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

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24 **Abstract**

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

36

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

38

39 **List of abbreviations**

PAH Polycyclic aromatic hydrocarbon

SAR Structure Activity Relationships

SCFA short chain fatty acid

40

41

42

43 **Introduction**

44 Mucilage is a thick, gluey substance produced by nearly all plants and some microorganisms.
45 Mucilage in plants plays several roles including the storage of water and food, seed germination, and
46 thickening membranes, that has long been further exploited by humans to be used as a food additive in
47 addition for its many health effects ¹. Among plant kingdom, cacti (and other succulents) and flax seeds
48 are especially rich sources of mucilage ². Consumers are demanding more natural, safe and sustainable
49 food ingredients. Consequently, some trends have emerged to replace synthetic or animal-based
50 emulsifiers with natural plant-based alternatives ³. With regards to its chemical composition, mucilage
51 belongs to the class of soluble dietary fibers, a polysaccharide in nature and constituted by large
52 molecules of sugars and uronic acids. Functional polysaccharides such as that of mucilage exhibit
53 different chemical compositions as well as physicochemical properties depending on the isolation
54 method, type of extraction and origin ⁴. For example, psyllium (*Plantago ovata*) seed is a major source
55 of mucilage and is composed of acidic and neutral heteropolysaccharide constituents. It is characterized
56 by β -D-1,4 linked xylopyranosyl units substituted by α -L-arabinofuranose moieties with a 3:1 xylose:
57 arabinose ratio ⁵. Flax seed mucilage heteropolysaccharides consist of a rhamno-galacturonan I acid
58 fraction and a highly branched arabinoxylan neutral polysaccharide fraction ⁶.

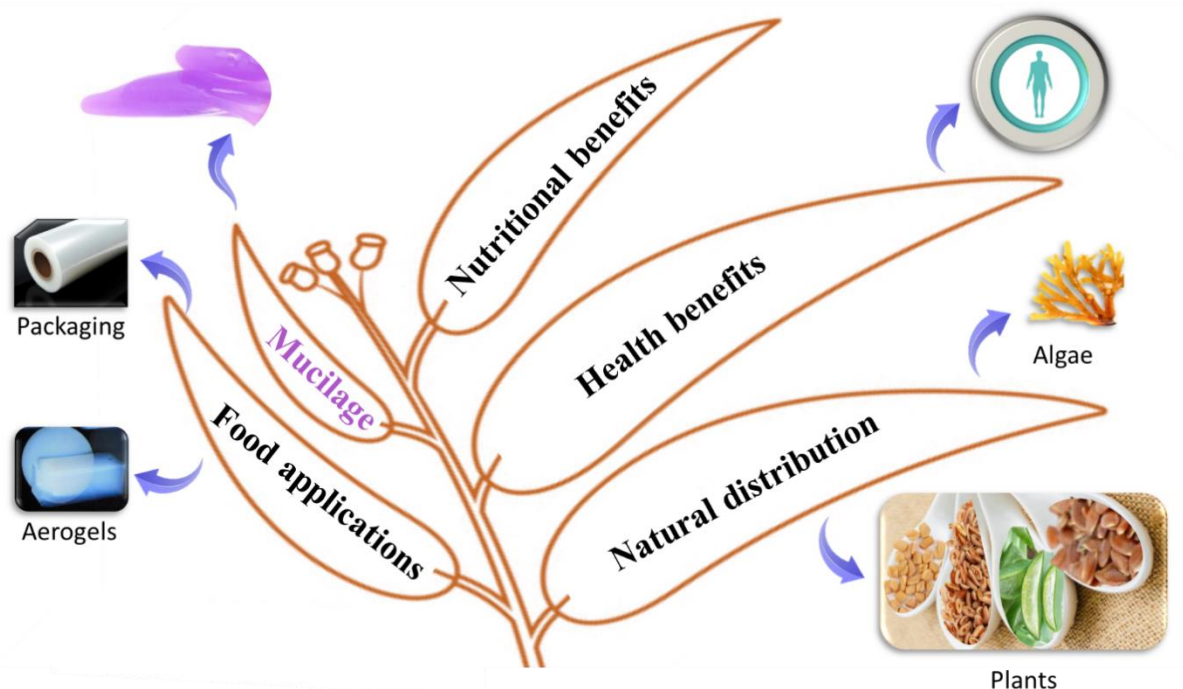
59 The distribution of mucilage is shared between plants and algae ⁷, and they include aloe, red
60 algae, cactus and legume seeds *i.e.*, fenugreek, with different compositions and/or uses ⁸. One of the
61 mucilage-producing plants is cactus that belongs to *Opuntia* genus and Cactaceae family. The plant
62 produces mucilage to retain water under the desert arid conditions. *Opuntia ficus-indica* is the most
63 plentiful among cactus, and cactus cladodes (modified stems) contain much more mucilage than the other
64 plant parts. Cactus cladodes were reported to be considered as highly valuable forage in diet for
65 ruminants. Young cladodes contained more water, protein, and phenolic compounds than mature ones
66 where as they contained less ash and fiber. Their gas production and digestibility parameters were

67 affected by collection period not by cladodes age. In vitro organic matter digestibility and microbial
68 biomass production were higher in young cladodes ⁹. One of the favorable characteristics of *O. ficus-*
69 *indica* was its high degradation and metabolized energy values, and lower gas production ¹⁰. The
70 mucilage yields varied between fresh and dried cladodes using the same extraction method. Another well
71 characterized plant source for mucilage is fenugreek seeds belonging to legumes. Fenugreek mucilage is
72 abundant in seeds, and is composed of galactomannans with the basic units being galactose and mannose
73 ¹¹.

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

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

81 **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 clear¹⁶. 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 metabolites¹⁷. Less attention has been focused to less popular polysaccharides as mucilage and or non-polysaccharides i.e., peptides¹⁸⁻²¹.

97 The use of prebiotics by probiotic organisms is a very selective one that involves numerous
98 factors such as the structure of the prebiotic in question as typically in the case of mucilage. For instance,
99 a highly branched arabinoxylan gel forming mucilage from psyllium seed (*Plantago ovata* Forsk)
100 structurally comprises of xylose monomers supported on the sides by arabinose and xylose, and is utilized
101 in the food and pharmaceutical industries due to its high polysaccharide content ^{5, 22}. Recently, it was
102 deduced that the gel forming structure of this mucilage enables the survivability of *Lactobacillus*
103 *acidophilus* in a yoghurt-based study, for improved physicochemical, sensory and functional qualities ²³.
104 The structural composition of these polysaccharides serves as the premise for prebiotic or novel
105 functional food development, as they are associated with mucilage prebiotic activity within the
106 gastrointestinal tract. The heteropolysaccharides in mucilage is generally classified as neutral or acidic.
107 The neutral polysaccharide is composed of D-galactopyranosyl-, D-glucopyranosyl- and D-
108 mannopyranosyl- units in the mole ratios of 4.5:7.5:1.0; whereas acid polysaccharide has mole ratios of
109 1.0:2.5:1.1, a main chain of β -(1 $\rightarrow$ 4)-linked D xylopyranose units with branching points in C-2 with 4-
110 O-methyl-D-glucuronic acid units and in C-3 with 2-O-L-fucopyranosyl-D-xylopyranose units ²⁴.
111 Praznik and colleagues ²⁵ identified that sequences of octa/nonasaccharide associated with mucilage from
112 *Hyptis suaveolens* L, stressing the relationship of their prebiotic activity to the availability of β -linked D-
113 Galp residues in the side chains of the molecules. The next section discusses in detail mucilage prebiotic
114 action and how it modulates gut bacteria in context to its chemical composition.

115 **Chemical composition, nutritional value and prebiotic potential of mucilage**

116 *Chemical composition and structure activity relationship*

117 Mucilages are mucopolysaccharides produced in early diverging non-vascular plant groups like
118 hornworts (Anthocerotophyta), extruded around organs for dehydration protection during growth and
119 reproduction among other functions ²⁶. They are composed of total, acidic or neutral polysaccharides or
120 heteropolysaccharides. Flowering plants and their organs like seeds, fruits, roots, leaves and stems,

121 secrete multifarious and physically diverse mucilage, mostly composed of cell wall materials ²⁷.
122 Mucilage is well recognized as a prebiotic functional food that can positively affect human intestinal
123 microbiota (**Fig.**) leading to the modulation of bowel habits concurrent with the reduction of several
124 ailments *i.e.*, intestinal tumors. The potential of mucilage as a prebiotic is attributed to its polysaccharide
125 nature, where the high content of soluble heteropolysaccharides, the main progenitor of short chain fatty
126 acids (SCFA) ²⁸, in mucilage helps to promote the growth of beneficial gut probiotic bacteria.

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

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

146 *O. ficus-indica* or nopal mucilage is composed of highly branched polysaccharides with (1→4)-
147 β-D-galacturonic acid and (1→2)-α-L-rhamnose units with trisaccharide side chains of (1→6)-β-D-
148 galactose moieties ³³. In their study, Guevara-Arauza et al. ³³ observed the supportive and growth
149 stimulating effect of the cactus mucilage on lactobacilli (23.8%), while suppressing the growth of
150 enterococci, enterobacteria, staphylococci, and clostridia (4%), hence exerting some prebiotic values.
151 The metabolism of mucilage by the simulated human gut microbiota led to increased production of
152 SCFAs up to 35% with propionate and butyrate levels reaching 50%, and increase of the useful
153 lactobacillipopulation. SCFAs are reported to possess immunomodulatory potential ²⁸, in addition to the
154 effect of propionate and butyrate as apoptosis inducer in gastrointestinal tract epithelial cells thus
155 suppressing inflammatory changes that may lead to any neoplastic activity ³⁴, and to rationalize for their
156 protective anti-cancer action inside the colon. These mucilage of complex branched-structure
157 polysaccharides from nopal reportedly contain L-arabinose, D-galactose, L-rhamnose, and oxane-
158 2,3,4,5-tetrol D-xylose, as the major neutral sugar units, with galacturonic acid at varying levels ³⁵.
159 Whether this is the only mechanism behind mucilage chemo-preventive action in the gut is yet to be
160 explored using other mechanism based assays. Another cactus family member, *Opuntia streptacantha*,
161 showed very interesting activities in a recent study. Reyes-Reyes et al. ³⁶ characterized *O.streptacantha*
162 mucilage and the fermentation products of its hydrolysates/oligosaccharides. The mucilage of this
163 unconventionally fibrous plant possesses 204.6 and 371.6 g/kg as insoluble dietary fiber and soluble
164 dietary fiber values, respectively, while its α-amylase-digested oligosaccharides stimulated the growth
165 of the commercial probiotic strains (*L. acidophilus*, *L. casei* and *B. animalis* subsp. *lactis*) *in vitro*, similar
166 to inulin ³⁶. The oligosaccharides later acted as sources of carbon for boosting the production of SCFAs
167 by the probiotic organisms, but the complexity of mucilage composition was not ascertained.

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

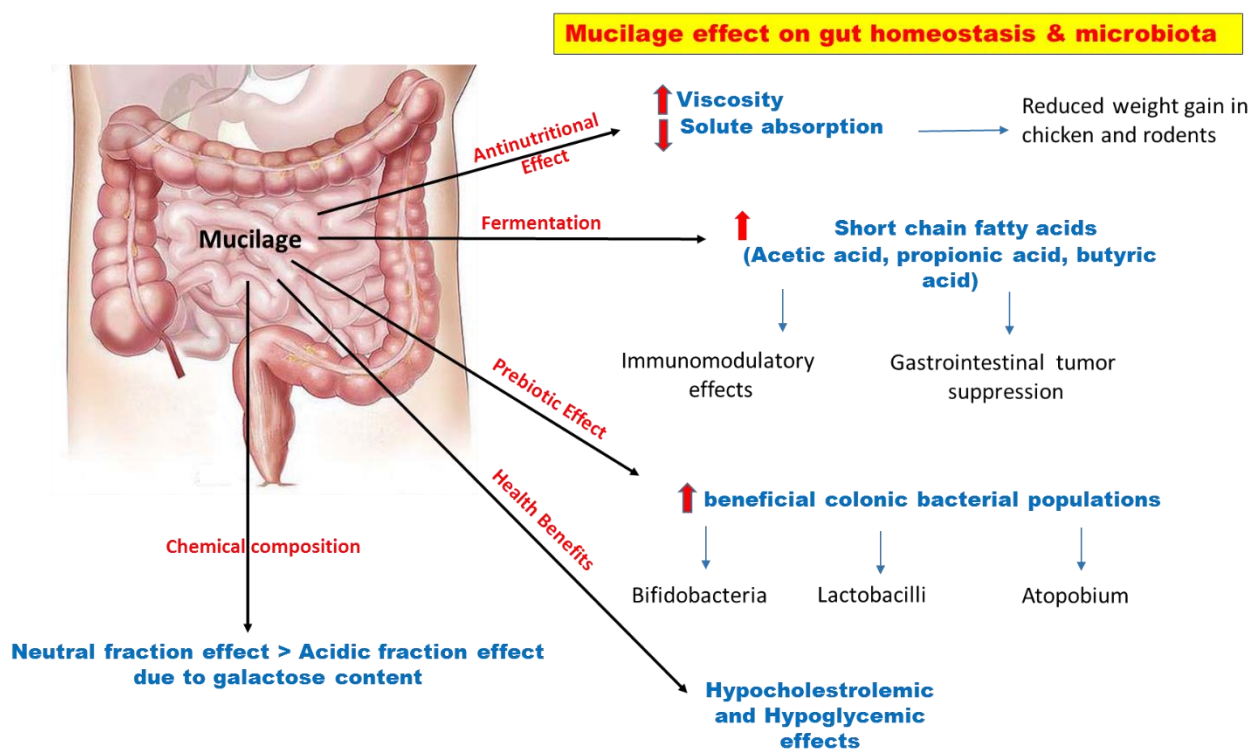


Fig. 2. The effect of mucilage and its metabolized chemicals on GIT and microbiota in terms of health benefits, prebiotic potential and anti-nutritional impact

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* strains³⁷, 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 content²⁰. **Figure 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 activity³⁸. 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

200 molecular weight. It was suggested that the arabinogalactan protein-associated low methoxy pectin found
201 abundantly in the seed mucilage hydrocolloid was more favored to be used by bifidobacteria and
202 lactobacilli than the hemicellulosic polysaccharides with high molecular weight found in the pulp
203 hydrocolloid. This might be due to carbohydrate-active enzymes (CAZymes) specific for degradation of
204 the seed mucilage hydrocolloid found in the colon bacteria genetic code.

205 The heteropolysaccharide from the mucilage of chia seeds (*Salvia hispanica L.*) characterized by
206 an anionic character was tested for its effect on gut microbiota where it showed an increase in
207 *Lactobacillus* and *Enterococcus* spp. populations ³⁹. In addition to its prebiotic activity, mucilage also
208 proved to be an efficient agent in probiotic bacteria microencapsulation as wall material. It was reported
209 to ameliorate the probiotic bacteria survival where it helped to preserve the count of probiotic cells during
210 storage, processing, and gastrointestinal digestion ⁴⁰. Chia seed mucilage showed a significant thermal
211 protection when used as an encapsulating agent for probiotic cells during processing and storage through
212 reduction of inlet air temperature ⁴¹. Our results show that the survival of *L. rhamnosus* encapsulated by
213 spray drying was negatively affected by the inlet air temperature, an effect that can be reduced when chia
214 seed mucilage, flaxseed mucilage, or inulin were incorporated into the encapsulation solution. Also,
215 mixtures of *Aloe vera* mucilage and agave fructans of high degree of polymerization were used to
216 encapsulate *Lactobacillus plantarum* probiotic strain using spray-drying process. The physicochemical
217 characteristics of the powders showed 10% less moisture contents and water activity between 0.195 and
218 0.3, suggesting stability during storage. Results revealed up to 70% survival rate (significantly different)
219 of the *L. plantarum* initial concentration likely attributed to the high degree of structural arrangement in
220 these mixtures of biopolymers ⁴².

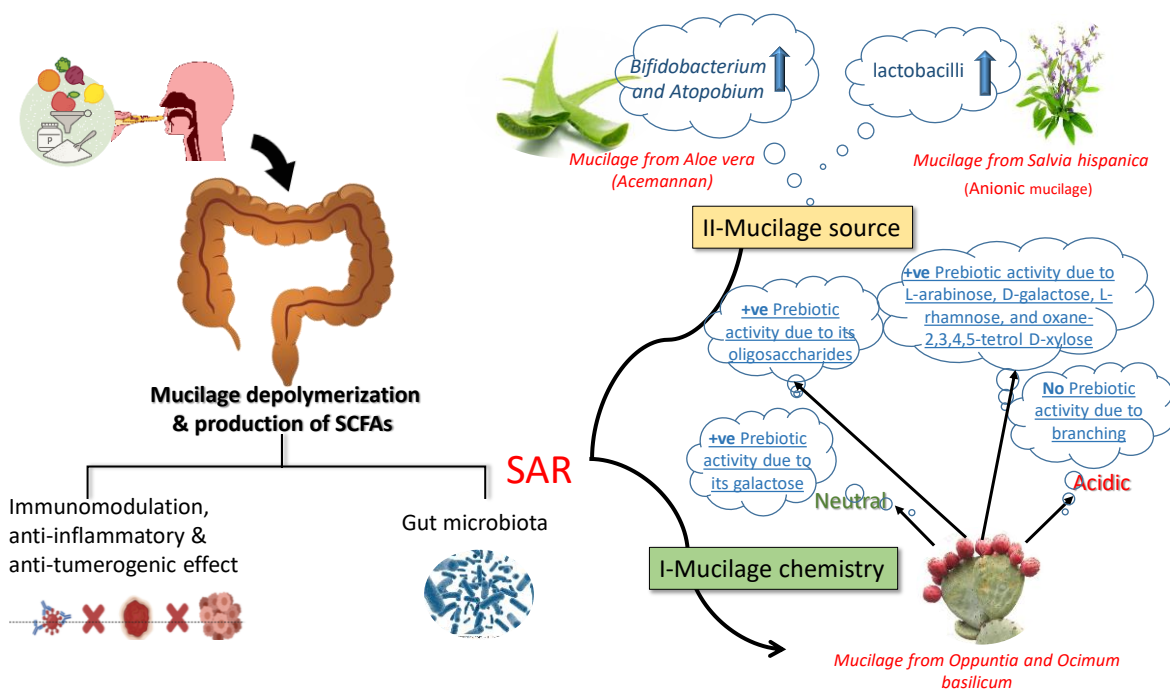
221 Recent studies have shown that prebiotic activity of mucilage is affected not only by its chemical
222 composition but rather external factors. It was reported that adjusting drying temperature and time can
223 improve *Opuntia cladodes*'s mucilage prebiotic characteristics despite the fact that the prebiotic profile

224 is not intensely sensitive to drying conditions ⁴³. An overview of the main factors revealed governing
225 mucilage prebiotic action is illustrated in **Fig. 3**. In general, neutral mucilage fraction appears to exhibit
226 a high prebiotic activity due to its galactose content in opposite to the acidic portion which shows no
227 prebiotic activity. Further, mucilage from various sources have differential effect on probiotic bacteria.

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

241

242



243

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

246 *Nutritional and anti-nutritional values*

247 It should be noted that not all fermentation mechanisms of mucilage yielded a nutritive effect *i.e.*,
 248 viscous properties of mucilage in linseed led to an anti-nutritional effect through increasing intestinal
 249 viscosity is mediated by the gut microflora ⁵⁰. Broiler chicken showed decreased weight gain when fed
 250 on linseed containing diet attributed to a reduction of fat and fatty acid digestibility. The anti-nutritional
 251 effect of linseed was overcome by substituting it with demucilaged linseed leading to an increase in
 252 nutritive value. Such fat malabsorption was attributed to viscosity increase in jejunal digesta at 70 folds
 253 higher in broiler chicken feeding on linseed (160 g/kg diet) in comparison to the control group. The
 254 reducing effect of mucilage on weight gain and fat digestibility in chicken and rats should be interpreted
 255 cautiously in terms of their effect on human beings due to the great variations in intestinal tracts
 256 physiology among the different species. Extrapolation of the previous findings to human applications

257 *i.e.*, treatment of obesity needs further investigations in spite of the fact that utilization of fat in humans
258 and rodents is reported to be fairly comparable ⁵¹. Moreover, it was reported that obese patients
259 administering mucilage containing diet showed better weight loss results than those observed in patients
260 supplemented with diet without mucilage ⁵². Another explanation for the decreased fat digestibility in
261 dogs administered flaxseed mucilage is *via* increasing viscosity leading to altering enzyme activity and
262 micelle formation thus decreasing absorption of the nutrients ⁵³.

263 **Mucilage as a food stabilizer, thickener, and foaming agent**

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

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

280 **Trending applications of Mucilage in nutraceuticals**

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

286 *Laxative effect*

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

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

298 *Hypo-lipidemic effect*

299 Mucilage has a notable role in reducing lipids blood level. This effect was related to the chemical
300 nature and isolation source of mucilage as stated in a previous study in which the authors isolated
301 mucilage from *Trigonella foenum-graecum* (galactomannan), *Colocasia esculenta* (arabinogalactan)
302 and *Dioscorea esculenta* (glucomannan) ⁶⁴. Fixed mucilage oral doses of 4 mg/100 g body weight daily

303 for a period of 8 weeks administered to male Albino rats showed lower total serum and tissues (liver and
304 aortic) lipid levels compared, with glucomannan providing the most hypolipidaemic effect *versus*
305 arabinogalactan the least. This effect might be attributed to the decrease in the synthesis of VLDL by
306 hepatocytes ⁶⁴. Another hypothesis might be related to the enhanced viscosity of these macromolecules
307 to elevate the intestinal content viscosity leading to decreased absorption of cholesterol or fatty acids as
308 well as reducing biliary cholesterol and bile acids reabsorption from GIT ⁶⁵. Although many successful
309 experimental studies were carried out, more active clinical trials for the co-administration of mucilage
310 with different anti-hyperlipidemic drugs should be conducted.

311

312 *Anti-hyperglycemic effect*

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

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

324 *1.1. Antioxidant*

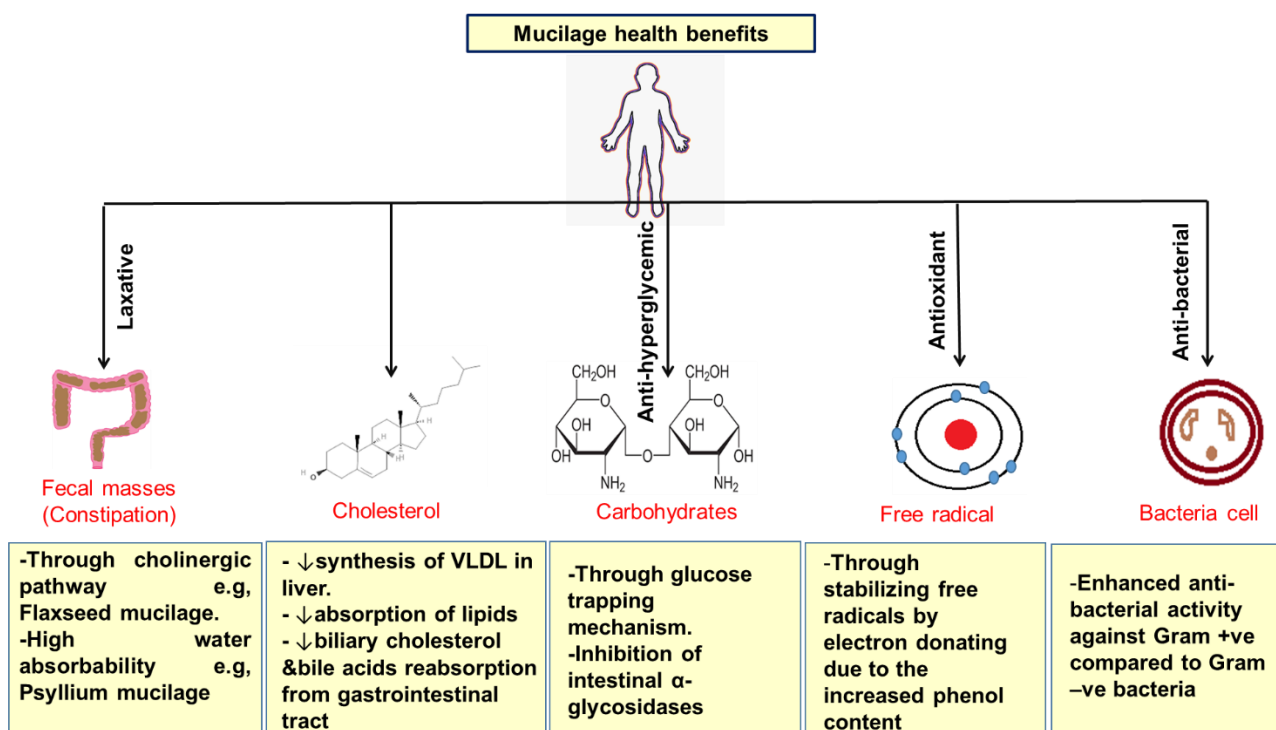


Fig. 4 An illustrative sketch showing the major health benefits of mucilage and the underlying mechanism in humans.

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

340 antioxidants at equal dose level and suggestive that combining mucilage with other antioxidants could
341 be advantageous especially from a safety point of view. A study conducted on okra mucilage indicated
342 that the reconstituted aqueous solution from okra mucilage powder showed good antioxidant activities
343 equal to 176 μmol Trolox equivalent/100 Ml ⁷⁹. One action mechanism of mucilage as antioxidant is
344 mediated *via* its chelating action on FeCl_2 and ferrozine. Comparatively, antioxidants scavenge free
345 radicals by donating hydrogen while chelating agents inactivate the redox reactions which in turn
346 mitigates against the generation of free radicals ⁸⁰. For detailed discussion of mucilage chelating activity,
347 please refer to the study of Zhi W. W. et al. ⁸¹.

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

355 *Anti-bacterial effect*

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

364 **Conclusion**

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

377 **Conflict of interest**

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

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382 **References**

- 383 1. X. Yang, J. M. Baskin, C. C. Baskin and Z. Huang, More than just a coating: Ecological
384 importance, taxonomic occurrence and phylogenetic relationships of seed coat mucilage,
385 *Perspect. Plant Ecol. Evol. Syst.*, 2012, **14**, 434-442.
- 386 2. A. M. Hamdani, I. A. Wani and N. A. Bhat, Sources, structure, properties and health benefits of
387 plant gums: A review, *Int. J. Biol. Macromol.*, 2019, **135**, 46-61.
- 388 3. D. J. McClements, L. Bai and C. Chung, Recent advances in the utilization of natural emulsifiers
389 to form and stabilize emulsions, *Annu. Rev. Food Sci. Technol.*, 2017, **8**, 205-236.
- 390 4. O. Añibarro, J. Pinela, Barros, A. Ciric, Silva, E. Coelho, Mocan, R. Calhella, Soković, M.
391 Coimbra and Ferreira, Compositional Features and Bioactive Properties of *Aloe vera* Leaf (Fillet,
392 Mucilage, and Rind) and Flower, *Antioxidants*, 2019, **8**, 444.
- 393 5. M. H. Fischer, N. Yu, G. R. Gray, J. Ralph, L. Anderson and J. A. Marlett, The gel-forming
394 polysaccharide of psyllium husk (*Plantago ovata* Forsk), *Carbohydr. Res.*, 2004, **339**, 2009-2017.
- 395 6. R. Naran, G. Chen and N. C. Carpita, Novel Rhamnogalacturonan I and Arabinoxylan
396 Polysaccharides of Flax Seed Mucilage, *Plant Physiol.*, 2008, **148**, 132.
- 397 7. A. D. Boney, Mucilage: The ubiquitous algal attribute, *Eur. J. Phycol.*, 1981, **16**, 115-132.
- 398 8. L. Ramsden, in *Chemical and Functional Properties of Food Saccharides*, ed. P. Tomasik, CRC
399 Press, Boca Raton, FL, USA, 2003, pp. 231-254.
- 400 9. S. El Otmani, M. Chentouf, J.-L. Hornick and J.-F. Cabaraux, Chemical composition and in vitro
401 digestibility of alternative feed resources for ruminants in Mediterranean climates: olive cake and
402 cactus cladodes, *J. Agric. Sci.*, 2019, **157**, 260-271.
- 403 10. T. G. Gasca, J. Kawas, R. G. Costa and H. Andrade-Montemayor, Nutritional composition, in
404 vitro degradability and gas production of *Opuntia ficus indica* and four other wild cacti species,
405 *Life Sci.*, 2015, **12**.

- 406 11. N. Khorshidian, M. Yousefi Asli, M. Arab, A. Adeli Mirzaie and A. M. Mortazavian, Fenugreek:
407 Potential Applications as a Functional Food and Nutraceutical, *Food Nutr. Res.*, 2016, **3**, 5-16.
- 408 12. A. D. Boney, Mucilage sheaths of spores of red algae, *J. Mar. Biolog. Assoc. U.K.*, 1975, **55**, 511-
409 518.
- 410 13. R. Kamel, S. M. Afifi, I. A. A. Kassem, N. A. Elkasabgy and M. A. Farag, Arabinoxylan and
411 rhamnogalacturonan mucilage: Outgoing and potential trends of pharmaceutical, environmental,
412 and medicinal merits, *Int. J. Biol. Macromol.*, 2020, **165**, 2550-2564.
- 413 14. G. R. Gibson, R. Hutkins, M. E. Sanders, S. L. Prescott, R. A. Reimer, S. J. Salminen, K. Scott,
414 C. Stanton, K. S. Swanson and P. D. Cani, Expert consensus document: The International
415 Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the
416 definition and scope of prebiotics, *Nat. Rev. Gastroenterol. Hepatol.*, 2017, **14**, 491.
- 417 15. T. J. Ashaolu, Immune boosting functional foods and their mechanisms: A critical evaluation of
418 probiotics and prebiotics, *Biomed. Pharmacother.*, 2020, **130**, 110625.
- 419 16. M. E. Sanders, D. J. Merenstein, G. Reid, G. R. Gibson and R. A. Rastall, Probiotics and
420 prebiotics in intestinal health and disease: from biology to the clinic, *Nat. Rev. Gastroenterol.*
421 *Hepatol.*, 2019, **16**, 605-616.
- 422 17. I. A. Neri-Numa and G. M. Pastore, Novel insights into prebiotic properties on human health: A
423 review, *Food Res. Int.*, 2020, **131**, 108973.
- 424 18. T. J. Ashaolu, Soy bioactive peptides and the gut microbiota modulation, *Appl. Microbiol.*
425 *Biotechnol.*, 2020, 1-9.
- 426 19. R. Roulard, E. Petit, F. Mesnard and L. Rhazi, Molecular investigations of flaxseed mucilage
427 polysaccharides, *Int. J. Biol. Macromol.*, 2016, **86**, 840-847.

- 428 20. M. Mueller, A. Čavarkapa, F. M. Unger, H. Viernstein and W. Praznik, Prebiotic potential of
429 neutral oligo- and polysaccharides from seed mucilage of *Hyptis suaveolens*, *Food Chem.*, 2017,
430 **221**, 508-514.
- 431 21. M. N. Nasrabadi, S. A. H. Goli, A. S. Doost, K. Dewettinck and P. Van der Meeren, Bioparticles
432 of flaxseed protein and mucilage enhance the physical and oxidative stability of flaxseed oil
433 emulsions as a potential natural alternative for synthetic surfactants, *Colloids Surf. B.*
434 *Biointerfaces*, 2019, **184**, 110489.
- 435 22. W. Kaialy, P. Emami, K. Asare-Addo, S. Shojaee and A. Nokhodchi, Psyllium: a promising
436 polymer for sustained release formulations in combination with HPMC polymers, *Pharm. Dev.*
437 *Technol.* , 2014, **19**, 269-277.
- 438 23. S. Z. Mehrinejad Choobari, A. A. Sari and A. Daraei Garmakhany, Effect of *Plantago ovata* Forsk
439 seed mucilage on survivability of *Lactobacillus acidophilus*, physicochemical and sensory
440 attributes of produced low-fat set yoghurt, *Food Sci. Nutr.*, 2021, **9**, 1040-1049.
- 441 24. G. O. Aspinall, P. Capek, R. C. Carpenter, D. C. Gowda and J. Szafranek, A novel L-fuco-4-O-
442 methyl-D-glucurono-D-xylan from *Hyptis suaveolens*, *Carbohydr. Res.*, 1991, **214**, 107-113.
- 443 25. W. Praznik, A. Čavarkapa, F. M. Unger, R. Loeppert, W. Holzer, H. Viernstein and M. Mueller,
444 Molecular dimensions and structural features of neutral polysaccharides from the seed mucilage
445 of *Hyptis suaveolens* L, *Food chem.*, 2017, **221**, 1997-2004.
- 446 26. S. Viudes, V. Burlat and C. Dunand, Seed mucilage evolution: diverse molecular mechanisms
447 generate versatile ecological functions for particular environments, *Plant Cell Environ.*, 2020,
448 **43**, 2857-2870.
- 449 27. A. F. Galloway, P. Knox and K. Krause, Sticky mucilages and exudates of plants: Putative
450 microenvironmental design elements with biotechnological value, *New Phytol.*, 2020, **225**, 1461-
451 1469.

- 452 28. G. T. Macfarlane, H. Steed and S. Macfarlane, Bacterial metabolism and health-related effects of
453 galacto-oligosaccharides and other prebiotics, *J. Appl. Microbiol.*, 2008, **104**, 305-344.
- 454 29. B. Gullón, P. Gullón, F. Tavaría, J. L. Alonso and M. Pintado, In vitro assessment of the prebiotic
455 potential of Aloe vera mucilage and its impact on the human microbiota, *Food Funct.*, 2015, **6**,
456 525-531.
- 457 30. T. J. Ashaolu, B. Saibandith, C. T. Yupanqui and S. Wichienchot, Human colonic microbiota
458 modulation and branched chain fatty acids production affected by soy protein hydrolysate, *Int. J.*
459 *Food Sci. Nutr.*, 2019, **54**, 141-148.
- 460 31. V. Tremaroli and F. Bäckhed, Functional interactions between the gut microbiota and host
461 metabolism, *Nature*, 2012, **489**, 242-249.
- 462 32. M. P. Quezada, C. Salinas, M. Gotteland and L. Cardemil, Acemannan and Fructans from Aloe
463 vera (*Aloe barbadensis* Miller) Plants as Novel Prebiotics, *J. Agric. Food Chem.*, 2017, **65**,
464 10029-10039.
- 465 33. J. C. Guevara-Arauza, J. de Jesús Ornelas-Paz, D. J. Pimentel-González, S. Rosales Mendoza, R.
466 E. Soria Guerra and L. M. T. Paz Maldonado, Prebiotic effect of mucilage and pectic-derived
467 oligosaccharides from nopal (*Opuntia ficus-indica*), *Food Sci. Biotechnol.*, 2012, **21**, 997-1003.
- 468 34. E. Maciorkowska, E. Ryszczuk and M. Kaczmarek, The role of probiotics and prebiotics in
469 apoptosis of the gastrointestinal tract, *Prz. Gastroenterol.*, 2010, **5**, 88-93.
- 470 35. F. M. Goycoolea and A. Cárdenas, Pectins from *Opuntia* spp.: a short review, *J. Prof. Assoc.*
471 *Cactus Dev.*, 2003, **5**, 17-29.
- 472 36. M. Reyes-Reyes, J. A. Salazar-Montoya, L. I. Rodríguez-Páez and E. G. Ramos-Ramírez, In vitro
473 fermentation of oligosaccharides obtained from enzymatic hydrolysis of *Opuntia streptacantha*
474 mucilage, *J. Sci. Food Agric.*, 2019, **99**, 2883-2891.

37. J. M. Cruz-Rubio, R. Loeppert, H. Viernstein and W. Praznik, Trends in the Use of Plant Non-Starch Polysaccharides within Food, Dietary Supplements, and Pharmaceuticals: Beneficial Effects on Regulation and Wellbeing of the Intestinal Tract, *Sci. Pharm.*, 2018, **86**, 49.
38. S. P. Gannasin, S. Mustafa, N. M. Adzahan and K. Muhammad, *In vitro* prebiotic activities of tamarillo (*Solanum betaceum* Cav.) hydrocolloids, *J. Funct. Foods*, 2015, **19**, 10-19.
39. A. Tamargo, C. Cueva, L. Laguna, M. V. Moreno-Arribas and L. A. Muñoz, Understanding the impact of chia seed mucilage on human gut microbiota by using the dynamic gastrointestinal model simgi®, *J. Funct. Foods*, 2018, **50**, 104-111.
40. H. Liu, M. Xie and S. Nie, Recent trends and applications of polysaccharides for microencapsulation of probiotics, *Food Frontiers*, 2020, **1**, 45-59.
41. M. Bustamante, L. Laurie-Martínez, D. Vergara, R. Campos-Vega, M. Rubilar and C. Shene, Effect of Three Polysaccharides (Inulin, and Mucilage from Chia and Flax Seeds) on the Survival of Probiotic Bacteria Encapsulated by Spray Drying, *Appl. Sci.*, 2020, **10**, 4623.
42. L. I. Ceja-Medina, R. I. Ortiz-Basurto, L. Medina-Torres, F. Calderas, M. J. Bernad-Bernad, R. F. González-Laredo, J. A. Ragazzo-Sánchez, M. Calderón-Santoyo, M. González-ávila and I. Andrade-González, Microencapsulation of *Lactobacillus plantarum* by spray drying with mixtures of Aloe vera mucilage and agave fructans as wall materials, *J. Food Process Eng.*, 2020, **43**, e13436.
43. J. M. Cruz-Rubio, M. Mueller, R. Loeppert, H. Viernstein and W. Praznik, The Effect of Cladode Drying Techniques on the Prebiotic Potential and Molecular Characteristics of the Mucilage Extracted from *Opuntia ficus-indica* and *Opuntia joconostle*, *Sci. Pharm.*, 2020, **88**, 43.
44. D.-H. Kim, H. Kim, D. Jeong, I.-B. Kang, J.-W. Chon, H.-S. Kim, K.-Y. Song and K.-H. Seo, Kefir alleviates obesity and hepatic steatosis in high-fat diet-fed mice by modulation of gut

microbiota and mycobiota: targeted and untargeted community analysis with correlation of biomarkers, *J. Nutr. Biochem.*, 2017, **44**, 35-43.

45. G. Macori and P. D. Cotter, Novel insights into the microbiology of fermented dairy foods, *Curr. Opin. Biotechnol.*, 2018, **49**, 172-178.

46. T. J. Ashaolu, A review on selection of fermentative microorganisms for functional foods and beverages: the production and future perspectives, *Int. J. Food Sci. Nutr.*, 2019, **54**, 2511-2519.

47. T. J. Ashaolu and A. Reale, A holistic review on Euro-Asian lactic acid bacteria fermented cereals and vegetables, *Microorganisms*, 2020, **8**, 1176.

48. D. Laureys and L. De Vuyst, Microbial species diversity, community dynamics, and metabolite kinetics of water kefir fermentation, *Appl. Environ. Microbiol.*, 2014, **80**, 2564-2572.

49. L. Ould Saadi, F. Zaidi, T. Sanz and C. M. Haros, Effect of faba bean and chickpea mucilage incorporation in the structure and functionality of kefir, *Int. J. Food Sci. Technol.*, 2020, **26**, 503-511.

50. C. Alzueta, M. L. Rodríguez, M. T. Cutuli, A. Rebolé, L. T. Ortiz, C. Centeno and J. Treviño, Effect of whole and demucilaged linseed in broiler chicken diets on digesta viscosity, nutrient utilisation and intestinal microflora, *Br. Poult. Sci.*, 2003, **44**, 67-74.

51. M. Kristensen, K. E. B. Knudsen, H. Jørgensen, D. Oomah, S. Bügel, S. Toubro, I. Tetens and A. Astrup, Linseed Dietary Fibers Reduce Apparent Digestibility of Energy and Fat and Weight Gain in Growing Rats, *Nutrients*, 2013, **5**, 3287-3298.

52. G. Enzi, E. M. Inelmen and G. Crepaldi, Effect of a hydrophilic mucilage in the treatment of obese patients, *Pharmatherapeutica*, 1980, **2**, 421-428.

53. S. Nybroe, A. Astrup and C. R. Bjørnvad, Dietary supplementation with flaxseed mucilage alone or in combination with calcium in dogs: effects on apparent digestibility of fat and energy and fecal characteristics, *Int. J. Obes. (Lond)*, 2016, **40**, 1884-1890.

- 522 54. X. Huang, Y. Kakuda and W. Cui, Hydrocolloids in emulsions: particle size distribution and
523 interfacial activity, *Food Hydrocoll.*, 2001, **15**, 533-542.
- 524 55. R. Gheribi, Y. Habibi and K. Khwaldia, Prickly pear peels as a valuable resource of added-value
525 polysaccharide: Study of structural, functional and film forming properties, *Int. J. Biol.*
526 *Macromol.*, 2019, **126**, 238-245.
- 527 56. M. Mujtaba, B. Koc, A. M. Salaberria, S. Ilk, D. Cansaran-Duman, L. Akyuz, Y. S. Cakmak, M.
528 Kaya, K. M. Khawar and J. Labidi, Production of novel chia-mucilage nanocomposite films with
529 starch nanocrystals; An inclusive biological and physicochemical perspective, *Int. J. Biol.*
530 *Macromol.*, 2019, **133**, 663-673.
- 531 57. C. Soukoulis, C. Gaiani and L. Hoffmann, Plant seed mucilage as emerging biopolymer in food
532 industry applications, *Curr. Opin. Food Sci.*, 2018, **22**, 28-42.
- 533 58. S. Montes and H. Maleki, in *Colloidal Metal Oxide Nanoparticles*, eds. S. Thomas, A. Tresa
534 Sunny and P. Velayudhan, Elsevier, 2020, DOI: [https://doi.org/10.1016/B978-0-12-813357-](https://doi.org/10.1016/B978-0-12-813357-6.00015-2)
535 [6.00015-2](https://doi.org/10.1016/B978-0-12-813357-6.00015-2), pp. 337-399.
- 536 59. A. Ubeyitogullari and O. N. Ciftci, Fabrication of bioaerogels from camelina seed mucilage for
537 food applications, *Food Hydrocoll.*, 2020, **102**, 105597.
- 538 60. E. A. Makri and G. I. Doxastakis, Surface tension of *Phaseolus vulgaris* and *coccineus* proteins
539 and effect of polysaccharides on their foaming properties, *Food Chem.*, 2007, **101**, 37-48.
- 540 61. H. Yuan, Q. Ma, L. Ye and G. Piao, The traditional medicine and modern medicine from natural
541 products, *Molecules*, 2016, **21**, 559.
- 542 62. A. H. Palla and A.-H. Gilani, Dual effectiveness of flaxseed in constipation and diarrhea: possible
543 mechanism, *J. Ethnopharmacol.*, 2015, **169**, 60-68.
- 544 63. J. Wärnberg, A. Marcos, G. Bueno and L. A. Moreno, Functional benefits of psyllium fiber
545 supplementation, *Curr. Top. Nutraceutical Res.*, 2009, **7**, 55-64.

- 546 64. P. T. Boban, B. Nambisan and P. R. Sudhakaran, Hypolipidaemic effect of chemically different
547 mucilages in rats: a comparative study, *Br. J. Nutr.*, 2006, **96**, 1021-1029.
- 548 65. B. O. Schneeman, Building scientific consensus: the importance of dietary fiber. *Journal*, 1999.
- 549 66. G. S. Kumar, A. Shetty and P. Salimath, Modulatory effect of fenugreek seed mucilage and spent
550 turmeric on intestinal and renal disaccharidases in streptozotocin induced diabetic rats, *Plant*
551 *Foods Hum. Nutr.*, 2005, **60**, 87-91.
- 552 67. M. A. Nuñez-López, O. Paredes-López and R. Reynoso-Camacho, Functional and hypoglycemic
553 properties of nopal cladodes (*O. ficus-indica*) at different maturity stages using in vitro and in
554 vivo tests, *J. Agric. Food Chem.*, 2013, **61**, 10981-10986.
- 555 68. K. Juárez-Reyes, F. Brindis, O. N. Medina-Campos, J. Pedraza-Chaverri, R. Bye, E. Linares and
556 R. Mata, Hypoglycemic, antihyperglycemic, and antioxidant effects of the edible plant *Anoda*
557 *cristata*, *J. Ethnopharmacol.*, 2015, **161**, 36-45.
- 558 69. A. Kimura, J.-H. Lee, I.-S. Lee, H.-S. Lee, K.-H. Park, S. Chiba and D. Kim, Two potent
559 competitive inhibitors discriminating α -glucosidase family I from family II, *Carbohydr. Res.*,
560 2004, **339**, 1035-1040.
- 561 70. H. E. Lebovitz, Alpha-glucosidase inhibitors, *Endocrinol. Metab. Clin. North Am.*, 1997, **26**, 539-
562 551.
- 563 71. J. S. Aprioku, Pharmacology of free radicals and the impact of reactive oxygen species on the
564 testis, *J. Reprod. Fertil.*, 2013, **14**, 158.
- 565 72. C. Desmarchelier, J. Coussio and G. Ciccia, Antioxidant and free radical scavenging effects in
566 extracts of the medicinal herb *Achyrocline satureioides* (Lam.) DC. ("marcela"), *Braz. J. Med.*
567 *Biol. Res.*, 1998, **31**, 1163-1170.

- 568 73. K. Singh, M. Bhorl, Y. A. Kasu, G. Bhat and T. Marar, Antioxidants as precision weapons in war
569 against cancer chemotherapy induced toxicity–Exploring the armoury of obscurity, *Saudi Pharm.*
570 *J.*, 2018, **26**, 177-190.
- 571 74. J. A. Leopold, Antioxidants and coronary artery disease: from pathophysiology to preventive
572 therapy, *Coron. Artery Dis.*, 2015, **26**, 176-183.
- 573 75. P. K. Bagul, H. Middela, S. Matapally, R. Padiya, T. Bastia, K. Madhusudana, B. R. Reddy, S.
574 Chakravarty and S. K. Banerjee, Attenuation of insulin resistance, metabolic syndrome and
575 hepatic oxidative stress by resveratrol in fructose-fed rats, *Pharmacol. Res.*, 2012, **66**, 260-268.
- 576 76. S. Keshani-Dokht, Z. Emam-Djomeh, M.-S. Yarmand and M. Fathi, Extraction, chemical
577 composition, rheological behavior, antioxidant activity and functional properties of *Cordia myxa*
578 mucilage, *Int. J. Biol. Macromol.*, 2018, **118**, 485-493.
- 579 77. H. Li, X. Wang, Y. Li, P. Li and H. Wang, Polyphenolic compounds and antioxidant properties
580 of selected China wines, *Food Chem.*, 2009, **112**, 454-460.
- 581 78. C. Malsawmtluangi, K. Thanzami, H. Lahlhlemawia, V. Selvan, S. Palanisamy, R. Kandasamy
582 and L. Pachuau, Physicochemical characteristics and antioxidant activity of *Prunus cerasoides* D.
583 Don gum exudates, *Int. J. Biol. Macromol.*, 2014, **69**, 192-199.
- 584 79. C. Nampuak and K. Tongkhao, Okra mucilage powder: a novel functional ingredient with
585 antioxidant activity and antibacterial mode of action revealed by scanning and transmission
586 electron microscopy, *Int. Food Sci. Technol.*, 2020, **55**, 569-577.
- 587 80. W. Chaiyasit, D. J. McClements and E. A. Decker, The relationship between the physicochemical
588 properties of antioxidants and their ability to inhibit lipid oxidation in bulk oil and oil-in-water
589 emulsions, *J. Agric. Food Chem.*, 2005, **53**, 4982-4988.
- 590 81. W. W. Zhi, T. C. Wei, Y. W. Jen, W. H. Long, C. C. Lin, C. J. Der, L. M. Kuang and L. W. Tung,
591 Comparative study on the physicochemical and functional properties of the mucilage in the carpel

of *Nymphaea odorata* using ultrasonic and classical heating extractions, *Int. J. Biol. Macromol.*, 2018, **117**, 1367-1373.

82. Y. Y. Thoo, S. K. Ho, J. Y. Liang, C. W. Ho and C. P. Tan, Effects of binary solvent extraction system, extraction time and extraction temperature on phenolic antioxidants and antioxidant capacity from mengkudu (*Morinda citrifolia*), *Food chem.*, 2010, **120**, 290-295.

83. M. Jouki, S. A. Mortazavi, F. T. Yazdi and A. Koocheki, Optimization of extraction, antioxidant activity and functional properties of quince seed mucilage by RSM, *Int. J. Biol. Macromol.*, 2014, **66**, 113-124.

84. S. Tantiwatcharothai and J. Prachyawarakorn, Property improvement of antibacterial wound dressing from basil seed (*O. basilicum* L.) mucilage-ZnO nanocomposite by borax crosslinking, *Carbohydr. Polym.*, 2020, **227**, 115360.