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Mucilage as a functional food hydrocolloid: Ongoing and potential applications in prebiotics and nutraceuticals

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Abstract

Mucilage is a soluble dietary fiber used as a food additive to give foods a firmer texture, aside from its many health benefits and pharmacological properties. It is a polysaccharide in nature composed of large molecules of sugars and uronic acid moieties. Extraction of mucilage is attained from a wide variety of plant parts, including rhizomes, roots and seeds, and has also been reported in microorganisms. In this review, the nutritional and medicinal applications of mucilage are described in context to its different mucilage type. The current article capitalizes on state-of-the-art valorization practices of mucilage and its potential novel usages in the food industry, nutraceuticals, and as a prebiotic in addition to its nutritional and anti-nutritional values. Analysis of the prebiotic action of mucilage with respect to its structure activity relationship as well as how it modulates gut bacteria is presented for the first time and in context to its known health benefits inside the colon. It is recommended that more investigations are carried out to maximize its mucilage health benefits and ensure its safety especially upon long term usage.

Keywords: mucilage; functional food; food additive; prebiotic; gut microbiota

List of abbreviations

PAH	Polycyclic aromatic hydrocarbon
SAR	Structure Activity Relationships
SCFA	short chain fatty acid

Introduction

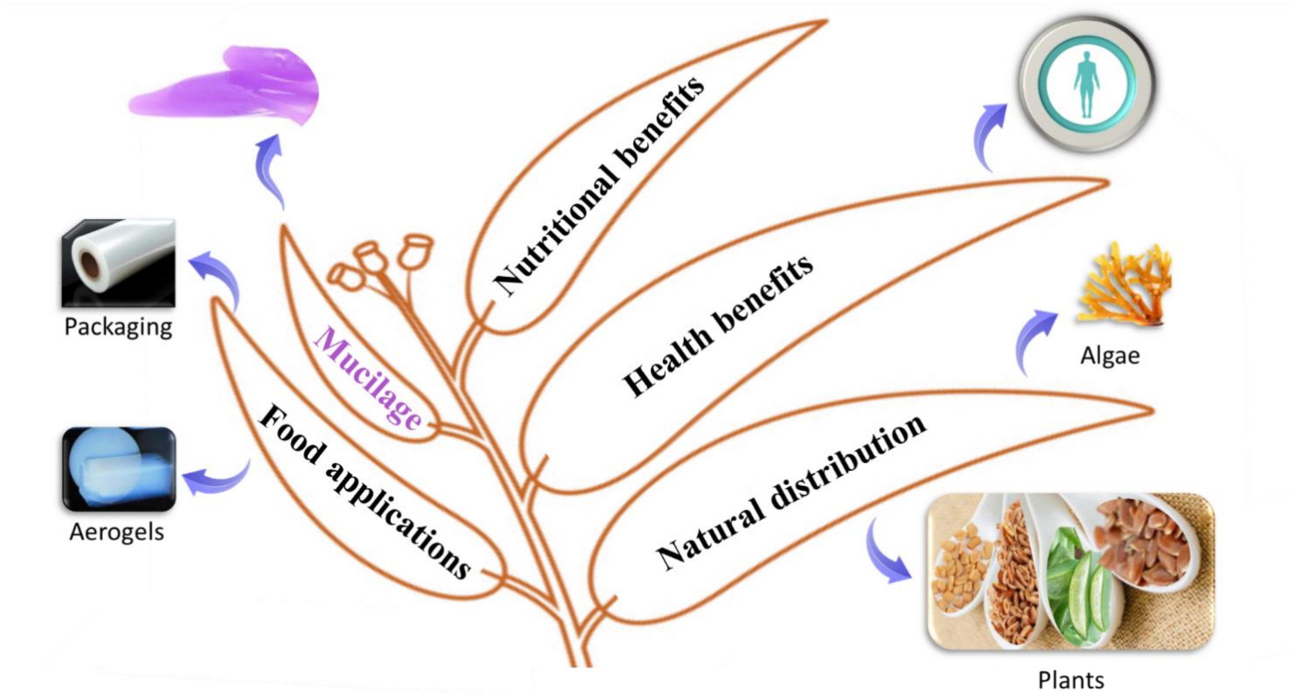
Mucilage is a thick, gluey substance produced by nearly all plants and some microorganisms. Mucilage in plants plays several roles including the storage of water and food, seed germination, and thickening membranes, that has long been further exploited by humans to be used as a food additive in addition for its many health effects [1]. Among plant kingdom, cacti (and other succulents) and flax seeds are especially rich sources of mucilage [2]. Consumers are demanding more natural, safe and sustainable food ingredients. Consequently, some trends have emerged to replace synthetic or animal-based emulsifiers with natural plant-based alternatives [3]. With regards to its chemical composition, mucilage belongs to the class of soluble dietary fibers, a polysaccharide in nature and constituted by large molecules of sugars and uronic acids. Functional polysaccharides such as that of mucilage exhibit different chemical compositions as well as physicochemical properties depending on the isolation method, type of extraction and origin [4]. For example, psyllium (*Plantago ovata*) seed is a major source of mucilage and is composed 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 [5]. Flax seed mucilage heteropolysaccharides consist of a rhamno-galacturonan I acid fraction and a highly branched arabinoxylan neutral polysaccharide fraction [6].

The distribution of mucilage is shared between plants and algae [7], and they include aloe, red algae, cactus and legume seeds *i.e.*, fenugreek, with different compositions and/or uses [8]. One of the mucilage-producing plants is cactus that belongs to *Opuntia* genus and Cactaceae family. The plant produces mucilage to retain water under the desert arid conditions. *Opuntia ficus-indica* is the most plentiful among cactus, and cactus cladodes (modified stems) contain much more mucilage than the other plant parts. Cactus cladodes were reported to be considered as highly valuable forage in diet for ruminants. Young cladodes contained more water, protein, and phenolic compounds than mature ones where as they contained less ash and fiber. Their gas production and digestibility parameters were affected by collection period not by cladodes age. In vitro organic matter digestibility and microbial biomass production were higher in young cladodes [9]. One of the favorable characteristics of *O. ficus-indica* was its high degradation and metabolized energy values, and lower gas production [10]. The mucilage yields varied between fresh and dried cladodes using the same extraction method. Another well characterized plant source for mucilage is fenugreek seeds belonging to legumes. Fenugreek mucilage is abundant in seeds, and is composed of galactomannans with the basic units being galactose and mannose [11].

Of marine origin, red algae provide a principal source for mucilage production. Mucilage of red algae could be found within the cell wall, which is composed of sulfated polysaccharides. Red algae mucilage has two classes - agar and carrageenan [12].

The current review is an extrapolation of our previous one focusing on the extraction methods, physicochemical and rheological properties, pharmaceutical and other industrial applications including the novel uses [13]. Current study extends to cover state-of-the-art valorization practices and uses of mucilage and its other potential novel usages as a functional food and in food industry (**Fig. 1**).

Fig. 1. An outline showing the review theme and covered topics related to mucilage properties and applications.



A brief overview of prebiotics: mucilage in focus

Unlike the previous definition of prebiotics as indigestible food ingredients capable of providing health benefits to the host through selective stimulation of the activity of gut microorganisms, it is now acceptable to define prebiotics as substrates solely used by the host microbes in order to confer health benefits [14, 15]. When probiotics and prebiotics are combined, the resultant synbiotics offer immensely useful effects and overall health benefits. Each human has a unique gut make-up with trillions of bacteria, which makes the overrated ecosystemic metabolism of prebiotics, their ecological niche, and their mechanisms of action less clear [16]. Common prebiotics include the oligosaccharides like FOS (fructooligosaccharides), GOS (galactooligosaccharides), XOS (xylooligosaccharides), and inulin, which are utilized by colonic probiotic microorganisms, such as lactobacilli, bifidobacteria, faecalibacteria, roseburia, eubacteria and *Saccharomyces*, in order to produce short chain and branched chain fatty acids among other metabolites [17]. Less attention has been focused to less popular polysaccharides as mucilage and or non-polysaccharides i.e., peptides [18-21].

The use of prebiotics by probiotic organisms is a very selective one that involves numerous factors such as the structure of the prebiotic in question as typically in the case of mucilage. For instance, a highly branched arabinoxylan gel forming mucilage from psyllium seed (*Plantago ovata* Forsk) structurally comprises of xylose monomers supported on the sides by arabinose and xylose, and is utilized in the food and pharmaceutical industries due to its high polysaccharide content [5, 22]. Recently, it was deduced that the gel forming structure of this mucilage enables the survivability of *Lactobacillus acidophilus* in a yoghurt-based study, for improved physicochemical, sensory and functional qualities [23]. The structural composition of these polysaccharides serves as the premise for prebiotic or novel functional food development, as they are associated with mucilage prebiotic activity within the gastrointestinal tract. The heteropolysaccharides in mucilage is generally classified as neutral or acidic. The neutral polysaccharide is composed of D-galactopyranosyl-, D-glucopyranosyl- and D-mannopyranosyl- units in the mole ratios of 4.5:7.5:1.0; whereas acid polysaccharide has mole ratios of 1.0:2.5:1.1, a main chain of ß-(1→4)-linked D xylopyranose units with branching points in C-2 with 4-*O*-methyl-D-glucuronic acid units and in C-3 with 2-*O*-L-fucopyranosyl-D-xylopyranose units [24]. Praznik and colleagues [25] identified that sequences of octa/nonasaccharide associated with mucilage from *Hyptis suaveolens* L, stressing the relationship of their prebiotic activity to the availability of β-linked D-Galp residues in the side chains of the molecules. The next section discusses in detail mucilage prebiotic action and how it modulates gut bacteria in context to its chemical composition.

Chemical composition, nutritional value and prebiotic potential of mucilage

Chemical composition and structure activity relationship

Mucilages are mucopolysaccharides produced in early diverging non-vascular plant groups like hornworts (Anthocerotophyta), extruded around organs for dehydration protection during growth and reproduction among other functions [26]. They are composed of total, acidic or neutral polysaccharides or heteropolysaccharides. Flowering plants and their organs like seeds, fruits, roots, leaves and stems, secrete multifarious and physically diverse mucilage, mostly composed of cell wall materials [27]. Mucilage is well recognized as a prebiotic functional food that can positively affect human intestinal microbiota (**Fig.**) leading to the modulation of bowel habits concurrent with the reduction of several ailments *i.e*., intestinal tumors. The potential of mucilage as a prebiotic is attributed to its polysaccharide nature, where the high content of soluble heteropolysaccharides, the main progenitor of short chain fatty acids (SCFA) [28], in mucilage helps to promote the growth of beneficial gut probiotic bacteria.

For example,*Aloe vera* mucilage encompasses a high level of acemannan or carrysin polysaccharide with a backbone of β-(1→4)-D-mannose residues acetylated at the C-2 and C-3 positions and side chains of galactose and arabinose attached to the C-6 carbon [29]. Using the *in vitro* model of human colonic microbiota fermentation, its mucilage prebiotic activity was assessed and observed to significantly increase the growth of bifidobacteria and *Atopobium*, probiotic microorganisms associated with SCFAs *i.e*., acetate production. These organic acids or SCFAs confer immense health benefits to the gut and overall well-being of the host. Acetate is quite useful for muscle and tissue functioning, while propionate and butyrate are equally important for liver and colonic mucosa functions, respectively [30]. Acetate and propionate also follow the β-oxidation pathway in colon cells, move along the portal vein to the liver, and provide the platform for gluconeogenesis and lipogenesis [30, 31]. A review of the systemic actions of SCFAs is though beyond the scope of the current study. Acemannan, the major constituent of *Aloe vera* mucilage, possessed prebiotic activity compared to the prebiotic standard inulin [32]. Addition of *A. vera* mucilage increased the bacterial populations in fecal batch cultures with a significant increase for the acetic acid producers *Bifidobacterium* as well as *Atopobium* indicating a unique bifidogenic effect being the first evidence reporting the stimulatory effect on the beneficial intestinal bifidobacteria colonies following *in vitro* fermentation with *A. vera* mucilage. Compared to inulin well reported extraction and optimization methods, much less is presented regarding acemannan, predominant polysaccharide in the

Aloe vera mucilage. Screening of the different other *Aloe* species can prioritize for its production at industrial scale.

O. ficus-indica or nopal mucilage is composed of highly branched polysaccharides with (1→4)-*β*-D-galacturonic acid and (1→2)-*α*-L-rhamnose units with trisaccharide side chains of (1→6)-*β*-D-galactose moieties [33]. In their study, Guevara-Arauza et al. [33] observed the supportive and growth stimulating effect of the cactus mucilage on lactobacilli (23.8%), while suppressing the growth of enterococci, enterobacteria, staphylococci, and clostridia (4%), hence exerting some prebiotic values. The metabolism of mucilage by the simulated human gut microbiota led to increased production of SCFAs up to 35% with propionate and butyrate levels reaching 50%, and increase of the useful lactobacillipopulation. SCFAs are reported to possess immunomodulatory potential [28], in addition to the effect of propionate and butyrate as apoptosis inducer in gastrointestinal tract epithelial cells thus suppressing inflammatory changes that may lead to any neoplastic activity [34], and to rationalize for their protective anti-cancer action inside the colon. These mucilage of complex branched-structure polysaccharides from nopal reportedly contain L-arabinose, D-galactose, L-rhamnose, and oxane-2,3,4,5-tetrol D-xylose, as the major neutral sugar units, with galacturonic acid at varying levels [35]. Whether this is the only mechanism behind mucilage chemo-preventive action in the gut is yet to be explored using other mechanism based assays. Another cactus family member, *Opuntia streptacantha*, showed very interesting activities in a recent study. Reyes-Reyes et al. [36] characterized *O.streptacantha* mucilage and the fermentation products of its hydrolysates/oligosaccharides. The mucilage of this unconventionally fibrous plant possesses 204.6 and 371.6 g/kg as insoluble dietary fiber and soluble dietary fiber values, respectively, while its α-amylase-digested oligosaccharides stimulated the growth of the commercial probiotic strains (*L. acidophilus, L. casei* and *B. animalis* subsp. *lactis*) *in vitro,* similar to inulin [36]. The oligosaccharides later acted as sources of carbon for boosting the production of SCFAs by the probiotic organisms, but the complexity of mucilage composition was not ascertained.

The mucilage of chan seeds (*Hyptis suaveolens* L.) contains 1:1 acidic to neutral polysaccharide fractions. The neutral polysaccharide fraction proved to significantly increase the growth of tested probiotic bacteria mainly lactobacilli (*L. paracasei* DN114001, *L. rhamnosus* GG, *B. infantis, L. plantarum, L. brevis, L. bulgaricus, Lc. lactis, L. fermentum and S. thermophilus*) in turbidity measurements, with such activity found mostly attributed to the external *β*-D-galactopyranose sugar moieties. It was also concluded that the prebiotic activity of the neutral fraction was related to the availability of *β*-galactosidase enzyme responsible for galactose units' removal, in the *Lactobacillus* strains. In contrast, acidic fraction showed no prebiotic activity in spite of its xylose content where xylo-oligosaccharides are reported as promising prebiotics. This might be due to the extensive branching of xylose units leading to a decreased accessibility for fermentation by probiotic strains [20]. All polysaccharide types tested supported the growth of probiotics with more than 78% of the probiotic strains thriving in the neutral fraction, in relation to the externally available galactose units; characteristic of a prebiotic potential with a delayed but long lasting effect [20]. Thus, it may be safe to deduce that varying types of mucilage and/or their derived polysaccharides could exhibit prebiotic potentials at different timing efficaciously. Structure activity relationship (SAR) relationships to determine motifs in mucilage backbone mediating for its prebiotic action should now follow and in different mucilage type *i.e.,* neutral *versus* acidic. Such studies can also aid in designing novel mucilage dietary fibers of even improved action in the future.

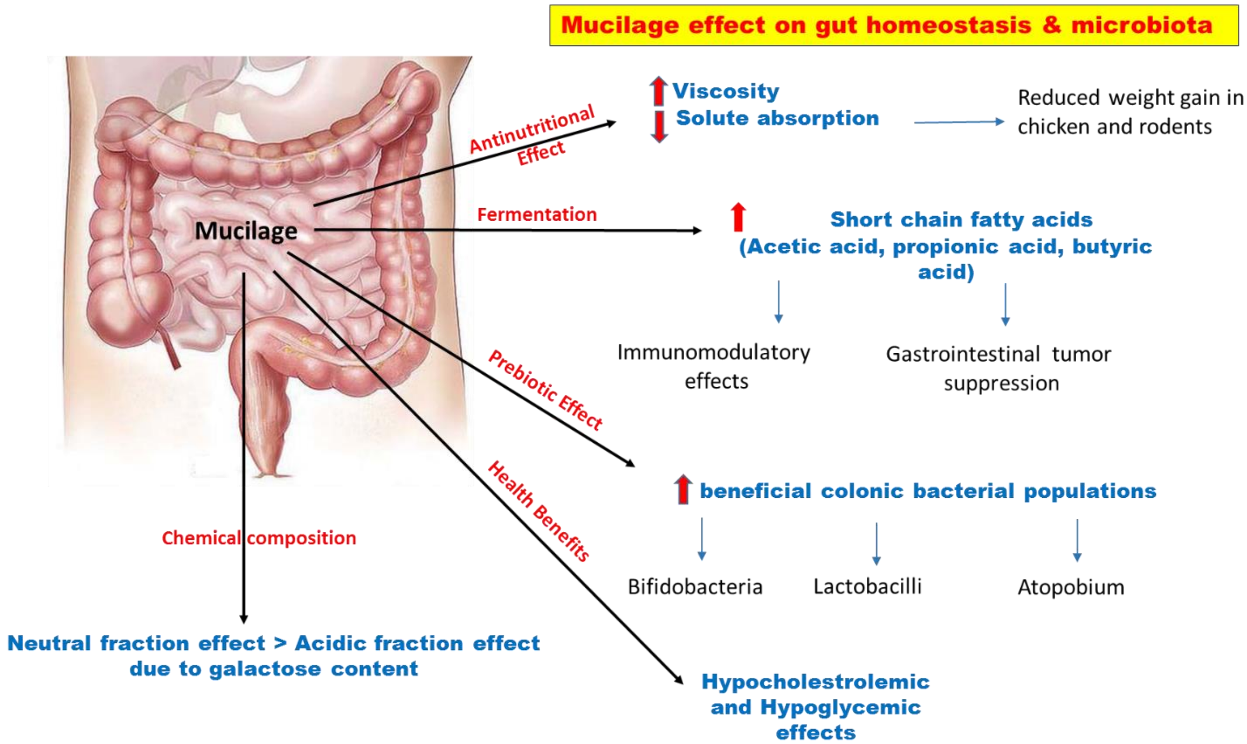


Fig. 2. The effect of mucilage and its metabolized chemicals on GIT and microbiota in terms of health benefits, prebiotic potential and anti-nutritional impact

Likewise, heteropolysaccharide mucilage of basil seeds (*Ocimum basilicum)* contains acidic and neutral polysaccharide fractions at a 1:1 ratio. The neutral polysaccharide fraction showed high abundance of terminal β-linked D-galactopyranose moieties and induced the growth of *Lactobacillus* strains [37], while the acidic portion showed no prebiotic activity. This was in agreement with previously reported results of chan seeds neutral polysaccharide fraction where both showed prebiotic potential mostly attributed to their galactose high content [20]. F**igure 3** summarizes the main SAR or types in mucilage to affect its prebiotic action.

Hydrocolloids from pulp and seeds of tamarillo (*Solanum betaceum* Cav.) were recently reported to possess prebiotic activity [38]. Both hydrocolloids showed an increase in the beneficial bifidobacteria and lactobacilli growth concurrent with a decrease in pathogenic bacteria proliferation where the low molecular weight seed mucilage hydrocolloid showed better results than the pulp hydrocolloid with high molecular weight. It was suggested that the arabinogalactan protein-associated low methoxy pectin found abundantly in the seed mucilage hydrocolloid was more favored to be used by bifidobacteria and lactobacilli than the hemicellulosic polysaccharides with high molecular weight found in the pulp hydrocolloid. This might be due to carbohydrate-active enzymes (CAZymes) specific for degradation of the seed mucilage hydrocolloid found in the colon bacteria genetic code.

The heteropolysaccharide from the mucilage of chia seeds (*Salvia hispanica L.*) characterized by an anionic character was tested for its effect on gut microbiota where it showed an increase in *Lactobacillus* and *Enterococcusspp*. populations [39]. In addition to its prebiotic activity, mucilage also proved to be an efficient agent in probiotic bacteria microencapsulation as wall material. It was reported to ameliorate the probiotic bacteria survival where it helped to preserve the count of probiotic cells during storage, processing, and gastrointestinal digestion [40]. Chia seed mucilage showed a significant thermal protection when used as an encapsulating agent for probiotic cells during processing and storage through reduction of inlet air temperature [41]. Our results show that the survival of *L. rhamnosus* encapsulated by spray drying was negatively affected by the inlet air temperature, an effect that can be reduced when chia seed mucilage, flaxseed mucilage, or inulin were incorporated into the encapsulation solution Also, mixtures of *Aloe vera* mucilage and agave fructans of high degree of polymerization were used to encapsulate *Lactobacillus plantarum* probiotic strain using spray-drying process. The physicochemical characteristics of the powders showed 10% less moisture contents and water activity between 0.195 and 0.3, suggesting stability during storage. Results revealed up to 70% survival rate (significantly different) of the *L. plantarum* initial concentration likely attributed to the high degree of structural arrangement in these mixtures of biopolymers [42].

Recent studies have shown that prebiotic activity of mucilage is affected not only by its chemical composition but rather external factors. It was reported that adjusting drying temperature and time can improve *Oppuntia* cladodes's mucilage prebiotic characteristics despite the fact that the prebiotic profile is not intensely sensitive to drying conditions [43]. An overview of the main factors revealed governing mucilage prebiotic action is illustrated in **Fig. 3**. In general, neutral mucilage fraction appears to exhibit a high prebiotic activity due to its galactose content in opposite to the acidic portion which shows no prebiotic activity. Further, mucilage from various sources have differential effect on probiotic bacteria.

From another perspective, studies have attempted to fortify prebiotic or functional food drinks with plant- and/or seed-based mucilage in order to attain better overall gut health benefits. Kefir for instance, is a functional fermented drink with a mix of more than 50 lactic acid bacteria (LAB) and yeast species, and is reportedly rich in essential vitamins, to possess antimicrobial, anti-allergenic, anti-carcinogenic, anti-obesity, and gut microbiota modulatory properties [44-48]. This drink made with milk or water by fermentation is worth more than €78.7 million in North America as it is a popular beverage globally. The water type (water kefir) is popular in Mexico, and it a LAB fermented sweetened water containing dextran components [48]. The effect of faba and chickpea mucilage addition to kefir drinks was observed for a 4 weeks storage period at 4° C, followed by microbial viability, physicochemical and sensory evaluation, revealing that the probiotic bacterial load increased remarkably as well as acidity during those weeks [49]. The mucilage fortified kefir additionally demonstrated increased quality and prebiotic potential. However, the sensory values of the kefir were lower than that of the control in terms of acceptability, even though these differences were insignificant.

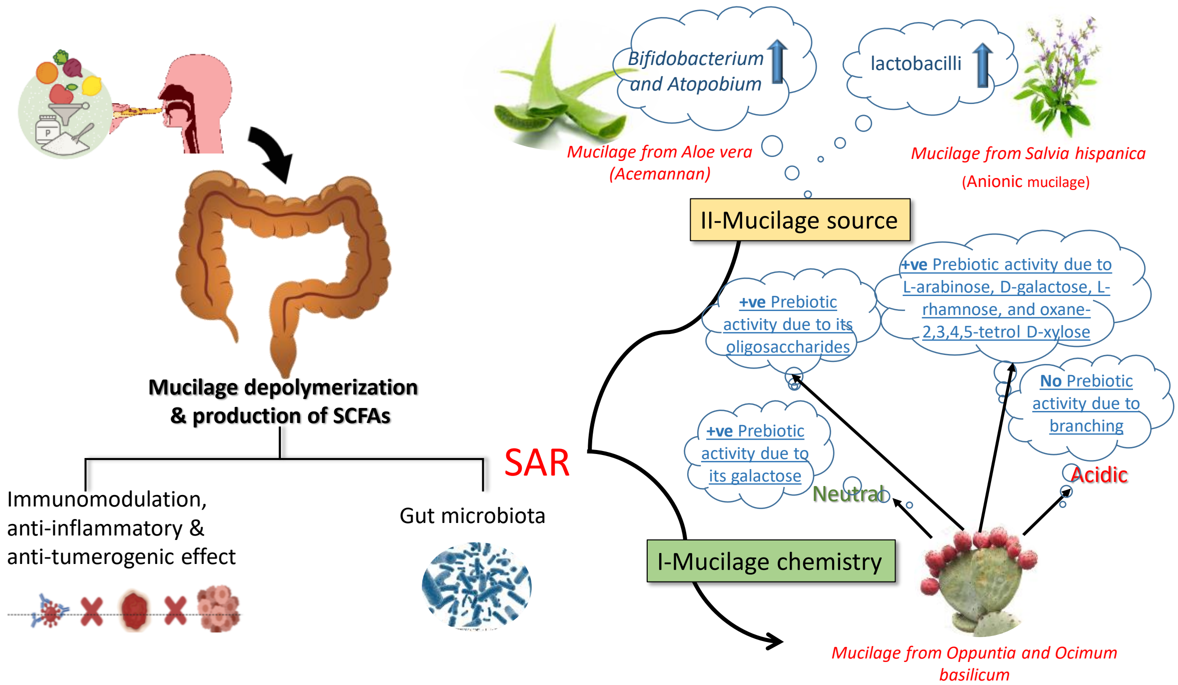


Fig. 3. Overview of mucilage motifs structure activity relationship SAR or types i.e., acidic, neutral affecting its prebiotic activity

Nutritional and anti-nutritional values

It should be noted that not all fermentation mechanisms of mucilage yielded a nutritive effect *i.e.*, viscous properties of mucilage in linseed led to an anti-nutritional effect through increasing intestinal viscosity is mediated by the gut microflora [50]. Broiler chicken showed decreased weight gain when fed on linseed containing diet attributed to a reduction of fat and fatty acid digestibility. The anti-nutritional effect of linseed was overcome by substituting it with demucilaged linseed leading to an increase in nutritive value. Such fat malabsorption was attributed to viscosity increase in jejunal digesta at 70 folds higher in broiler chicken feeding on linseed (160 g/kg diet) in comparison to the control group. The reducing effect of mucilage on weight gain and fat digestibility in chicken and rats should be interpreted cautiously in terms of their effect on human beings due to the great variations in intestinal tracts physiology among the different species. Extrapolation of the previous findings to human applications *i.e.*, treatment of obesity needs further investigations in spite of the fact that utilization of fat in humans and rodents is reported to be fairly comparable [51]. Moreover, it was reported that obese patients administering mucilage containing diet showed better weight loss results than those observed in patients supplemented with diet without mucilage [52]. Another explanation for the decreased fat digestibility in dogs administered flaxseed mucilage is *via* increasing viscosity leading to altering enzyme activity and micelle formation thus decreasing absorption of the nutrients [53].

Mucilage as a food stabilizer, thickener, and foaming agent

Mucilage constitute one of the most important hydrocolloids used as natural thickening, texturizing, stabilizing, and gelling agents in the food industry [54]. In the field of hydrocolloids, aqueous mucilage solution exhibited high viscoelastic properties similar to those of synthetic polymers [55]. Mucilage, as a biopolymer component, is economically preferred over synthetic polymers owing to its natural availability, biocompatibility, biodegradability and non-toxicity [56]. Soukoulis C. et al [57] discussed in details the most recent advancements in the field of mucilage application in dairy and bakery products in addition to food emulsion, packaging, powders and particulates.

Aerogels represent a class of highly porous materials with 90%–99% air assembled into three-dimensional nanostructured form. There is a growing demand for more food-grade aerogels having diverse functional properties to expand their potential food applications [58]. Camelina mucilage aerogels were formed using supercritical carbon dioxide with nanoporous structure to be used as low-cost food thickeners and stabilizers [59]. Although that mucilage solution exhibit weak foaming properties, they can increase the foaming properties of protein probably by increasing bulk-phase viscosity and creating a cohesive flexible biopolymeric film that prevents air-bubble coalescence [60], such property can be useful in food formulations. The use of mucilage in food industry is expected indeed to expand over the next years because of its various benefits on quality characteristics as well as dietary function.

Trending applications of Mucilage in nutraceuticals

With an increasing interest on how natural medicine improves life quality, increasing consumption of nutraceuticals is observed worldwide [61], with the additional value of being low cost and of less side effects. This section focuses on the major health benefits of mucilage asides from its mechanical properties as depicted in **Fig. 4**, and how to maximize these benefits using further technological developments of the naturally occurring mucilage.

Laxative effect

One of the most popular health benefits of mucilage is its laxative effect. Flaxseed possesses a pronounced laxative effect due to its richness in mucilage mediated through the cholinergic pathway. However, the same seed possess an opposing effect acting an antidiarrheal attributed for the presence of flaxseed oils mediated through activating K^+ channels [62]. Hence, for more specific actions, optimized seed extraction should be carried out to improve recovery of mucilage only. Among the most famous commercial mucilage resources is psyllium mucilage.

A side effect of using psyllium mucilage for treating constipation include intestinal distress *i.e.*, bloating and flatulence owing to the high fiber content and doses required to attain the desired action [63]. Hence, designing a pharmaceutical dosage form with sustained activity and/or combining mucilage with another laxative drug of different action mechanism can help provide more effective actions at much lower doses.

Hypo-lipidemic effect

Mucilage has a notable role in reducing lipids blood level. This effect was related to the chemical nature and isolation source of mucilage as stated in a previous study in which the authors isolated mucilage from *Trigonella foenum-graecum* (galactomannan), *Colocasia esculenta* (arabinogalactan) and *Dioscorea esculenta* (glucomannan) [64]. Fixed mucilage oral doses of 4 mg/100 g body weight daily for a period of 8 weeks administered to male Albino rats showed lower total serum and tissues (liver and aortic) lipid levels compared, with glucomannan providing the most hypolipidaemic effect *versus* arabinogalactan the least. This effect might be attributed to the decrease in the synthesis of VLDL by hepatocytes [64]. Another hypothesis might be related to the enhanced viscosity of these macromolecules to elevate the intestinal content viscosity leading to decreased absorption of cholesterol or fatty acids as well as reducing biliary cholesterol and bile acids reabsorption from GIT [65]. Although many successful experimental studies were carried out, more active clinical trials for the co-administration of mucilage with different anti-hyperlipidemic drugs should be conducted.

Anti-hyperglycemic effect

Mucilage possesses a favorable effect in ameliorating blood sugar level either in hyperglycemic rodents or humans [66, 67]. This effect might be attributed to the unique structure and rheological properties of mucilage having increased viscosity and enhanced swelling properties that aids in lowering blood glucose levels by trapping mechanism [67]. This trap mechanism can be further explained based on the inhibitory effect of mucilage on intestinal α-glycosidases [68].

α-glycosidases is an enzyme responsible for the hydrolytic cleavage of oligosaccharide liberating α-glucose [69]. α-Glycosidases inhibition decelerates the rate of glucose liberation (**Fig. 4**) and hence delays the rate of glucose absorption into the blood [70] concurrent with lower glycemic index. Hence, mucilage could offer an excellent strategy for avoiding abrupt increase in postprandial blood glucose and to militate against diabetic complications. Nevertheless, for chronic administration with other antidiabetic drugs, determination of any potential drug interaction should be clearly examined.

1.1. Antioxidant

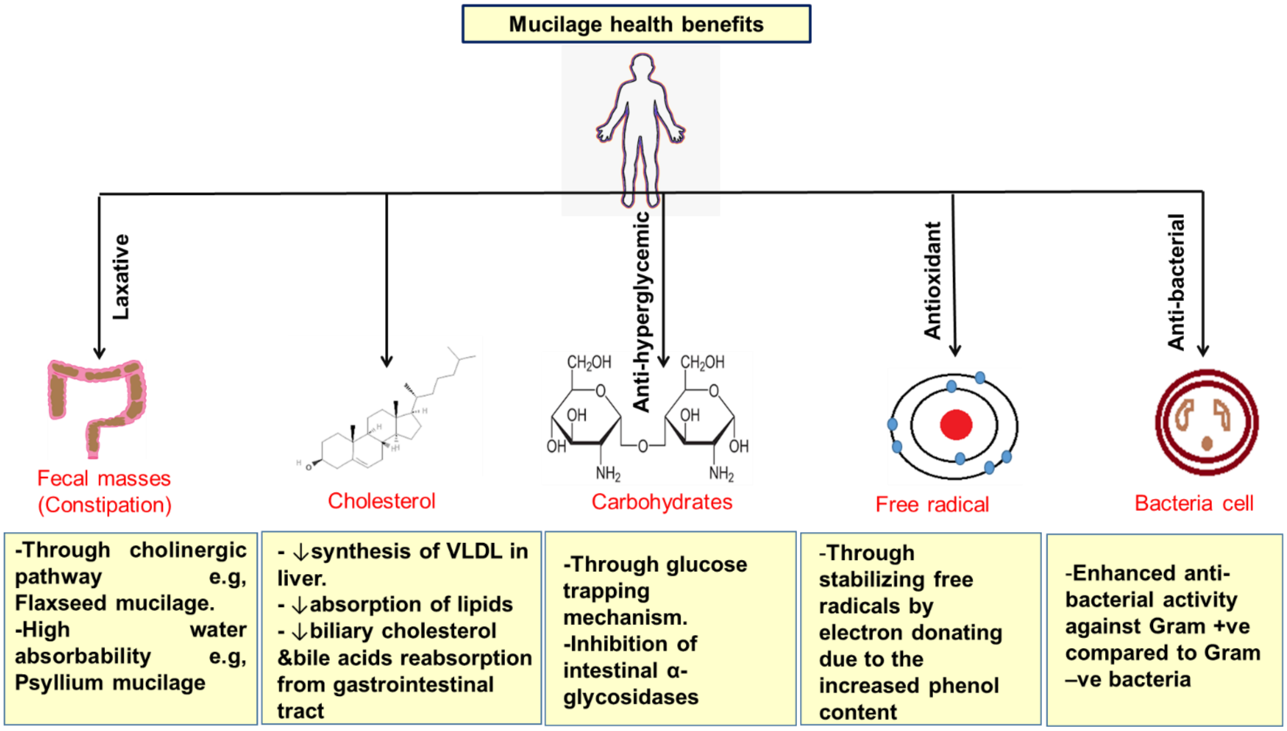


Fig. 4 An illustrative sketch showing the major health benefits of mucilage and the underlying mechanism in humans.

Oxidation is a chemical reaction producing free radicals inside the body resulting in chain reactions which could harm the living cells [71]. Oxidative stress is not classified as a disease but rather an underlying cause for other diseases and their complications. Antioxidants are chemicals which scavenge free radicals [72], and to account for their recommended use in nutraceuticals as a prophylactic measure of several diseases *i.e.*, colon cancer [73], heart diseases [74] and diabetes complications [75]. A study conducted by Keshani-Dokht et al. [76] compared the antioxidant activity of *Cordi amyxa* mucilage in comparison to butylated hydroxyl anisole and ascorbic acid. Results revealed that the antioxidant action was directly proportional to the added mucilage dose and opposite to that observed in case of the other two scavengers. This concentration-dependent effect of mucilage might be attributed to the increased phenol content which is considered hydrogen donating and consequently producing more stable compounds [77, 78]. Albeit, butylated hydroxyl anisole is more efficient at lower levels compared to mucilage though less safe. In general, mucilage antioxidant activity is rather weak compared to synthetic antioxidants at equal dose level and suggestive that combining mucilage with other antioxidants could be advantageous especially from a safety point of view. A study conducted on okra mucilage indicated that the reconstituted aqueous solution from okra mucilage powder showed good antioxidant activities equal to 176 μmol Trolox equivalent/100 Ml [79]. One action mechanism of mucilage as antioxidant is mediated *via* its chelating action on $FeCl_2$ and ferrozine. Comparatively, antioxidants scavenge free radicals by donating hydrogen while chelating agents inactivate the redox reactions which in turn mitigates against the generation of free radicals [80]. For detailed discussion of mucilage chelating activity, please refer to the study of Zhi W. W. et al. [81].

As previously mentioned, the type of mucilage might affect its physicochemical properties and accordingly its effect. However, the applied extraction condition (mainly time and temperature) can also affect antioxidant activity [81]. For example, increasing the extraction time from *Morinda citrifolia* fruit enhanced its antioxidant activity [82]. In contrast, a decrease in antioxidant activity of quince seed mucilage was obtained by elevating extraction temperatures, which might be endorsed to the thermolabile properties of phenolic compounds in quince seed mucilage [83]. Such hypothesis needs to be further tested using other mucilage types and/or from other resources to be more conclusive.

Anti-bacterial effect

Mucilage possesses a potential antibacterial activity against several strains of bacteria. Films prepared from chia mucilage and loaded with starch nanocrystals succeeded to enhance the antibacterial activity of mucilage against several types of bacteria such as *Pseudomonas aeruginosa*, *Escherichia coli* and *Staphylococcus aureus* [56]. Basil seed mucilage hydrogels loaded with zinc oxide nanoparticles possessed an enhanced anti-bacterial activity action more against Gram +ve bacteria compared to Gram –ve type which might be attributed for their differences in cell wall composition. Further investigations are required to prepare membrane active mucilage based formulations against Gram –ve bacteria [84]. Mucilage detailed anti-bacterial activity was discussed elsewhere [79].

Conclusion

This review presented a holistic overview of plant-based mucilage for the first time with regards to its different applications in food industries and as a functional food. Its prebiotic effect cannot be dissociated from its muco/poly/heterosaccharides composition, exerted alone or in food fortification. As a safe biological macromolecule, it has potential as a functional food ingredient owing to its laxative, hypo-lipidemic, anti-hyperglycemic, antioxidant as well as anti-bacterial effects. Compared to the many action mechanism assays reported in literature to substantiate for these health effects, more clinical studies are now warranted to guarantee mucilage maximal benefit and safety. For example, the anti-obese effects of mucilage and on fat digestibility in animals acting as anti-nutrient should be interpreted cautiously in humans due to the great variations in intestinal tracts of the different species. These anti-nutritional properties of mucilage should be also considered in clinical trials especially if to be consumed over long time. Obvious structure activity relationship exists in mucilage as a prebiotic that has yet to be examined in detail and post chemical modification to generate more active analogues.

Conflict of interest

Authors declare no actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations

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