus indica***	Mechanical press Precipitation with ethanol	3%	Galactose 54% Arabinose 34% Xylose 10% Galacturonic acid 9% Backbone chain made of (1→4) linked β-D-Galp residues	Film-forming properties Emulsifying and foaming properties Good water-holding capacity	[41]
Fruit peels ***Opuntiadillenii haw***	Microwave assisted extraction Precipitation with ethanol	16%	-	Gelling properties Good thermal stability	[42]

-Not specified, MW: Molecular weight. DPPH: 2,2-diphenyl-1-picrylhydrazyl. BHT: Butylated hydroxytoluene. TCA: Trichloroacetic acid. NaCl: Sodium Chloride. KCl: Potassium Chloride. NaNO3: Sodium nitrate. NMR: Nuclear Magnetic Resonance. FTIR: Fourier Transform InfraRed spectroscopy.

3. Cactus Mucilage for Developing Standalone Films

Edible films made up from natural polysaccharides are facing huge interest due to their potential industrial applications. In the last few years, mucilage from quince, flax, chia, *Balangu, Dracocephalum moldavica* seeds, okra fruits (*Abelmoschus esculentus*), and cactus (Cactaceae) have been used to develop edible films with unique properties [33,43–48]. Likewise, cactus mucilage from different varieties and different plant organs was employed to develop bio-based materials. Espino Diaz et al. [49] developed films from mucilage of *O. ficus indica* cladodes in the presence of glycerol with or without calcium (Table 2). This study showed that, at pH 3, films were very elastic and difficult to handle. However, between pH 4 and pH 8, films were strong enough to easily handle and characterize. In the latter case, the color of the obtained films varied from light yellow at a low pH to yellow-green at a high pH. Color saturation was affected by pH and calcium content. Chroma values were higher in mucilage films prepared at a high pH without calcium. In a previous study, Gheribi et al. [33] developed edible films using mucilage from a cactus and investigated the effect of various plasticizers. The obtained glycerol plasticized films had higher TS (>1MPa) and EB (>60%) than those developed by Espino Diaz et al. [49] (0.95 MPa and 24%, respectively). Moreover, water vapor permeability (WVP) values of the former films were lower than the latter ones (63.8 and 98–147 gmm/m^2 d KPa, respectively). This seems to be related to differences in mucilage chemical composition, which is deeply affected by the origin of cladodes and the extraction method [33]. Cactus mucilage films can also be successfully developed with plasticizers other than glycerol, which is proven by Gheribi et al. [33] who found that sorbitol-plasticized films showed the best TS and water vapor barrier properties, while polyethylene glycol (PEG) 400 plasticized films showed the highest glass transition temperature (49 °C) and thermal stability (up to 171 °C).

Although cactus mucilage films exhibited some unique properties, their mechanical and barrier properties are inferior when compared to conventional plastic materials, which limit their industrial applications. For these reasons, some studies focused on the development of composite materials using cactus mucilage and other biodegradable polymers (Table 2). In this context, Lira Vargas et al. [50] developed glycerol-plasticized films based on cactus mucilage/gelatin and cactus mucilage/gelatin/beeswax. The concentration of cactus mucilage was fixed at 0.5% while the concentrations of the other components were incorporated at a concentration range of 0.25–0.5%. The obtained composites had medium-to-high roughness resulting from the lumpiness of cactus mucilage and the smoothness of gelatin. The addition of beeswax increased the lumpiness and decreased the transparency of composite films. The ternary blend significantly increased TS and decreased water vapor, O_2, and CO_2 permeabilities (Table 2). The authors mentioned that, despite the reinforcement of the mechanical and barrier properties after blending the mucilage with gelatin and beeswax, the characteristics of the resulting biomaterials are still poor, which limit their practical application. Recently, the use of PVA, which is a synthetic and biodegradable polymer with excellent mechanical and barrier properties, has been proposed as an alternative to surmount these limitations. For this purpose, Gheribi et al. [34] blended Cactus (*O. ficus indica*) mucilage with PVA at four different ratios. The results of this study showed that PVA addition improved physical, mechanical, thermal, and barrier properties of mucilage films. The composite at 80:20 (mucilage/PVA) was selected as the optimal blend, which leads to an increase in TS, EB, and the water contact angle by 165%, 14%, and 24%, respectively. Dominguez et al. [51] 45 studied the properties of ternary composites made of chitosan, PVA, and cactus (*O. tomentosa*) mucilage. In this study, PVA and chitosan concentrations were varied, while mucilage concentration was set at 10%. The obtained composites were stable and homogeneous. However, the addition of mucilage led to more hydrophilic films with higher water vapor permeability (WVP) and water uptake than neat PVA and chitosan films. Furthermore, Guadarrama-Lezama et al. [36] investigated the effect of blending citric pectin with cactus mucilage at different concentrations and concluded that the films' microstructure was compact, smooth, and homogeneous below 12% of mucilage. The addition of cactus mucilage, even at high concentrations, increased thermal stability and decreased water vapor permeability (WVP) and solubility of the developed bio-composites.

Previous studies generally correlated the reinforced thermal and physical properties to intermolecular interactions occurring within the film network between the functional groups of cactus mucilage and those of the incorporated polymers. The obtained results proved that cactus mucilage is compatible with many biodegradable polymers such as PVA, chitosan, starch, and citric pectin, which may lead to countless industrial applications.

In another study, Lopez Garcia et al. [35] compared the direct incorporation of mucilage withthe addition of water-ethanol extracted mucilage and studied the effect of both methods on chemical, thermal, and mechanical properties of a starch/chitosan/PVA/mucilage *Opuntia joconsotle* composite. The direct addition of mucilage caused microphase separation in the film network while films from extracted mucilage had no clear aggregation or microphase separations, which means that the films' components were homogeneously dispersed in extracted mucilage and indirectly-added mucilage. For mechanical properties, films from directly added mucilage showed slightly lower values than films with extracted mucilage.

In addition to cladodes, mucilage from other organs of the cactus can be used to develop edible films. Damas et al. [52] exploited *Cereus hildmannianus* fruits, which is a widespread cactus species in Brazil, for the extraction of mucilage. This was further used to develop glycerol-plasticized edible films. This study confirmed the previous findings showing that the addition of plasticizers is mandatory for cactus mucilage films development, regardless of the organ or the species of the plant. The authors suggested that mucilage from *Cereus Hildmannianus* fruits can be successfully used as a film-forming and coating material thanks to its high nutritional value and the interesting functional properties of the resulting films. Moreover, Gheribi et al. [41] used a prickly pear peel for the extraction and characterization of its mucilage. The extracted mucilage showed interesting film-forming properties and had an economic value as the raw material, which is considered a by-product. Lastly, Oliveira et al. [53] evaluated the ability of mucilage from *Pereskia Aculeata* leaves to develop edible films plasticized with glycerol. The obtained films were flexible and cohesive, with a smooth surface and good thermal stability. The authors concluded that the non-toxic and non-transparent films could find interesting applications for the coating of light sensitive food products.

The different studies mentioned above demonstrated that cactus mucilage films are particularly interesting for their flexibility, gas, and grease barrier properties as well as their thermal stability. However, their drawbacks include poor mechanical resistance and high affinity to water. The properties of cactus mucilage films are intimately related to polysaccharide composition and structure, which is highly branched and particularly rich in hydrophilic groups [33,36,52].

Table 2. Based on cactus mucilage.

Composition	Mucilage Extraction	Film-Forming Conditions	Main Properties	References
Mucilage (cladodes of *Opuntia ficus indica* + PVA	Pressing of cladodes inner part, filtration, precipitation with ethanol, drying (50 °C, 24 h)	Mucilage/PVA (90:10, 80:20, 70:30 and 60:40) PEG 200 30% Casting onto plastic petri dishes Drying at 50 °C for 24 h Storage at 53% RH and 25 °C	Thickness 0.16–0.19 mm WVP 35–474 g mm/m^2 d kPa TS 2–6 MPa EB50–60% WCA90°–115° Tg 39–60 °C Tm 198–213 °C	[34]
Mucilage (*Opuntia ficus indica* fruit peels)	Pressing of cladodes inner part, filtration, precipitation with ethanol, drying (50 °C, 24 h)	Mucilage 4% wt/wt Glycerol 40% Casting onto plastic petri dishes Drying at 40 °C for 48 h Storage at 53% RH and 25 °C	Thickness 0.17 mm WVP 53 g mm/m^2 d kPa TS ~1 MPa EB ~66% WCA ~91° Tg 41 °C	[41]
Mucilage (*Pereskia aculeata Miller* leaves)	Homogenization with water in a blender, filtration, centrifugation, precipitation, freeze drying	Mucilage 1.5–2% Glycerol 20–25%	TS 1.2–5.2 MPa EB 22%–46% YB 5.4–69 MPa	[53]
Citric pectin + Mucilage (*Opuntia ficus indica cladodes*)	Immersion in $CaCl_2$ solution for 24 h, filtration, storage at 4 °C	Citric pectin 2 g/100 mL water Cactus mucilage 5, 10, 12, 14 16, 18, and 20 g/100 g water Glycerol 5 mL Casting onto acrylic plates Drying at 50 °C, overnight Storage 52% RH at 25 °C	WVP 1.5–1.7 × 10^{-9} g/m d Pa TS 0.5–0.8 MPa YM 0.9–1.7 MPa EB 25%–41% Tm 209–310 °C	[36]
Mucilage (cladodes of *Opuntia ficus indica*) + plasticizers (glycerol, sorbitol, PEG 200 and PEG 400)	Pressing of cladodes inner part, filtration, precipitation with ethanol, drying (50 °C, 24 h)	Mucilage 4%, plasticizer 40% Casting onto plastic petri dishes Drying 40 °C, 48 h Storage 53% RH, 25 °C, 48 h	Thickness ~0.2 mm WVP 22–64 g mm/m^2 d kPa TS 1–2.5 MPa EB 50%–65% WCA 85° Tg 30–50 °C	[33]

Table 2. *Cont.*

Composition	Mucilage Extraction	Film-Forming Conditions	Main Properties	References
Starch + PVA + mucilage (*Opuntia joconsotle*) + chitosan+ glycerol	Direct mucilage: Grinding, filtration, centrifugation Extracted mucilage: Precipitation with ethanol, pH adjusted to 3.5 with HCl	Mucilage 2.5–27% PVA 11–14% Chitosan 11–16% Starch 27–36% Glycerol 22–30% Casting onto glass petri dishes Drying in 35 °C for 48 h Storage in polyethylene bags in a desiccator at 22 °C	YM ~0.2 GPa H 19–22 MPa	[35]
PVA + chitosan + mucilage (*Opuntia tomentosa*)	Mixing in blender, centrifugation, precipitation with ethanol	Mucilage 10% PVA 8%, 23%, 38%, 53%, and 68% Chitosan 8%, 23%, 38%, 53%, and 68% Glycerol 14% Casting onto glass plates Drying with a convective dehydrator at 40 °C for 4 h	Thickness 0.05–0.07 mm WVP 3066–852 mL/mm^2 d Pa TS 30–50 MPa EB 10–70%	[51]
Mucilage (*Cereus hildmannianus* fruits)	Water extraction at 60 °C, Filtration, centrifugation, Precipitation with ethanol, washing with acetone, drying (40 °C, 24 h)	Mucilage 1% Glycerol 1%–4% Casting onto Teflon plates Drying at 23 °C for 48 h Storage at 55% RH and 23 °C	Thickness 0.1–0.17 mm WVP 0.32–1.1 g mm/m^2 h kPa TS 3–28 MPa EB 0.4–19% YM40-2359 MPa WCA 75°–108°	[52]
Mucilage (*Opuntia ficus indica* cladodes) + gelatin + beeswax	Mixing with water at 90 °C, decantation, centrifugation, precipitation with ethanol, dialyze, freeze drying	Mucilage 0.5% (30 °C) Gelatin 0.25–0.5% (60 °C) Beeswax 0.25–0.5% (60 °C) Glycerol 0.6%, Tween 80 0.4% Casting and drying at 24 °C, 50% RH for 1–3 days	Thickness 0.02–0.04 mm WVP 13–116 × 10^{-12} mol m/s m^2 Pa O_2P 3–14 × 10^{-12} mol m/s m^2 Pa CO_2P 3–9 × 10^{-12} mol m/s m^2 Pa TS 0.5–2.7 MPa	[50]
Mucilage (*Opuntia ficus indica* cladodes) + glycerol + $CaCl_2$	Crushing, homogenization in water at 85°, filtration, centrifugation, precipitation with ethanol, washing with ethanol, freeze drying	Mucilage 4%, glycerol 50%, $CaCl_2$ 30% pH (3, 4, 5.6, 7, 8) RH 30%, 25 °C. Casting onto glass petri dishes coated with Teflon Drying at room temperature for 24h Storage at 50% RH and 25 °C	Thickness 0.109–0.131 mm WVP 98–147 g mm/m^2 d KPa TS 0.3–0.95 MPa EB 15–24%	[49]

WVP: Water vapor permeability.O_2P: Oxygen permeability.CO_2P: Carbon dioxide permeability. TS: Tensile strength. EB: Elongation at break. YM: Young modulus. H: Hardness. WCA: Water contact angle. Tg: Glass transition temperature. Tm: Melting temperature. PVA: Polyvinyl alcohol. RH: Relative humidity. PEG: Polyethylene glycol.

4. Cactus Mucilage as a Coating Material

Currently, coatings constitute an innovative primary packaging material able to preserve foodstuffs and extend their shelf life. Coating materials should prevent deterioration of physical and nutritional quality of the coated product. In addition, they should preserve the sensorial and organoleptic properties, which determine the consumer appreciation of the final product. Cactus mucilage has been effectively used as a coating material, particularly for highly perishable fruits, minimally processed products, and fresh cut or sliced ones (Table 3).

The use of cactus mucilage as a coating material has been studied for the first time by Del Valle et al. [32] who applied cactus mucilage on strawberries to extend their shelf life. Coated strawberries showed better firmness than uncoated ones, which may enhance their resistance to mechanical damage during storage and, thereby, reduce economic losses. Polysaccharidic coatings act as a barrier to water transfer by slowing foodstuff dehydration and maintaining its firmness [1,32,54]. Moreover, the red color of strawberries was maintained for 5 days but was then reduced for both coated and uncoated fruits because of fruit browning. For sensorial properties, coated strawberries were preferred over uncoated ones during the storage period. Likewise, Oluwaseun et al. [55] used cactus mucilage to coat papaya fruits and confirmed that coating treatment, applied on the fruit surface, affected its internal atmosphere and, thus, delayed its ripeness during storage at room temperature. Cactus mucilage-based coating effectively reduced yeast and mold counts in coated papaya fruits to one-half. Moreover, aerobic psychrotrophic and mesophilic bacteria counts decreased from 11 to 4–6 CFU/g and from 9 to 4–6 CFU/g, respectively. To the best of our knowledge, no research has established the antimicrobial activity of the cactus mucilage. However, Oluwaseun et al. [55] attributed the reduction in microbial counts observed in coated papaya fruits to the modified atmosphere generated by the cactus mucilage-based coatings. The cactus mucilage has the potential to act as an effective barrier against gaseous exchange between the environment and coated fruit by reducing O_2 permeability and promoting CO_2 accumulation in the atmosphere around the fruit. In this sense, many studies reported the efficacy of cactus mucilage coatings, with or without glycerol, for reducing microbial growth [54,56].In another study, Trevino-Garza et al. [54] demonstrated that mucilage/chitosan coatings on fresh-cut pineapples significantly reduced yeast and mold (from 6.6 CFU/g for uncoated fruits to 3–5 CFU/g for coated ones), total aerobic (from 4.7 CFU/g for uncoated fruits to 3.6–4 CFU/g for coated ones), and psychrotrophic (from 4.1 CFU/g for uncoated fruits to 2.4–3.8 CFU/g for coated ones) counts at the end of storage at 4 °C. Moreover, the applied coating significantly reduced *Listeria monocytogenes* and *Salmonella typhi* counts. The authors attributed the reduction in microbial growth to the antimicrobial effect of chitosan and a low storage temperature (4 °C). Allegra et al. [56] reported that, during the entire storage period at 4 °C, *O. ficus-indica* mucilage-based coatings did not induce any microbial growth inhibition in breba figs. However, coated figs showed a significantly lower growth of *Enterobacteriaceae* compared with uncoated ones.

The dipping method is the most widely used one for the coating application. However, Zegbe et al. [57] developed and characterized films from cactus mucilage and then used them to coat guava fruits. The method used in this study was effective in maintaining guava fruit color, firmness, and soluble solids and dry matter concentrations during the storage carried out at room temperature. However, the incorporation of a mixture of glycerol and polyethylene glycol (PEG) as a plasticizer in film formulation increased fruit weight loss.

Since 2017, the number of published studies on the use of cactus mucilage as a coating material has increased and all of them reported reinforcement in firmness, better appearance, and extended shelf life for cactus mucilage-coated products. Dipping, which consists of immersing the food product in film-forming solution that is basically composed of a polymeric matrix and additives, is the most extensively used process for cactus mucilage-based coatings. Nevertheless, Garza et al. 49 used layer-by-layer dipping, which consists in immersing pineapple cubes alternately into mucilage and chitosan solutions. This coating process seemed to be effective in protecting fresh cut pineapple and extending its shelf life by six days, in comparison with the uncoated fruits. In fact, mucilage/chitosan coating may act as a polymeric barrier on the fruit surface by decreasing water vapor transmission and weight loss by almost 10%. Such a barrier effect may be particularly ensured by the great water binding capacity of mucilage, as explained by the authors. Moreover, coated fruits exhibited higher firmness than uncoated ones on the 18th day of storage at 4 °C. In fact, cactus mucilage crosslinked with chitosan act as an effective physical and mechanical barrier reducing juice leakage and delaying respiratory metabolism reactions [54] In another study, Bernardino-Nicanor et al. [58] used brushing as a coating application method of mucilage (*Opuntia Robusta*) on tomatoes. The coating method and the cactus species used in this study were shown effective in maintaining firmness and reducing the weight loss of tomatoes. However, lycopene content remained higher in uncoated tomatoes on the 21st day of storage. In this study, mucilage was extracted from parenchymatous and chlorenchymatous tissues and the authors confirmed that parenchymatous tissue mucilage was more effective as edible coating for tomatoes. Apart from ***Opuntia*** *ficus indica* and ***Opuntia*** *Robusta*, mucilage from *Opuntia elatior Mill* species was used for coating guava fruits and this treatment significantly affected firmness, pH, titratable total acidity, total soluble acids, and sensory attributes [59] More recently, Morais et al. [1] blended the cactus mucilage with cassava starch in order to coat minimally-processed yam. Yam coated with neat mucilage showed lower weight loss than roots coated with a mixture of starch and mucilage because of the hygroscopic aspect of starch. This study particularly highlighted the effect of mucilage coating in increasing polyphenol content, which was synthesized as a defense mechanism against browning reactions occurring in minimally processed yam.

Regardless of its species or extraction and application methods, cactus mucilage can be considered an effective material in extending shelf life of food products and preserving their qualitative attributes (Table 3). Further research is needed to investigate the effect of the incorporation of antimicrobial agents on the antimicrobial properties of cactus mucilage-based coatings for food product applications.

Table 3. Coatings based on cactus mucilage.

Composition	Mucilage Extraction	Coated Product	Coating Method and Conditions	Main Effects	References
Mucilage (spineless cactus cladodes) + cassava starch + glycerol	Immersion in a solution containing 5 mg/L citric acid	Minimally processed yam (*Dioscorea spp.*)	Immersion Storage in Nylon packages for 10 days at 5 °C.	Fresh mass loss was reduced Visual and sensory quality were maintained Increase in phenolic compounds	[1]
Mucilage (cladodes of *O. ficusindica* +*Aloe debrana*)	Cladodes were pressed and sieved	Mango (*Mangiferaindica L.*)	Dipping	Quality deterioration was slowed Good appearance was maintained Total soluble solids content was maintained after 16 days of storage Organoleptic properties of mucilage-coated fruits were better than control and aloe gel-coated fruits	[60]
Mucilage (cladodes of *O. elatior Mill.*)	-	Guava (*Psidiumguajava L.*)	Immersion Storage at 10 °C for 4–16 days	Reduction of weight and firmness loss	[59]
Mucilage (from parenchymatous and chlorenchymatous tissues of *O. Robusta*)	Extraction with water or ethanol from parenchyma or chlorenchyma (high speed blending), filtration, drying.	Tomatoes (*Lycopersicumsculentum*)	Brushing (3 times) Storage at 20 °C	Enhanced firmness Reduced weight loss Fruit ripening during storage was delayed	[58]
Mucilage (cladodes of *O. ficusindica*) + glycerol	Crushing of cladodes, homogenization in water, filtration, precipitation with ethanol, drying	'Dottato' fig (*Ficuscarica L.*) fruit	Dipping Storage in refrigerator at 4 °C and 85% RH for 14 days	Weight loss was decreased Fig shelf life was extended Brightness, visual appearance, and firmness were maintained Lower microbial cell densities Reduced Enterobacteriaceae counts Coating attenuated the decrease in amino acids' content and increased the amount of carbohydrates and other key metabolites	[57,61]
Mucilage (cladodes of *O. ficusindica*) + glycerol +chitosan	Blending of cladodes, homogenization in water, centrifugation, precipitation with ethanol, drying	Fresh-cut pineapple (*Ananascomosus*)	Dipping using layer-by-layer process Storage in plastic containers at 4 °C for 18 days.	Weight loss and softening of fruits were reduced Color, odor, flavor, and texture were preserved Sensory acceptance was extended by 6 days in comparison with the control	[54]

Table 3. *Cont.*

Composition	Mucilage Extraction	Coated Product	Coating Method and Conditions	Main Effects	References
Mucilage (cladodes of *O. ficusindica*) + glycerol/tween 20	Crushing of cladodes, homogenization in water, filtration, precipitation with ethanol, drying	Fresh kiwifruit (*Actinidiadeliciosa*) slices	Dipping Storage in sealed polyethylene terephthalate packages at 5 °C and 90% RH for 12 days	Firmness as well as ascorbic acid and pectin contents were maintained Visual quality and flavor were preserved	[62]
Mucilage (cladodes of *O. ficusindica*) + glycerol/PEG	Homogenization in water, filtration, precipitation with ethanol, drying	Unprocessed Guavas (*PsidiumGuajava L.*)	Fruits were coated with processed films Storage for 6–8 days at 27 °C and 20% RH	Extended shelf life Quality attributes were maintained High firmness Total soluble solids and dry matter concentrations were maintained	[57]
Mucilage (cladodes of *O. ficusindica*)	Homogenization in water, centrifugation	Carica papaya Fruit	Dipping, drying Storage for 6 weeks at 27 °C and 55%–60% RH	Higher firmness Extended shelf life Lower microbial load (total aerobic psychrotrophic)	[37]
Mucilage (cladodes of *O. ficusindica*) + glycerol	Homogenization in water, centrifugation	Strawberry (*Fragariaananassa*)	Dipping, drying Storage for 10 days at 5 °C and 75% RH	Extended shelf life Greater firmness Color was not affected by coating Sensorial analysis revealed consumer's preference for coated fruits over uncoated ones	[32]

5. Conclusions

Cactus mucilage has been widely used for several industrial applications. The use of this bio-polymer as a packaging material to ensure food safety and quality will open new opportunities and trends in food packaging. Whether used as edible film or coating, cactus mucilage showed promising properties for the future improvement of packaging systems. The use of cactus mucilage could also be economically profitable due to its low cost, availability, and effectiveness when used as primary packaging for food products. Future studies are needed to reinforce mechanical and barrier properties of cactus films and to grant better antimicrobial activity formucilage coatings.

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