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A review on recent advances of plant mucilages and their applications in food industry: Extraction, functional properties and health benefits

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ABSTRACT

Plant mucilages have been used for many applications as stabilizers, emulsifiers, thickening or gelling agents, viscosity modifiers, encapsulating agents and food packaging materials (stand-alone films, coatings). In these studies, it has been reported that plant mucilages have potential to extend the shelf-life of food products when applied as coatings or packaging films by reducing the oxidative reactions, microbial spoilage. Besides, they exert required mechanical integrity, and/or barrier against water, and provide active properties as carriers of aroma compounds or antioxidant and antimicrobial agents. Along with their digestive health promoting activities, mucilages also can be used as a fat replacer to reduce the calorie of added food product. Acting as biopolymeric encapsulating agent, mucilages can protect antioxidant and antimicrobial compounds or retain viability of probiotic bacteria in gastrointestinal system with their controlled release properties.

This review shows an overview of literature concerning the chemistry, extraction and recent uses of seed mucilage in food industry including encapsulation, emulsion/stabilization, edible film or coating applications, as well as their possible health benefits or employement for drug delivery purposes.

1. Introduction

Mucilage is a complex water-soluble polysaccharide which is mainly composed of monosaccharides and uronic acids linked with glycosidic bonds, glycoproteins and bioactives (Aftab et al., 2020; Beikzadeh, Khezerlou, Jafari, Pilevar & Mortazavian, 2020; Cakmak, Mama & Yilmaz, 2021; J.H. Chiang et al., 2021; Dybka-Stępień, Otlewska, Góźdź & Piotrowska, 2021; Nazari, 2021). The seed coats of the plants belonging to Brassicaceae, Solanaceae, Linaceae, and Plantaginaceae family contain rich source of complex polysaccharides like mucilage or gums (Aftab et al., 2020). Similarity in the physical structure and composition of gums and mucilages creates confusion, and these terms are often used interchangeably, but they do have different meanings (Beikzadeh et al., 2020). Gums are pathologic and extracellular compounds produced when plants are damaged and the gums are easily dissolved in water. However, mucilages are naturally occurring physiological compounds which produce slimy masses (Beikzadeh et al., 2020; Hedayati, Niakousari, Babajafari & Mazloomi, 2021).

The protein and dietary fiber fractions of mucilage display their water affinity and gel-forming capacity, while their lipid fraction possess oil holding capacity (J.H. Chiang et al., 2021). They have numerous functional properties including high-water absorption capacity, emulsifying, gelling and film forming ability, thickening or viscosity modifying properties, and bioadhesibility (Cakmak et al., 2021; Dybka-Stępień et al., 2021; Haile, Sibhat & Molla, 2020; Hesarinejad et al., 2018; Rostamabadi, Falsafi, Nishinari & Rostamabadi, 2022). Most of the plant mucilages including flaxseed, psyllium, balangu, basil, camelina seed, *Plantago lanceolate* seed and *Malva parviflora* leaves exhibit shear-thinning behavior over a wide range of shear rate (up to 1000 s^{-1}) (Hesarinejad et al., 2018; Komijani, Mohebbi & Ghorani, 2022; Liu, Shim, Tse, Wang & Reaney, 2018; Munir et al., 2021; Rezaeinia, Emadzadeh & Ghorani, 2020; Ubeyitogullari & Ciftci, 2020). So they have various benefits as a potential plant-based food additive which can compete with the commercial gums, and improve the liquid, semi-solid or solid food structures. Besides, they can act as a fat replacer

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without adversely affecting sensory properties of the added food product (Akhtar, Khan & Khalid, 2022).

Seed mucilages are considered good candidates to incorporate into food formulations due to their thickening, emulsifying, and viscosity/consistency modifying properties, also high performance biodegradable packaging films or coatings can be obtained from various mucilage sources (Beikzadeh et al., 2020). Edible films or coatings made of mucilages have potential to replace petroleum-based plastics and reduce their adverse environmental impacts. Besides, they have modifiable structure to present good gas barrier properties, carriers of active agents or aromas (active packaging), preventing from contamination, reducing spoilage, avoiding undesired reactions in foods such as browning (enzymatic) (Khatri, Panigrahi, Prajapati & Bariya, 2020), dehydration (moisture loss) (Treviño-Garza, García, Heredia, Alanís-Guzmán, & Arévalo-Niño, 2017), or oxidation (Jouki, Mortazavi, Yazdi & Koocheki, 2014). Along with these properties, high extraction yields, providing simple and cost-effective processing options, and high availability make mucilage source a good candidate to be used in food packaging applications (Olawuyi, Kim & Lee, 2021). Therefore, various mucilage sources including flaxseed (de Paiva et al., 2021), chia seed (M. Mujtaba et al., 2019, 2019), cactus (Gheribi et al., 2018), fenugreek seed (Mohite & Chandel, 2020), and sage (Amini & Razavi, 2020) have been studied for their film forming abilities and their impact on shelf life when used as carriers of active agents (Karami, Kamkar, Shahbazi & Misaghi, 2019; Kozlu & Elmacı, 2020; Nourozi & Sayyari, 2020; Ozturk, Karakaya, Yıldız & Saracoglu, 2019; Shahbazi, Shavisi & Karami, 2021).

Plant-based food ingredients drive attention by being sustainable and creating less carbon foot print compared to animal-based ingredients. Since the world's population is constantly growing along with unequal distribution of food supply and production, our dietary patterns inevitably shift to consumption of more plant-based foods and developing plant-based ingredients is essential (Sabaté & Soret, 2014). Therefore, food scientists always look for alternative ingredients in order to meet the increasing food demand. It has been estimated that total hydrocolloid market (as a food additive) of food industry excluding Chinese market was over 7.5 billion $ in 2020 and expected to exceed 8.7 billion $ in 2025 (Seisun & Zalesny, 2021). Moreover, those estimations heavily consider the expansion of current hydrocolloid market where gelatin took the first place. It should also be noted that seaweed hydrocolloids or plant-based mucilage markets are booming due to sustainable food production and consumption trends. From this point, seed mucilages had a great potential since they are versatile substances both using as a food additive as well as a biodegradable food packaging/coating material for extending the shelf-life of applied food.

The aims of this review are to (1) focus on functional properties of the plant mucilages when used as an additive in food products, (2) as a biopolymer for food packaging applications, and (3) their digestion behavior and health benefits including, antimicrobial, antioxidant, antidiabetic and antihyperlipidemic properties as summarized in Fig. 1.

2. Methodology

A comprehensive systematic literature review was performed to gain a deeper understanding of the role and applications of plant mucilage in the food industry, including theirs functional properties and health benefits, and the methods used for extraction. Our search for relevant articles was conducted across major research engines, Scopus and Web of Science, using keywords related to plant mucilage and its applications. We searched for articles across two research engines (Scopus, Web of Science and Google Scholar) using the string: (ALL ("plant mucilage" OR "plant-derived mucilage" OR "mucilage in plants" OR "plant gums" OR "mucilage extraction" OR "biobased packaging") AND ALL ("hydrocolloid" OR "chemistry" OR "encapsulation" OR "extraction" OR "coating" OR "functional properties" OR "digestion" OR "antimicrobial"). Our search was limited to articles that were published until August 20, 2022. After eliminating duplicates, we identified 6990 articles that met our criteria. In the first stage of our review process, we assessed the relevancy of each article by reading its abstract and excluding review papers and studies that did not involve primary data collection from individuals. This process resulted in a final pool of 199 articles that were deemed relevant to our research objectives. The selected articles were then carefully reviewed to assess their relevancy, with a focus on the applications of plant mucilage in the food industry. These applications included the use of plant mucilage as stabilizers, emulsifiers, thickening or gelling agents, viscosity modifiers, encapsulating agents, and food packaging materials, as well as its functional properties. In conclusion, our systematic literature review provided a comprehensive understanding of the role and applications of plant mucilage in the food industry. It offered valuable insights into the functional properties and health benefits of plant mucilage, as well as the various extraction techniques used. Additionally, it provided a detailed analysis of the applications of plant mucilage as food ingredients and food packaging materials. The findings of this review can serve as a valuable resource for researchers, manufacturers, and policymakers in the food industry who are interested in the development and utilization of plant mucilage.

3. Chemical composition and characterization of mucilages

Mucilage, which is composed of soluble dietary fibers, is found in the wide variety of plant parts, including rhizomes, roots (e.g. orchid), seeds (e.g. quince), fruit (e.g. okra), leaves (e.g. baobab), stems (e.g. mamaku) and bark (e.g. *Grewia ferruginea*). It is formed by immersion and soaking of the plant parts in water allowing the aqueous phase thickens (Ritzoulis, 2017). Chemical composition of mucilages depends on plant species, and the plant part, but mucilage is commonly composed of a mixture of polysaccharides (Kassem et al., 2021; Nazari, 2021). Significant variation in the chemical composition of all different plant mucilage is attributed to various reasons. In addition to species of plant, different extraction, precipitation and drying methods used for obtaining powdered mucilage may cause those compositional variations (Dybka-Stępień et al., 2021; Liu et al., 2021). Also, climatic conditions, geographical origins, genetic modifications, environmental conditions, plant maturity stage and agricultural practices have significant effect on the chemical composition of mucilages (de Falco, Amato & Lanzotti, 2017; Halász, Tóth, Börcsök & Preklet, 2022; Silva et al., 2019). Although there are a few studies in the literature elaborating the chemical compositions and structural characteristics of mucilages, the biological characteristics can be affected from mentioned factors. Such as abinoxylan fractions in tomato seed mucilage exhibiting anti-inflammatory mechanisms or prevention of oxidative stress and enterocolitis depending on the extraction conditions of cress seed mucilage (Akl, Taha, Mohamed & Mohamed, 2021; Nascimento, Baggio, Werner, Iacomini & Cordeiro, 2016).

Chia mucilage is a highly viscous anionic heteropolysaccharide even at low concentrations, with soluble dietary fibers (6%) being its major component of total carbohydrates (Goh et al., 2016). It contains D-glucose, D-xylose, D-mannose, L-arabinose, galacturonic acid, glucuronic acid residues, and methyl glucuronic acid (Coban & Coban, 2020; Hernandez, 2012; Lin, Daniel & Whistler, 1994; Timilsena, Adhikari, Kasapis & Adhikari, 2016). Its structure was described as 4-*O*-methyl-α-D-glucuronopyranosyl residues, occurring as the branches of *O*-2 from β-D-xylopyranosyl residues in the main chain, consisting of (1→4)-β-D-xylopryanosyl-(1→4)-α-D-glucopyranosyl-(1→4)-β-D-xylopyranosyl units with a ratio of 2:1:1 for Xyl:Glc:GlcA (Lin et al., 1994). Lin et al. (1994) proposed the structure of chia mucilage as a tetrasaccharide with 4-*O*-methyl-α-D-glucuronopyranosyl residues with β-D-xylopyranosyl branches in the main chain. The protein content of chia seed mucilage was found to be between 5.1–12.1%, and lipid content was between 0.9–2.8% depending on the extraction conditions (Fernandes & Salas-Mellado, 2017; Wang, Lu & Kuo, 2022).

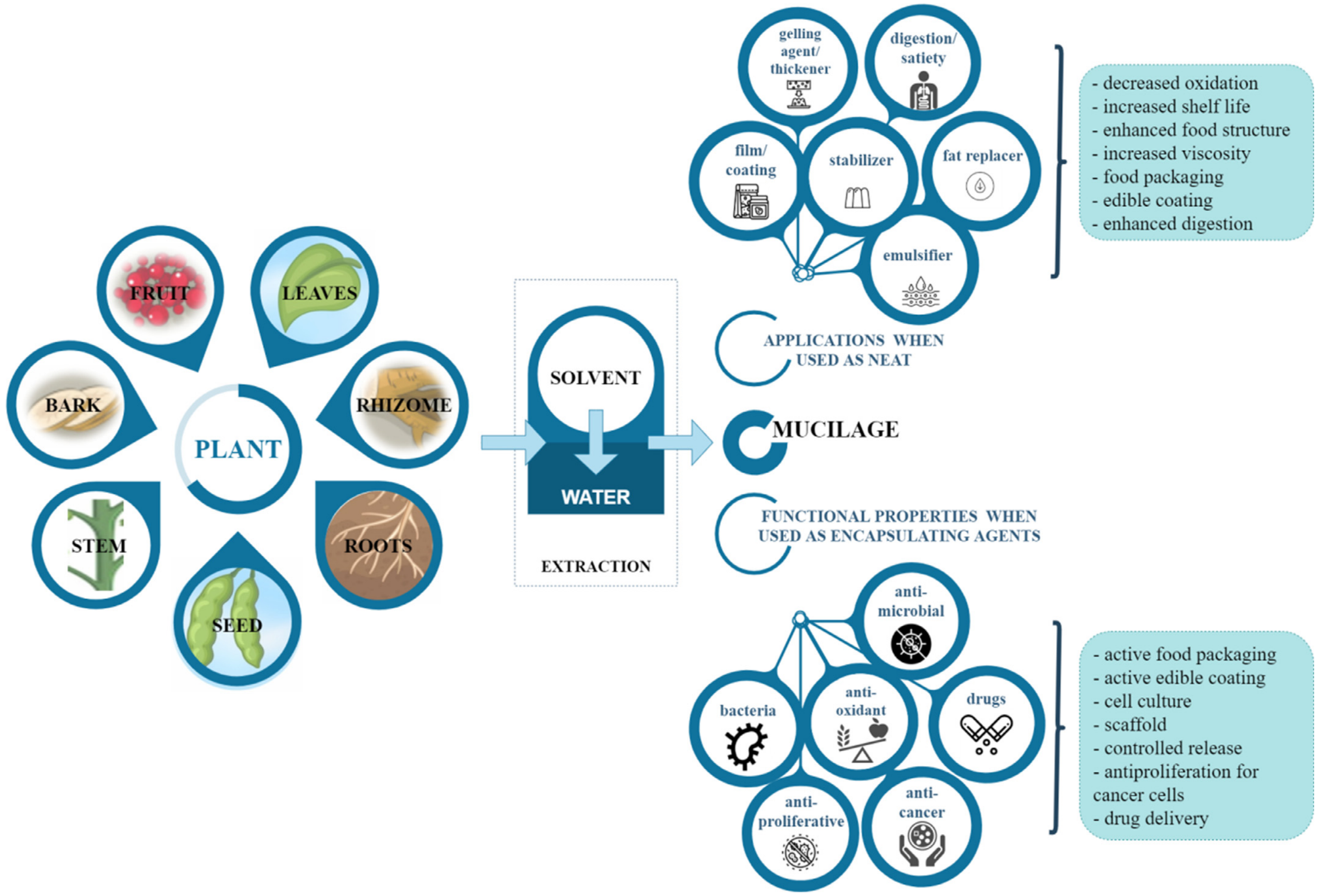

Fig. 1. Illustration of plant-based mucilage sources and their current uses.

Flaxseed (linseed) mucilage, found in the hull of the seed that consists four layers and has heterogeneous polysaccharide content, characterized as a mixture of neutral arabinoxylans and acidic rhamnose-containing polysaccharides (Puligundla & Lim, 2022; Waghmare, Preethi, Moses & Anandharamakrishnan, 2022). It is composed of D-xylose, D-arabinose, L-arabinose, D-glucose, D-galactose, D-rhamnose, L-rhamnose, D-fructose, and galacturonic acid (Dubois et al., 2020; Wu, Li, Wang, Zhou & Mao, 2010; Ziolkovska, 2012). Flaxseed mucilage has similar functionality with guar gum such as having high water binding capacity and being able to form thermo-reversible gels with desired rheological properties (Puligundla & Lim, 2022). Therefore, it has a great potential to replace the commercial gums in novel food formulations with its functional properties (Cakmak et al., 2021).

Psyllium (*Plantago ovata*) mucilage consists of acidic and neutral heteropolysaccharide constituents. It is characterized by β-D-1,4 linked xylopyranosyl units substituted by α-L-arabinofuranose moieties with a 3:1 xylose: arabinose ratio (Fischer et al., 2004). The mucilage of psyllium, by being an indigestible oligosaccharide, is a prebiotic compound that can improve the viability of probiotic bacteria (Arabshahi & Sedaghati, 2022). Psyllium mucilage has a good film forming capacity as well as carrying natural antioxidant substances which may be incorporated into films for their antioxidant activity (Halász et al., 2022).

Nascimento et al. (2016) researched polysaccharides in the mucilage of tomato seeds and analyzed their monosaccharide composition. In this study, an arabinoxylan structure having $(1 \rightarrow 4)$-linked β-D xylose units as the main chain and a low proportion of branching (~ 5.6%) with side chains of single arabinose or xylose units was observed. The linear structure with short side chain branches of tomato seed mucilage makes it an inexpensive biodegradable material alternative for film forming applications (Ghadiri Alamdari, Salmasi & Almasi, 2021).

Ritzoulis et al. (2014) summarized the composition of mucilage extracted from quince seeds as the mixture of cellulose, water-soluble polysaccharides, and amino acids with the most abundant ones being; glutamic acid, aspartic acid, and asparagine. They referred to the study of Lindberg et al. (1990) that reported the major water-soluble polysaccharide in mucilage of the seeds of quince, is a partially-O-acetylated (4-O-methyl-D-glucurono)-D-xylan with a very high amount of glucuronic acid residues. Vignon and Gey (1998) reported that it was composed of D-Arabinose, D-Xylose, D-Galactose, D-Glucose (Ara:Xyl:Gal:Glc) in the proportions of 8:54:4:34. Arabinose, a mixture of methylated and unmethylated aldobionic acids, and a cellulosic fraction were liberated in the hydrolysis of quince seed mucilage. Xylose was identified in the further hydrolysis of the aldobionic acids (Jouki, Tabatabaei Yazdi, Mortazavi & Koocheki, 2013). Due to its antimicrobial, antioxidant and antiulcerative properties, quince seed mucilage shows wound healing effect and has potential uses in the production of three-dimensional cell culture platforms as a natural polymer (Allafchian, Jalali, Mousavi & Hosseini, 2020; Hemmati, Kalantari, Jalali, Rezai & Zadeh, 2012; Jafari, Baniasadi, Rezvanpour & Lotfi, 2021).

In the early and current literature, the chemical composition of mucilages are evaluated based on deciphering their polysaccharide nature, however it is also important to determine the toxicity especially when the mucilage is directly added into the food formulations. Recently, Deore and Mahajan (2021) reported that *Cassia uniflora* seed mucilage (> 2 g/kg) was a generally recognized as safe (GRAS) substance confirmed by the acute oral toxicity tests. The study of Kumar (2014) showed that the use of okra seed mucilage up to 4000 mg/kg caused no mortality and toxic symptoms. In another study, hydrogels of mucilage derived from aloe vera and *Artemisia vulgaris* used for drug release applications were evaluated in terms of their toxicity (Frasat et al., 2021). The analyses were performed with female albino rats and rabbits, and there was no significant change observed in various biochemical parameters after 14 days of use.

4. Mucilage extraction

Seed mucilages can be extracted by soaking parts of plants in water due to their water-soluble properties. Extraction conditions (pH, temperature, process time, seed/solvent ratio etc.) and solvents (type, concentration, supercritical solvent, etc.) used for extraction directly affect the extraction yield and quality of extracted mucilage. To increase the extraction yield and the quality of extracted mucilage, various extraction techniques have been developed (Campos, Dias Ruivo, da Silva Scapim, Madrona & de C. Bergamasco, 2016; Kassem et al., 2021; Waghmare et al., 2022).

4.1. Conventional mucilage extraction

Conventional mucilaginous material extraction techniques from seed coats involve heating and/or agitation with mildly acidic, alkali or neutral water as a solvent (Fabre, Lacroux, Valentin & Mouloungui, 2015; Halász et al., 2022; Monrroy, García, Ríos & García, 2017; A. Ubeyitogullari & Ciftci, 2020; Wang et al., 2022). Besides, ethanol, ethylenediaminetetraacetic acid (EDTA), ammonium oxalate, sodium hydroxide, or hydrochloric acid solutions might be used for the precipitation of mucilage in the later stages of the extraction process (Monrroy et al., 2017; Morales-Tovar, Ramos-Ramírez & Salazar-Montoya, 2020; Wang et al., 2022; Zhao, Qiao & Wu, 2017).

In solvent-based extraction technique the mucilage is extracted via distilled hot water or cold water under continuous stirring or shaking (Dybka-Stępień et al., 2021). Then, the solution is filtered, and alcohol is added to the filtrate for precipitation of mucilage. To develop this technique, some physical pre-treatment applications such as crushing, dehulling, etc. may be needed. In some cases, agitation or homogenization are required to extract the mucilage effectively. Following the mixture of seed and water, the mucilaginous material gradually absorbs water, and filtration, agitation or centrifugation is needed to remove the mucilage from the bulk. Solvent extraction technique is one of the most modified techniques and sometimes stepwise extraction with the same solvent is recommended for obtaining mucilage fractions having different molecular weight, polysaccharide composition and functional properties (Puligundla & Lim, 2022; Razmkhah, Razavi, Mohammadifar, Koocheki & Ale, 2016; Zhao et al., 2017).

In addition to solvent-based extraction, various enzymes such as protease, α-amylase, mannanase, galactanase, xylanase, arabinase, cellulase, pectinase, hemicellulase, and β-glucanase are often utilized to extract the polysaccharides (Chiang & Lai, 2019; Ma et al., 2018; Wu et al., 2010; Yeh & Lai, 2022). However, increasing the enzyme concentration and the process (hydrolyzing) time might reduce the apparent viscosity of the extracted mucilage (Puligundla & Lim, 2022; Wu et al., 2010). Besides, enzyme assisted mucilage extraction might be employed as removing mucilaginous material. And this so-called “demucilaging” pretreatment is applied for further using the remaining seed itself as a fiber or protein source (Wu et al., 2010).

4.2. Novel methods for mucilage extraction

In addition to the conventional extraction methods, cold plasma, ultrasound, ultrasound coupled with enzymatic treatment and microwave-assisted applications are recently introduced as novel mucilage extraction methods (Han et al., 2016; Morales-Tovar et al., 2020; Niknam, Ghanbarzadeh, Ayaseh & Rezagholi, 2020; Safdar, Zhihua, Xinqi, Jatoi & Rashid, 2020; Yeh & Lai, 2022; Zielinska et al., 2022). As a non-thermal method, cold plasma treatment of okra pods, especially at longer process times (15–30 s), caused formation of the microcracks in the surface of okra which then helped to increase extraction yield, and the amount of rhamnose in water-soluble pectic fractions (Zielinska et al., 2022).

The ultrasonic extraction utilizes cavitation to extract the mucilages by disrupting the biological cell wall through the creation of pores. Thus, this process helps better penetration of solvent and accelerates mass transfer (Hedayati et al., 2021; Rostamabadi et al., 2022). Similar to cold plasma processing, the application of ultrasound for pomelo seed mucilage extraction was found more effective than enzymatic extraction in terms of mucilage yield (Yeh & Lai, 2022). However, Yeh and Lai (2022) reported that ultrasonic, enzyme-assisted, and ultrasound assisted enzymatic extraction methods increased glucose, mannose, arabinose and rhamnose fractions, whereas decreased the galactose and galacturonic acid compared to the conventional citrate buffer extraction due to destruction of cell wall integrity and cellulosic fractions possibly released from the matrix. Pereira et al. (2019) studied the high intensity ultrasonic extraction of mucilage from mutamba seeds, and according to their experimental design, both ultrasonic power and process time were found to be significantly effective ($p<0.0001$) on overall mucilage yield and the amount of total sugar in the mucilage. The highest yield and the highest total sugar amount were found at the highest ultrasonic power (600 W) for the longest process time (7 min), which was attributed to the pronounced effect of acoustic cavitation and the resultant formation of shock waves, microjets, turbulence, shear forces, and rise of pressure (Pereira et al., 2019).

The microwave-assisted mucilage extraction provides advantages in terms of reduction of extraction period, minimizing solvent consumption, and improved extraction efficiency compared to conventional methods (Felkai-Haddache et al., 2016). Cell wall integrity is destroyed by detaching the parenchymal cells with the effect of microwave radiation and improves the interaction between solvent and the soluble mucilaginous material (Safdar et al., 2020). Safdar et al. (2020) determined that the microwave-assisted flaxseed mucilage extraction took lower time compared to conventional (hot water, acid/alkali) or ultrasonic extraction methods, although the mucilage yield was lower compared to them and the purity of the extract was better in ultrasonic extracted mucilage. In contrast to this finding, Han et al. (2016) determined that microwave-assisted mucilage extraction at the optimized conditions from the peel of prickly pear fruit (*Opuntia dillenii* Haw.) reached higher yield (15.6%) compared to the hot water extraction (13.4%).

The primary goal of mucilaginous material extraction is to increase the mucilage yield by altering the processing conditions (power, temperature, process time, seed/water ratio etc.). However, extreme processing conditions may also decrease the purity of the mucilage extracted. The purity is measured by the amount of protein found in the mucilaginous extract, and the extracts with higher protein correspond to the lowest mucilage purity (Fabre et al., 2015; Niknam et al., 2020; Safdar et al., 2020; Wang et al., 2022).

5. Current and potential uses of mucilage in food industry

5.1. Utilization of mucilage in gel formation

Gels have potential to be used in food and pharmaceutical industry to deliver bioactive compounds. Different types of gels namely aerogels, xerogels, cryogels, hydrogels, oleogels, and bigels have been studied comprehensively for their potential application as bioactive agent carriers. However, evaluating their physicochemical stabilities and their effects on sensory properties of actual food samples are still needed. Moreover, changes in gel structures may occur during storage and therefore, it is important to consider following aging and rheological changes when gels are designed for food applications (Ferraro et al., 2022).

Hydrogels are 3D networks composed of polymers that are cross-linked chemically or physically and are able to hold a large amount of water in their structure (Kavousi, Fathi & Goli, 2017; Sacco et al., 2021). Devil's cotton (*Abroma augusta*) mucilage was successfully used to form hydrogels as probiotic carriers, where 95.6%, 96.12% and 96.8% of *Lactobacillus casei, Lactobacillus rhamnosus* and *Lactobacillus acidophilus* were embedded efficiently within the hydrogel structure, respectively (Roy et al., 2022).

Unlike hydrogels, aerogels are solid structures produced by removing the liquid within the gel network, and they have gained increasing interest due to their properties such as nanoporous structure, ultra-low density, and high surface area, which then provide high surface area and increase bioavailability of bioactive compounds (Abdelmonem et al., 2022; Falahati & Ghoreishi, 2019; Selvasekaran & Chidambaram, 2021; Ubeyitogullari & Ciftci, 2020). The scientific term for the solid structure that is produced by drying the liquid gel network depends on the drying method. Gels can be dried using supercritical CO_2 method, freeze-drying, or room temperature drying and the solid structures are referred as "aerogel", "cryogel" or "xerogel", respectively (Selvasekaran & Chidambaram, 2021). However, in literature these terms are often used interchangeably. For example, Abdelmonem et al. (2022) formed hydrogels using flaxseed mucilage followed by freeze-drying and referred to this process as "aerogelation". Apart from this, they also loaded hydrogels with curcumin and proved that it can be used for potential drug delivery applications of the low-cost cryogels produced from them (Abdelmonem et al., 2022).

Polysaccharide-type aerogels (starch, alginate, konjac glucomannan, pectin, carrageenan and cellulose) are the leading type of food grade aerogels due to their low cost and availability. To date, there are only a few studies that have utilised seed mucilage-based food-grade aerogels. Camelina seed mucilage was successfully utilized to form stable aerogels that showed solid-like rheological properties (Ubeyitogullari & Ciftci, 2020). In order to compare the aerogel properties and flaxseed lignan (secoisolariciresinol diglucoside) loading efficiency, flaxseed mucilage and β-glucan were utilized in the study of Comin, Temelli and Saldaña (2015). The aerogel volume and surface area of flaxseed mucilage based samples were found significantly higher than β-glucan including ones; however both aerogels had similar concentration of flaxseed lignin showing its high potential to be used as a delivery vehicle for health benefiting bioactive compounds (Comin et al., 2015). Balangu seed mucilage was also used to form aerogels with paracetamol loading, proving its potential use for drug delivery purposes (Falahati & Ghoreishi, 2019). Seed mucilage-based aerogels have the potential to extend not only the enrichment of foods with water-insoluble bioactives, but also has the thickening and stabilization effect for the food matrix.

Oleogels are functional ingredients that can mimic fats in meat products or used as a replacement of shortening in cake or other bakery products (Pehlivanoglu et al., 2018; Pérez-Álvarez et al., 2020). Oleogels are formed with polysaccharides namely; mucilage, gums, and fibers and vegetable oils including highly unsaturated fatty acids. The liquid oils are converted into solid gel-like structure using oleogelators, and the resulting oleogel resembles solid fats by its rheological, viscoelastic properties and firmness characteristics (Pehlivanoglu et al., 2018).

5.2. Utilization of mucilages as an additive in food formulations

Concerns about the negative health effects of consumption of high fat foods have led consumers and accordingly the food industry to put more emphasize on products with reduced fat. However, since fats contribute to the texture, flavor and stability of food products, it is difficult to achieve a standard product quality in reduced-fat products (Mun et al., 2009). Therefore, it is necessary to develop strategies to reduce fat content in food products that maintain the desired quality and sensory properties (B. Wu, Degner & McClements, 2013). Carbohydrates and proteins can be used as fat substitutes that have much lower calories, but they have to meet the texture and other sensory properties of fat.

Table 1 summarizes the results of several studies on utilization of plant mucilages as fat replacers. Even though sometimes the use of mucilages in the recipes may lead to undesired textural and sensorial effects, in some cases, such as in yoghurt, addition of mucilage leads to lower syneresis, which may be due to high water holding capacity of the mucilages. However, it is always important to evaluate the sensory characteristics of the reduced-fat products that are produced by using plant-based mucilages, as they may alter these attributes significantly (Fernandes & Salas-Mellado, 2017).

Chia mucilage has water affinity due to presence of proteins and lipid affinity due to its lipid compounds. Therefore, chia mucilage is used for fat/oil replacement in bread, cakes, cookies, dairy products, mayonnaise, and sausages; egg replacement especially for the design of vegetarian and specialty foods (free from foods for allergic people); gluten replacement to achieve the desired structural quality (e.g. pasta and cakes), emulsifier and stabilizer replacement to achieve the desired texture; mouthfeel properties like ice cream and to stabilize the product during transport and storage (e.g. ice cream), replacement of phosphates in meat products to bind more water and improve emulsification properties by regulating pH and ionic strength (Antigo, Stafussa, de Cassia Bergamasco & Madrona, 2020; J.H. Chiang et al., 2021).

Quinzio, Ayunta, López de Mishima and Iturriaga (2018) evaluated oil-in-water emulsions prepared with *Opuntia ficus-indica* L. Miller mucilage and compared with those prepared with other hydrocolloids (guar gum, xanthan gum, and carboxymethylcellulose). The authors concluded that the mucilage was suitable for use in food, mainly because it was easily extracted, inexpensive, and had similar properties with the most widely used commercial hydrocolloids. Similarly, Nikbakht Nasrabadi, Sedaghat Doost, Goli and Van der Meeren (2020) reported the production of an emulsion prepared with flaxseed mucilage to protect flaxseed oil from oxidation and control of lipid digestion, which may help to increase satiety. Câmara et al. (2020) reported that chia seed mucilage (both mucilage powder and chia seed mucilage-based emulsion) can be utilized as a good fat replacer with similar appetite sensation and satiety as pork back fat in bologna sausage.

5.3. Encapsulation of biologically active ingredients with mucilage

Functional biopolymers which are alternatives to synthetic ingredients are being investigated by food industry. Employement of hydrocolloid biopolymers for encapsulation shows promising results for protecting bioactive substances from oxidation and loss of nutritional value. Mucilages are good candidates for micro and nanoencapsulation of bioactive compounds, essential oils, and microorganisms (e.g. probiotics), due to their solubility, biodegradability, stability, and edibility, as well as their high molecular weight carbohydrate polymers. For instance, chia seed mucilage was found to be an effective wall material for the nanoencapsulation of chia seed oil, providing high encapsulation efficiency, loading capacity and better oxidative stability (de Campo et al., 2017). Moreover, in a study where nopal mucilage and mesquite gum were used together and separately as wall materials to encapsulate lemon essential oil, the nopal mucilage led to bigger average particle size but higher encapsulation efficiency and oxidative stability compared to the sample with mesquite gum alone (Cortés-Camargo et al., 2017). In addition, utilization of aloe vera mucilage together with agave fructans as wall materials and addition of several other hydrocolloids (gum Arabic, xanthan gum, guar gum, whey protein concentrate) to encapsulate probiotics achieved high survival rates and stable powders (Ceja-Medina et al., 2020). These results show that plant-based mucilages can be used in combination with other wall materials to improve desired properties of spray-dried powders.

Gastrointestinal disintegration behavior of encapsulation agents is an important consideration for nutraceutical release applications. It is well-known that mucilages have excellent disintegration behavior due to their swelling and absorption properties (Waghmare et al., 2022).

Table 1
Studies on fat replacement using plant-based mucilages in food products.

Product	Initial fat content	Fat replacer	Final fat content	Notes	Reference
Chicken meat model	Model recipe: 365 g ground meat + 135 g back fat + salt	Hoary basil seed mucilage	80% of the back fat was replaced.	Similar sensory perception to the control group was achieved.	Saengphol & Pirak, 2018
Mayonnaise	80.7%	Psyllium mucilage	38.2%	Textural characteristics and sensory properties aggravated with mucilage addition.	Amiri Aghdaei, Aalami, Babaei Geefan & Ranjbar, 2014
Mozzarella cheese	27.5%	Okra mucilage	13.2%	Organoleptic characteristics deteriorated with increasing mucilage concentrations. Masking with flavor or coloring agents needed.	Akhtar et al., 2022
Yoghurt	4.2%	Quince seed mucilage	2.5%	A decrease in syneresis was observed when mucilage was used. Color did not change.	Nikoofar, Hojjatoleslamy, Shakerian & Molavi, 2013
Yoghurt	3.9%	Chia seed mucilage	<1%	Mucilage addition decreased the syneresis level, while color and sensory acceptance worsened.	Ribes, Peña, Fuentes, Talens & Barat, 2021

There are several studies showing that mucilages can be used for controlled release of nutraceuticals. In the study of Taheri, Kashaninejad, Tamaddon and Jafari (2021), vitamin D_3 resistant to the acidic conditions of the stomach and intended to be released in the small-intestine conditions, was encapsulated with a complex of β-lactoglobulin and cress seed mucilage. As a result, 15% vitamin D_3 release was observed under gastric conditions and 70% under small intestinal conditions in the first 30 min. Also, cress seed mucilage protected the pepsin recognition site in β-lactoglobulin by acting as a barrier and controlled proteolysis under in vitro gastric conditions. Under the alkaline environment of intestinal conditions, the dispersion of mucilage and swelling of particles facilitated the penetration of intestinal fluids thus particles were easily hydrolyzed under intestinal conditions (Taheri et al., 2021). In addition, there are also studies in which controlled release of curcumin, that has low water solubility and is sensitive to alkaline conditions and oxidation, was performed by encapsulation with a complex coacervate of cress seed mucilage and sodium caseinate. Lycopene, which is lipophilic, sensitive to oxidation and has low bioavailability in the small intestine, was successfully released under simulated gastrointestinal conditions by a three-layered nanofiber of zein/ basil seed mucilage/ zein Kavousi, Fathi and Goli, (2018); Komijani et al., (2022). Medina-Torres et al. (2019) investigated aloe vera mucilage as an encapsulation agent for gallic acid. The results showed that mucilage was effective as a wall material, and the encapsulated compound retained its antioxidant activity regardless of the thermal process (spray drying). Similarly, da Silva Stefani et al. (2019) encapsulated flaxseed oil in the form of nanoparticles with chia seed mucilage and used them for enrichment of orange juice. The prepared nanoparticles showed good structuring ability and good bioaccessibility of flaxseed oil after in vitro digestion, indicating the potential of chia seed mucilage as a good structuring/wall material agent for nanoencapsulation applications.

Studies on the use of mucilage for the release of bioactive substances are mostly concerned with bioactive loading capacity, toxicity, and simple in vivo studies. Detailed in vivo studies are needed to better understand the performance of these bioactive-loaded polymer systems. In addition, it is necessary to study how these bioactive-loaded polymer systems interact with cells, tissues and organs before their use in foods (Rostamabadi et al., 2022).

The electrospraying and electrospinning process requires a polymeric solution to manufacture nano/micro capsules or fibers under high voltage application while the solution passes through a thin capillary (Cakmak, Kumcuoglu & Tavman, 2018; Charles et al., 2022; Dehghani, Noshad, Rastegarzadeh, Hojjati & Fazlara, 2020; Hadad & Goli, 2018). The solvent of the polymeric solution evaporates, whereas the electrospun or electrosprayed fibers or particles reach the ground collector.

Recently, plant seed mucilages are used for the production of electrosprayed particles (or nanocapsules) and electrospun (nano) fibers as biopolymeric wall materials for encapsulation of biologically active substances as a novel method (Allafchian et al., 2020; Allafchian, Saeedi & Jalali, 2022; Charles et al., 2022; Dehghani et al., 2020; Golkar, Allafchian & Afshar, 2018, 2019; Hadad & Goli, 2018; Jafari et al., 2021; Komijani et al., 2022; Kurd, Fathi & Shekarchizadeh, 2017). For this purpose, basil, chia, flax, yellow mustard, and *Alyssum lepidium* seeds' mucilages can be used individually or with another polymeric material (polyvinyl alcohol in most cases) for producing electrosprayed capsules or electrospun nanofibers (Charles et al., 2022; Dehghani et al., 2020; Golkar et al., 2018; Hadad & Goli, 2018; Karami, Kamkar, Shahbazi & Misaghi, 2021; Komijani et al., 2022; Kurd et al., 2017; Rentería-Ortega et al., 2021). Successful encapsulation studies were found in the literature with seed mucilage to increase the stability of the active substance or controlled release namely for cardamom, *Ziziphora clinopodioides* essential oil, thymol and carvacrol, lycopene and glucose oxidase (Charles et al., 2022; Dehghani et al., 2020; Komijani et al., 2022; Rentería-Ortega et al., 2021). The encapsulation efficiencies varied greatly depending on the electrospray/spinning conditions, concentration of the active substance or mucilage/polymer ratio, but it reached up to 95.6% which demonstrated the suitability of plant seed mucilages as biocompatible alternatives.

Plant seed mucilages are an interest of medical applications other than food industry, such as *Alyssum lepidium, Plantago major*, flaxseed, quince and balangu seed mucilage, which were employed for the production of biocompatible and 3D electrospun cell culture scaffolds or drug delivery applications (Allafchian et al., 2020, 2022; Doostan, Doostan, Mohammadi, Khoshnevisan & Maleki, 2023; Golkar et al., 2018, 2019). For this purpose, antibacterial agents, antibiotics or antinflammatory drugs such as ciprofloxacin hydrochloride, cefixime trihydrate, tetracycline hydrochloride, and diclofenac can be successfully encapsulated with *Hibiscus rosa sinensis* leaf, *Lallemantia royleana* seed, quince seed, basil seed and *Mimosa pudica* seed mucilages, respectively for controlled release of active substances as drugs or wound dressings (Deore & Mahajan, 2022; Ghumman et al., 2022; Hosseini & Nabid, 2020; Massey, Iqbal, Rehman, Iqbal & Iram, 2022; Sahu, Chouksey & Ganju, 2022). Depending on the encapsulated model drug, mucilages are used for colonic, floating, gastric, mucoadhesive, oral, ocular, and topical drug delivery applications (Deore & Mahajan, 2022; Gaikwad, Patil & Killedar, 2022; Mahmood et al., 2022; Nayak, Pal & Das, 2013; Shahid et al., 2021; H. Yu, Wu, Lin & Feng, 2020). Besides, electrospun wound dressings can be readily produced from polyvinyl alcohol (PVA) cross-linked with quince seed or sage seed mucilages (Jafari et al., 2021; Yekrang, Saghafi, Yousefi & Ghaffari, 2022). Antibacterial agents such as silver nanoparticles or ciprofloxacin can also be added into wound dressing compositions for providing the antimicrobial activity (Massey et al., 2022).

The plant mucilage itself rarely possesses antibacterial/antifungal activity as it was observed in flaxseed, sage seed and aloe vera mucilage (Castillo et al., 2010; Doostan et al., 2023; Yekrang et al., 2022). Their antimicrobial activity are associated with the components presented at the structure of mucilage such as uronic acids and its derivatives (Vignesh & Nair, 2018). The antimicrobial properties of the mucilages are attributed to the damage of cell membrane, thus leaking out the vital constituents and hence cell death (Yekrang et al., 2022). Also, unsaturated fatty acids or phenolic compounds extracted together with the mucilage are reported to be responsible for the antimicrobial activity (D'souza et al., 2023; Doostan et al., 2023).

5.4. Mucilage-based edible films and coatings

The increasing concerns on the environmental impacts of petroleum-based plastics, inadequate rates of recycling or composting facilities and increasing demands on safe and healthier foods have made scientists to find alternative methods or materials to solve these problems (Yemenicioğlu, Farris, Turkyilmaz & Gulec, 2020). Thus, biodegradable polymeric materials extracted from seed mucilage have become one of the options to be used in food packaging applications including stand-alone films or thin layer coatings (Beikzadeh et al., 2020). Along with their thickening and emulsifying effects, seed mucilage is an appropriate candidate to form an edible film, which can improve the performance of stand-alone films (filler effect), provide active properties (e.g. antimicrobial, antioxidant), as well as having potential to carry the active compounds such as enzymes, vitamins, flavors, nanoparticles, antioxidants, antimicrobial agents, probiotics, and colorants by its encapsulation effect (Hashemi, Khaneghah, Ghahfarrokhi, & Eş, 2017; Kalegowda, Chauhan, & Urs, 2017; Kamel, Afifi, Kassem, Elkasabgy & Farag, 2020; Niknam, Ghanbarzadeh, & Hamishehkar, 2019; Oluwaseun, Samuel & Sunday, 2014; Treviño-Garza, García, Heredia, Alanís-Guzmán, & Arévalo-Niño, 2017; Zegbe, Mena-Covarrubias & Domínguez-Canales, 2015). The advantages of seed mucilage when used as edible coatings or films include; i) high extraction yields, ii) low cost, iii) sustainable/renewable source, iv) good compatibility with various active ingredients that can be used to obtain active packaging films, v) ease of extraction, vi) potential to improve the overall performance of other biopolymers when used as fillers.

5.4.1. Film forming/coating ability of seed mucilage

Seed mucilage contains varying amounts of polysaccharides to be used as edible packaging materials (Olawuyi et al., 2021). For instance, flaxseed mucilage is made of acidic pectic like materials and neutral arabinoxylans with an ability to form thermo-reversible gels (Puligundla & Lim, 2022), whereas basil seed mucilage is mainly composed of glucomannan, xylan, and glucan and can be turned into biodegradable elastic films with various plasticizers (Beikzadeh et al., 2020). Therefore, the coating/film materials obtained from mucilage show diverse properties depending on the source, structural/macromolecular properties and extraction techniques applied to the seeds (Olawuyi et al., 2021).

The formation of film or coating solutions require some structural and functional properties such as solubility, certain rheological characteristic (required viscosity), spreadability/wettability, good stabilizing/encapsulation ability to carry other active components within the polymeric structure (compatibility) (Kumar & Neeraj, 2019). These properties also decide mucilage polysaccharides to be applied as spraying, dipping, spreading (based on viscosity), stand-alone films, emulsified films with various oils, carriers of food additives including antioxidant and antimicrobial agents (Hashemi, Khaneghah, Ghahfarrokhi, & Eş, 2017; Kalegowda, Chauhan, & Urs, 2017; Kamel et al., 2020; Niknam, Ghanbarzadeh, & Hamishehkar, 2019).

The structural and macromolecular aspects of mucilages (the number of hydrophobic groups, molecular weight and distribution, presence of branches, linkages) extracted from seeds with their complexity and diversity (heteropolysaccharides) has an impact on the final film or coating properties (Hung & Lai, 2019; Olawuyi & Lee, 2021). For instance, high molecular weight polysaccharides form highly viscous film forming solutions due to the high intermolecular interactions, and may result in low water solubility while short side chained polysaccharides give disrupted interchain entanglements with lower viscosity solutions (Guo, Hu, Wang & Ai, 2017; Nie et al., 2019). As stated by Dos Dos Santos, Souza, Teixeira, Vicente and Cerqueira (2015), the ratio of mannose to galactose found in various mucilage sources had a critical role on the final film properties. The authors reported that high mannose/galactose ratio resulted in lower water vapor permeability (WVP) values due to the high intermolecular forces, which did not allow the diffusion of water molecules from the films. Similarly, the higher arabinose to xylose ratio presented a highly branched structure with better gel forming abilities (L. Yu et al., 2017). However, linear mucilage polysaccharides have been reported to show better film forming abilities with higher viscosities when compared to the branched polymers (Patova, Golovchenko & Ovodov, 2014).

5.4.2. Mucilages as stand-alone films

Recently, various edible films made of polysaccharides obtained from flaxseed, chia, basil, cress, quince, okra seeds, and aloe vera have been studied by different researchers (Beigomi, Mohsenzadeh, & Salari, 2018; Gheribi et al., 2018; Hashemi, Khaneghah, Ghahfarrokhi, & Eş, 2017; Karami et al., 2019; Sadeghi-Varkani, Emam-Djomeh, & Askari, 2018). However, compared with stand-alone films prepared from synthetic conventional polymers, seed mucilage polysaccharide-based stand-alone films have limited applications due to their weak barrier and mechanical properties (Olawuyi et al., 2021). Therefore, oxygen/water vapor barrier properties, resistance to water, optical properties (transparency), thermal stability, and mechanical performance as well as consumer acceptance properties of seed mucilage-based films have been improved by blending with other biopolymers, and adding fillers or plasticizers (Gheribi et al., 2018), as summarized in Table 2. In these applications, the rigidity of films is reduced to obtain a flexible structure and the intermolecular interactions are improved to decrease the diffusion of gas/water vapor molecules throughout the polymeric structure. Even though mucilage has good oxygen barrier properties, Marvdashti, Koocheki, & Yavarmanesh (2017) blended *Alyssum homolocarpum* seed mucilage-based films with PVA to further improve the oxygen permeability with the help of increased interaction and reduced free spaces between polymer chains. Similarly, addition of lipids has been shown to decrease the water vapor permeability of mucilage films due to the increase in hydrophobicity of the structure leading to close micro-voids of water passage (Hashemi, Khaneghah, Ghahfarrokhi, & Eş, 2017; Niknam, Ghanbarzadeh, & Hamishehkar, 2019). The addition of lipids and common plasticizers also increased transparency and decreased water solubility (Beigomi, Mohsenzadeh, & Salari, 2018; Mohammadi Nafchi et al., 2017). On the other hand, plasticizers lead to increased chain mobility, flexibility, thickness and intermolecular spacing thus, decrease the tensile strength (de Paiva et al., 2021). However, the addition of nanofillers resulted in both increased flexibility and tensile strength of quince seed mucilage edible films (Shekarabi, Oromiehie, Vaziri, Ardjmand & Safekordi, 2014). Recent studies are summarized in Table 2, the detailed explanations can be found in other studies (Beikzadeh et al., 2020; Olawuyi et al., 2021; Salehi, 2019).

5.4.3. Mucilages as coating material

The improvement of mucilage seed-based stand-alone films has been possessed by the addition of various components, as discussed earlier. However, this is not required for mucilage-based direct food coating applications (Olawuyi et al., 2021). In recent years, seed mucilage-based coating materials have been effectively used for various types of foods such as minimally processed, highly perishable fresh fruits and vegetables or meat products (Gheribi & Khwaldia, 2019). A thin film layer is applied onto the surface of food product as a coating aiming to protect the food against oxidation, microbial spoilage, loss of firmness and weight, UV-light effects and delay ripening (Kumar & Neeraj, 2019). The thickness and effectiveness of coating on the food surface depend on the seed mucilage's film forming abilities including the compatibility of mucilage and food surface, spreadability and (hydrophobicity) wetting

Table 2
The enhancement/improvement of mucilage seed-based films using additives.

Source	Additives or Composite ingredient	General conclusion	Reference
Basil seeds	*Origanum vulgare* essential oil (1–6%)	The water vapor permeability was decreased. The biological activity was enhanced.	Hashemi, Khaneghah, Ghahfarrokhi, & Eş, 2017
Cactus cladodes	Plasticizer (glycerol, sorbitol, polyethylene glycol 200 or 400 at 40%)	Water vapor barrier properties enhanced. Tensile strength, thermal stability, and elongation were increased.	Gheribi et al., 2018
Cactus cladodes	Polyvinyl alcohol (90–60 wt ratio)	Water contact angle increased. The gas and light barrier and mechanical properties enhanced.	Gheribi & Khwaldia, 2019
Chia seed	Clove oil (0.1–1.0%, v/v)	The antimicrobial activity was enhanced. Tensile strength, elongation, and transparency reduced.	Capitani et al., 2016
Chia seed	Starch nanocrystals (3, 6%)	Good antimicrobial and antioxidant properties were obtained. Thermal and mechanical properties were enhanced.	M. Mujtaba et al., 2019
Chia seed	Cellulose nanofibers (3, 6%)	Mechanical properties were improved. High antioxidant and antimicrobial activities were obtained. Antiproliferative properties towards cancer cells were obtained.	M. Mujtaba et al., 2019
Fenugreek seed	Nanoclays (montmorillonite, halloysite, nanomer at 2.5–7.5%)	Oxygen barrier, thermal properties and antimicrobial activity were improved. Tensile strength increased and elongation decreased (up to 5% clay addition)	Memiş, Tornuk, Bozkurt & Durak, 2017
Fenugreek seed	Taro starch (combination, 1:1, 1:2, 1:3, 2:1)	Rupture strength improved and water affinity decreased with the increasing starch content.	Mohite & Chandel, 2020
Flaxseed	Polyvinyl alcohol (1:1, weight ratio)	The thermal stability was enhanced. Rigidity and resistance were reduced and flexibility was improved.	de Paiva et al., 2021
Okra pod	Corn starch (4–11%)	The water vapor permeability and solubility were lowered. Good mechanical and thermal properties and swelling capacity were obtained.	Araújo et al., 2018
Psyllium seed	Modified starch	The water solubility, water vapor permeability and tensile strength were reduced. The elongation was increased.	Sadeghi-Varkani, Emam-Djomeh, & Askari, 2018
Quince seed	Nanoclay (Cloisite 30B)	Tensile strength and elongation were increased. The gas barrier properties were improved.	Shekarabi et al., 2014
Sage seed	Oleic, stearic, palmitic acids (10–25%)	Moisture uptake, water vapor permeability, solubility, and elongation were decreased. The contanct angle, tensile strength, and opacity were increased.	Amini & Razavi, 2020

abilities (Salehi, 2019). Thus, the surface properties of the food product to be coated and the wettability of seed mucilage based coating solution are the most important parameters that have to be known before coating to obtain a good barrier on the food surface with favorable shelf life (Vieira et al., 2016). To enhance the coating properties of seed mucilage solutions, blending with other polymers, adding different plasticizers, applying layer by layer dipping, spraying or applying film as coating directly, and addition of active ingredients such as antimicrobial and antioxidant agents have been studied by various authors (Oluwaseun et al., 2014; Treviño-Garza, García, Heredia, Alanís-Guzmán, & Arévalo-Niño, 2017; Zegbe et al., 2015). In these modification techniques, the wetting ability of seed mucilage is altered regarding hydrophobic/hydrophilic properties, interaction with the food surface and higher preservative effects (increasing the shelf life based on the requirements of food product) (Beikzadeh et al., 2020). Various coating applications to extend the shelf life of fresh products (post-harvest), meat products, dairy products or semi-processed food products are shown in Table 3.

6. Gastrointestinal behavior and colonic functions of mucilages

In recent years, the demand for plant-based food products has increased compared to animal-based products due to their positive effects on both sustainability and health. Studies have shown that plant-based foods rich in dietary fiber, oligosaccharides, and unsaturated fatty acids can reduce the incidence of cardiovascular diseases, cancer, aging, atherosclerosis, and neurodegenerative diseases. In this sense, plant mucilages are potential component to fulfill beneficial properties on health and can be used as a functional ingredient in food formulations (Kassem et al., 2021; Sá, Moreno & Carciofi, 2020).

Understanding the gastrointestinal behavior of mucilage is crucial to determine its potential health-promoting properties. Mucilages are large and branched polysaccharides composed of various sugar and uronic acid units linked with glycosidic bonds in beta configuration. It is known that the beta configuration of mucilages is indigestible by the enzymes of human digestive system, while the intestinal flora partially digests the mucilage forming short-chain fatty acids (Bone & Mills, 2013; Ciudad-Mulero, Fernández-Ruiz, Matallana-González & Morales, 2019; Waghmare et al., 2022). This is also confirmed by a study on the resistance of flaxseed and chia mucilage to the acidic conditions of gastric and pancreatic enzymes. Flaxseed mucilage was reported to be hydrolyzed by 1.5% and chia mucilage by 5.6% at pH 1, while the percent of hydrolysis ranged from 2.6% for flaxseed mucilage to 10.3% for chia mucilage with pancreatic enzymes. These results suggest that seed mucilage is partially digested in the gastrointestinal tract and the remaining undigested substrate could be used as a prebiotic source for commensal bacteria in the gut (Lai, How, Ghazali & Pui, 2021).

Recent studies on the behavior of chia seed mucilage during in vitro digestion have shown that the viscosity of chia mucilage was slightly reduced. This suggests that chia mucilage maintain its structure thanks to resistance to acidic conditions and enzymatic degradation during digestion. In addition, in vitro studies have shown that the apparent viscosity in the stomach increases as a function of the concentration of chia mucilage. It is believed that this behavior restricts the movement of molecules during digestion, causing a denser and compact structure, which prevents access to enzymes and digestive juices. With all these properties taken into account, chia mucilage is a functional ingredient that can help delay gastric emptying, slow digestion and increase the food functionality. In the small intestine, chia mucilage has been observed to increase the viscosity of the medium by inversely proportional to the concentration. This is due to the high concentration of mucilage that precipitates with the effect of peristaltic movements when passing from the stomach to the small intestine and does not preserve its structure (Câmara et al., 2020; Lazaro, Puente, Zúñiga & Muñoz, 2018; Tamargo, Cueva, Laguna, Moreno-Arribas & Muñoz, 2018; Vera, Laguna, Zura & Muñoz, 2020, 2019). Ribes, Gallego, Barat, Grau and Talens (2022) reported that chia mucilage added to chicken and vegetable purees can be used in food products designed for individuals with dysphagia because it maintains the consistency and viscosity and hardly

Table 3
Recent applications of edible films and coatings with mucilage.

Mucilage type	Concentration (%, wt.)	Additives/Composite ingredient	Application type	Food product	General conclusion	Reference
Aloe vera	1 or 2	Chitosan (1–2%)	Coating	Tomatoes	The total soluble sugar, phenolic content, lycopene, and pectate lyase activity were increased. The ascorbic acid concentration and titratable acidity were reduced.	Khatri et al., 2020
	33	–	Coating	Cherry laurel fruit	The weight and firmness losses, color change, and ethylene production were delayed	Ozturk et al., 2019
	50	–	Coating	Lotus root slices	The weight loss, enzymatic browning, enzyme activities, total aerobic bacteria count, leakage, and oxidation levels were reduced.	Ali et al., 2019
	50 and 100	Fagonia indica extract (1%)	Coating	Sapodilla fruits	The weight loss, firmness loss were reduced. The antioxidant capacity, phenolic content was increased.	Khaliq, Ramzan & Baloch, 2019
	50	–	Coating	Raspberry	The respiration and ripening were delayed.	Hassanpour, 2015
	2	Gum arabic (10%) Thyme oil (1%) Chitosan (1%)	Coating	Avocado	The anthracnose, the loss of firmnes, and color change were reduced and fungicidal effect was improved.	Bill, Sivakumar, Korsten & Thompson, 2014
	50	Cysteine (0.5%)	Coating	Apple slice	The browning, weight loss, and softening were delayed. The aerobic bacterial and fungal growth was reduced.	Song, Jo, Song, Min & Song, 2013
Basil	0.1	Aloe vera gel (30%, wt.)	Coating	Apricot	The firmness, titratable acidity, and antioxidant activity were increased. The ethylene production/respiration rate, and weight loss were reduced.	Nourozi & Sayyari, 2020
	3	Echinacea extract (0.5–3%, wt.)	Coating	Strawberry	The antioxidant, superoxide dismutase and antimicrobial activities were increased. The shelf life was extended.	Moradi, Emamifar & Ghaderi, 2019
	10 g/L	Thymol (6–10%, wt.)	Coating	Shrimp	The microbial growth and total volatile basic nitrogen values were decreased.	Khazaei, Esmaiili & Emam-Djomeh, 2017
	10	Cumin seed essential oil (20% w/v)	Coating	Tomato	The weight loss, color change, and titratable acidity were decreased.	Tabaestani, Sedaghat, Pooya & Alipour, 2013
Flaxseed	2	Chitosan *Ziziphora clinopodioides* oil (0.25 and 0.5%) Sesame oil (0.5–0.75%)	Film	Raw minced trout	The growth of patogenic bacteria was reduced.	Karami et al., 2019
	0.75, 1, and 1.25	Xanthan gum (0.5%)	Coating	Cheddar cheese	Moisture content was reduced. The lipolysis and protein content were increased.	Soleimani-Rambod, Zomorodi, Raeisi, Asl & Shahidi, 2018
	0.3 °Brix	Alginate (20 g/L) Ascorbic acid (15 g/L) Probiotics (10 g/L)	Coating	Fresh-cut yacon	The weight loss, darkening and color change were decreased. The number of probiotic bacteria was preserved.	Rodrigues, Cedran & Garcia, 2018
	0.3, and 0.6	Lemon grass essential oil (200–800 ppm)	Coating	Pomegranate arils	The microbial growth, weight loss, and ripening index were decreased.	Yousuf & Srivastava, 2017
	1.5, and 4.0	Aloe vera gel Nopal cactus (4%) Pullulan (6.5%) Chitosan (1.5%)	Layer by layer coating	Fresh-cut pineapple	The softening, color change, weight loss and microbial growth were reduced.	Treviño-Garza, García, Heredia, Alanís-Guzmán, & Arévalo-Niño, 2017
Quince	5	Okra mucilage (1:1) Bacterial cellulose nanofibers (0.5 and 1%) *Eryngium planum* extract (0.25 and 0.5%)	Coating	Strawberry	The microbial growth, weight loss, titratable acidity, and color changes were reduced.	Karami et al., 2021
	1	–	Coating	Mandarin slices	The softening, weight loss, and color change were reduced. The shelf life was prolonged.	Kozlu & Elmacı, 2020
	0–4	Green tea extract (5–20%)	Coating	Fried shrimps	The peroxide values and hardness were decreased.	Noshad, Nasehi & Anvar, 2017
	1	Oregano or thyme (1–2%)	Film	Trout fillets	The oxidation and microbial spoilage were delyed and the shelf life was extended.	Jouki, Yazdia, Mortazavia, Koocheki & Khazaei, 2014

alters the flow behavior during oral digestion compared with other alternative (commercial) thickeners.

6.1. Prebiotic activity

Mucilage is also known as a prebiotic component that has a positive effect on the microbiota of the colon (Kassem et al., 2021). There are several studies on plant seed mucilage to stimulate the growth of probiotic bacteria, which is one of the most important functions in the colon, and to protect the biological activities of probiotic bacteria exposed to heat, acid, oxygen and bile salts (Soukoulis, Gaiani & Hoffmann, 2018). In the study by Cruz-Rubio, Mueller, Viernstein, Loeppert and Praznik (2021), the prebiotic potential of polysaccharides and oligosaccharides in the structure of mucilages isolated from *Opuntia ficus-indica* and *Opuntia joconostle* was investigated. The prebiotic potential of high molecular weight heteropolysaccharides in both *Opuntia* species was found to be quite low because the four bacteria species used in the study did not possess pectin- and complex polysaccharide-degrading enzymes. The fermentability of low molecular weight poly- and oligosaccharides by the bacterial species was found to be higher due to the low galacturonic acid residues in these fractions. Mueller, Čavarkapa, Unger, Viernstein and Praznik (2017) investigated the prebiotic potential of poly- and oligosaccharides isolated from the seed mucilage of *Hyptis suaveolens* by separating them into total, acidic and neutral fractions. It was reported that the neutral fraction significantly increased the growth of various probiotic strains thanks to the galactose units located externally of their side chains, while the acidic fractions showed no prebiotic effect. The prebiotic potential of mucilage depends on the nature of its polysaccharide profile; the high concentration of soluble heteropolysaccharide promotes synthesis of short-chain fatty acids. In addition, studies have shown that the prebiotic activity of mucilage is influenced by external factors as well as by its chemical structure (Kassem et al., 2021). Roy et al. (2022) found that probiotic bacteria embedded in *Abroma augusta* mucilage were preserved and retained their viability under simulated gastrointestinal conditions at both high and low temperatures. Similarly, encapsulation of probiotic *Lactobacillus casei* with alginate and flaxseed mucilage protected the bacteria from simulated gastrointestinal conditions (Shafizadeh, Golestan, Ahmadi, Darjani & Ghorbani-HasanSaraei, 2020).

6.2. Antioxidant activity

Polysaccharides in the structure of plant mucilage have excellent antioxidant activity, which can prevent cell damage caused by reactive oxygen species. In addition, these polysaccharides can increase the content of superoxide dismutase, which supports the antioxidant mechanism. It has been found that carbohydrates from okra mucilage also shows antioxidant activity, which can help reduce lipid peroxidation reactions that cause beta cell destruction (Dantas, Alonso Buriti & Florentino, 2021). Mucilages extracted from various sources such as *Opuntia ficus-indica, Malva parviflora* leaves, Hollyhock’s root, and *Corchorus olitorius* L. were found to be the potent natural antioxidants, and their antioxidant activity was directly proportional to the added dose (Amiri, Roshani Saray, Rezazad-Bari & Pirsa, 2021; Messina et al., 2021; Munir et al., 2021; Oh & Kim, 2022). In a study with yam mucilage, it was reported that pre-purified polysaccharide had higher antioxidant activity compared to crude polysaccharide, implying that the impurities had no antioxidant activity (Huang, Xie, Yu & Shen, 2020).

In general, the antioxidant activity of mucilages is significantly higher than that of other hydrocolloids due to their conformation and polyphenolic compounds (Hedayati et al., 2021). Keshani-Dokht, Emam-Djomeh, Yarmand and Fathi (2018) also found that there is a positive relationship between the phenolic content of *Cordia myxa* mucilage and its antioxidant activity. The method used for extraction of the mucilage is one of the factors affecting the antioxidant activity. Extraction with ultrasound can improve antioxidant activity by disrupting high molecular weight compounds such as polysaccharides and changing their structures (Hedayati et al., 2021). According to Akl et al. (2021) and Niknam, Mousavi and Kiani (2020), the antioxidant activity of mucilage extracted with ultrasound was found to be higher than that of mucilage extracted with the conventional hot water extraction method. This finding was attributed to the cell hydrolysis and disruption of cell walls due to the effects of ultrasonic waves (Akl et al., 2021). In a study investigating the effects of different extraction methods (hot water, alkaline/acid, ultrasound-assisted, and microwave-assisted extraction) on the extraction of flaxseed mucilage and antioxidant activity, it was also reported that the mucilage obtained by ultrasound-assisted extraction had the highest antioxidant activity (Safdar et al., 2020).

6.3. Antidiabetic and antihyperlipidemic effect

Type 2 diabetes (T2D) is one of the leading causes of death in the world, and the risk of T2D can be reduced by lifelong dietary changes, especially with the consumption of high fiber foods. Several studies have shown that soluble dietary fiber improves glycemic response, and this effect has been attributed to its physicochemical properties such as; increased viscosity, delayed gastric emptying, and fermentability (Kay et al., 2017). Therefore, the identification of new sources of dietary fiber is an emerging area of research, and mucilage is one of them. Kay et al. (2017) investigated the different soluble dietary fibers from mustard, fenugreek, and flaxseed mucilage in pudding formulations. The authors reported that consumption of all the puddings resulted in lower blood glucose and plasma insulin at a given time point, and is likely to provide acute postprandial glycemic response benefits in people at risk for T2D.

Attia, Khalifa, Fahim and Kamel (2021) also studied oral administration of 250 mg/kg of mucilage extracted from the bulbs of *Hippeastrum vittatum* to rats. The study resulted in a decrease of elevated blood glucose levels of approximately 57% and 66% after 2 and 3 h after consumption, respectively. Apart from this direct effect, a therapeutic agent, gliclazide, loaded in microparticles of Isabgol shell mucilage showed prolonged hypoglycemic effect and increased bioavailability compared to the pure drug (Kumar, Mazumder, Sharma & Ahmed, 2021). Sefi, Chaâbane, Rafrafi and Zeghal (2019) reported the administration of aloe vera mucilage to alloxan-induced diabetic rats. The results of the study showed that the aloe vera mucilage corrected glycemia, while it has also improved lipid status due to its high content of polysaccharides and glycoproteins.

Mucilages, as soluble dietary fiber, have the potential to lower blood lipid levels. This mechanism is based on the soluble fibers found in mucilage, which exert their effect on the hepatic mechanism by increasing the loss of bile acid and decreasing the absorption of cholesterol, as well as inhibiting the hepatic synthesis of free fatty acids (de Abreu Silva, Verneque, Mota & Duarte, 2021). Uddin Zim, Khatun, Khan, Hossain and Haque (2021) investigated the antidiabetic and antihyperlipidemic effects of okra mucilage on alloxan-induced diabetic mice. Administration of powdered mucilage at a dose of 150 mg/kg for three weeks reversed fasting blood glucose levels, and improvement in cholesterol, triglyceride, and LDL levels was observed. Similarly, Tamargo, Martin, Navarro del Hierro, Moreno-Arribas and Muñoz (2020) reported the potential of chia mucilage as an innovative source for improving lipid and glycemic profiles. The authors examined a dynamic gastrointestinal model in combination with absorption kinetics to investigate the effect of chia seed mucilage on the bioaccessibility of glucose, dietary lipids, and cholesterol. The results showed that the presence of 0.95% chia mucilage reduced the bioaccessibility of glucose by 66.7%. Bioaccessibility of free fatty acid, cholesterol, and bile salts was also significantly reduced by 56.1%, 37.2%, and 64.6%, respectively.

Conclusions

Plant mucilages by being natural biopolymeric substances have various uses as food additive, as well as food packaging applications. It can act like emulsifying, thickening, gelling and film forming agent, besides having excellent encapsulating properties. Stand-alone films and coating solutions prepared using plant mucilage can replace the petroleum-based polymers in food packaging applications due to their biodegradable nontoxic nature and structural properties that allow carrying active ingredients along with presenting required viscosity during surface coating. Besides, the mechanical, thermal, barrier, optical, and morphological properties of the final coating or film product can be adjusted by using different techniques such as; changing the mucilage source, combining with other biodegradable polymers, and adding fillers. However, further studies are required to optimize the formulations which can compete with petroleum-based polymers from both an economical and technical point of view.

The potential of mucilage including seeds and other plant parts is not fully discovered by food industry, and it's hard to estimate the size of plant mucilage market numbers due to their presence as a food additive is not yet approved. Moreover, the approval of mucilages as a food additive by the legal authorities such as U.S. Food and Drug Administration (FDA), or European Food Safety Authority (EFSA) and declaring on the label is rather expensive and requires challenging bureaucracy. However, there is an abundance of plants naturally carrying mucilage and the extraction yield is very high compared to other commercial hydrocolloids. Furthermore, the encapsulation and controlled release functions of mucilages are not limited to the food industry but also have a remarkable capability for using in pharmaceutical applications.

Ethical statement

The authors declare that there is no human and animal involving data used.

The manuscript was written according to the journal instructions. With the submission of this manuscript, I would like to undertake that the above mentioned manuscript has not been published elsewhere or is not under consideration of publication by another journal. The authors declare that they have no conflict of interest. All the authors have read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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