Chia seed mucilage (*Salvia hispanica* L.): An emerging biopolymer for industrial application

Mucilagem de sementes de chia (*Salvia hispanica* L.): Um biopolímero emergente para aplicação industrial

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ABSTRACT
Biopolymers are widely distributed in nature and have a wide variety of biological properties and applications. Chia (*Salvia hispanica* L.) is an herbaceous plant that belongs to the Lamiaceae family, which when in contact with water exude the fraction of soluble fiber in the form of mucilage. In view of the above, this study aims to provide an overview of the characteristics and applications of chia mucilage that make it a biopolymer of industrial interest. The data collection was carried out in the databases: SciELO (Scientific Electronic Library Online), Science Direct, MDPI, Wiley Online Library, Springer and Periodical capes using the following descriptors: "Chia Seed Mucilage", "Technological Properties", "Biological Activities", and "Applications" in alone and in association. After the critical analysis of the selected articles, it was possible to conclude that the chia mucilage has numerous and unique physical-chemical, chemical and technological properties. Applications in the food field are among the most used in view of the industrial perspective. However, the infinite potential that this biomaterial has for the pharmaceutical and agricultural industries is undeniable.

Keywords: chia seed mucilage, technological properties, biological activities, applications.

RESUMO
Os biopolímeros são amplamente distribuídos na natureza e possuem uma ampla variedade de propriedades biológicas e aplicações. A chia (*Salvia hispanica* L.) é uma planta herbácea pertencente à família Lamiaceae, que quando em contato com a água exala a fração de fibra solúvel na forma de mucilagem. Diante do exposto, este estudo tem como objetivo fornecer um panorama sobre as características e aplicações da mucilagem da chia que a tornam um biopolímero de interesse industrial. A coleta de dados foi realizada nas bases de dados: SciELO (Scientific Electronic Library Online), Science Direct, MDPI, Wiley Online Library, Springer e Periodical capes utilizando os seguintes descritores: "Chia Seed Mucilage", "Technological Properties", "Biological Activities ", e "Aplicações" isoladamente e em associação. Após a análise crítica dos artigos selecionados, foi possível concluir que a mucilagem da chia possui inúmeras e únicas propriedades físico-químicas, químicas e tecnológicas. As aplicações na área de alimentos estão entre as mais utilizadas do ponto de vista industrial. No entanto, é inegável o potencial infinito que este biomaterial tem para as indústrias farmacêutica e agrícola.

Palavras-chave: mucilagem da semente de chia, propriedades tecnológicas, atividades biológicas, aplicações.

1 INTRODUCTION

Biopolymers are widely distributed in nature, with exoskeletons from some arthropods, not plant cell walls and in some fungi and bacteria [1]. Most of them are macromolecular polysaccharides that have a complex structure formed by 10 or more monosaccharides [2, 3]. These high molecular weight carbohydrates consisting of simple sugars, such as glucose, galactose, mannose, fructose, connected by alpha and / or beta-glycosidic bonds [4]. These macromolecules have a wide variety of biological properties and applications, with potential antioxidants [5, 6], antitumor [7], anticancer [8] and immunomodulators [9].

There is great interest in researching natural molecules, since, in addition to being low cost and presenting unique attributes such as biocompatibility, biodegradability and low toxicity, they have unique physical-chemical characteristics such as high viscosity, which make them attractive for industrial use due their unique emulsifying, thickening, gelling, dispersing and stabilizing properties [10,11,12]. Thus, in recent years these biomaterials have been drawing the attention of scholars due to their distinct structures and compositions, since they directly affect their functional properties and biological activities, making them, therefore, more attractive than those of synthetic origin [13, 14].

In this context, chia (*Salvia hispanica* L.) is an herbaceous plant that belongs to the Lamiaceae family native to Mexico and Guatemala, however, it is widely distributed around the world [15, 16]. Its composition varies according to the color of the seeds, which can vary between black and white (**figure 1a**). However, they are composed of innumerable natural antioxidants, oil (30% to 40%), of which 60% corresponds to α-linoleic acid (omega 3), proteins (15% to 25%) and fibers (18% to 30%), and when in contact with water exudate the fraction of soluble fiber in the form of mucilage [17, 18, 19].

Chia seed mucilage is capable of forming highly viscous solutions at low concentration, exhibits excellent properties of water retention, gel formation, syneresis control and emulsion stabilization (Avila-de la rosa et al., 2015; Capitani et al. al., 2015; Dick et al., 2015; Timilsena et al., 2016), as well as great potential for forming films for food, pharmaceutical and cosmetic purposes (Muñoz et al. 2012). In this perspective, this study aims to provide an overview of the characteristics and applications of chia seed mucilage (*Salvia hispanica* L.) that make it a biopolymer of industrial interest.

2 METHODS

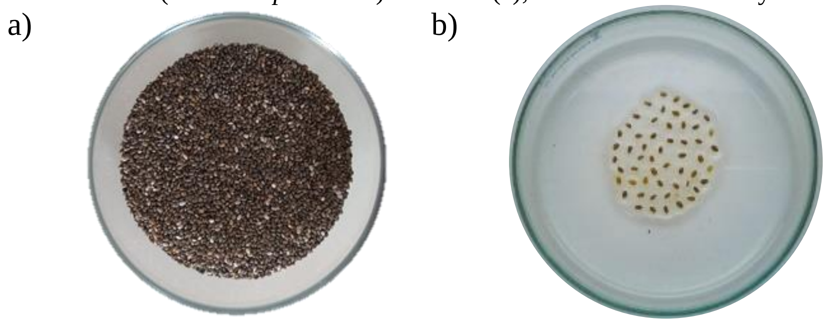
In view of the above, this study aims to provide an overview of the characteristics and applications of chia seed mucilage (*Salvia hispanica* L.) that make it a biopolymer of industrial interest. The data collection was carried out in the databases: SciELO (Scientific Electronic Library Online), Science Direct, MDPI, Wiley Online Library and Springer using the following descriptors: "Chia Seed Mucilage", "Technological Properties", "Biological Activities", and "Applications" individually and in association.

The selection of articles was carried out according to the following inclusion criteria: full articles published in English containing the aforementioned descriptors, published between 2012 and 2020. Articles related to the characterization and application of other plant or seed mucilages were excluded from the study.

3 MUCILAGE EXTRACTED FROM CHIA SEED

The mucilaginous exudate produced and released by the chia seed has a yellow and light color, is odorless and highly viscous, as shown in **figure 1b**. This biomaterial has high levels of moisture (12.69 ± 0.37 g. $100g^{-1}$) and ash (10.88 ± 0.31 g. $100g^{-1}$) and is mainly composed of carbohydrates (59.49 g. $100g^{-1}$). However, it has a protein fraction (9.38 ± 0.02 g. $100g^{-1}$) and a lipid fraction (1.98 ± 0.06 g. $100g^{-1}$) in its centesimal composition [25].

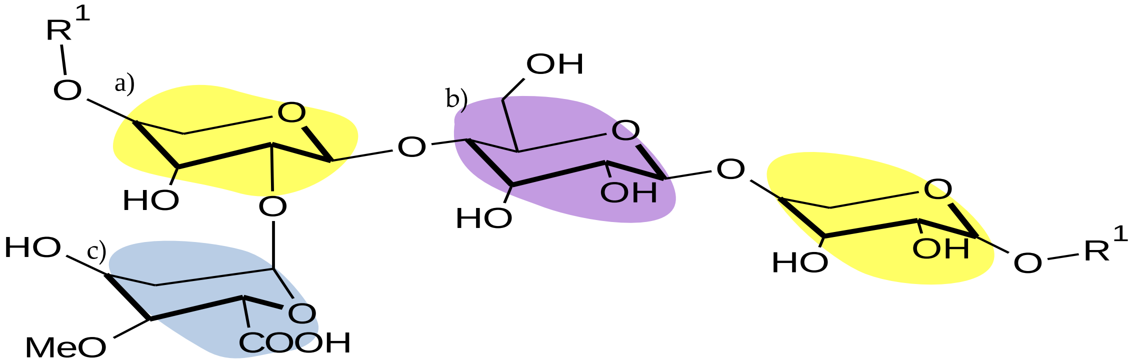
Figure 1. Chia seed (*Salvia hispanica* L.) in natura (a); after 30 minutes of hydration (b).



Source: Ramos et al., 2021.

According to Lin, Daniel & Whistler [26] the chia seed mucilage (MChS) is made up of a heteropolysaccharide that has 3 fractions of the same composition D-xylose (38.5 ± 2.4%), D-glucose (19.6 ± 3.2%) and 4-O-methyl-α-D-glycouronic acid (18.7 ± 2.1%), in the proportion of 2: 1: 1 (tetrapolysaccharide) whose molecular weight ranges from 0.8 to 2 x 10^6 Da, as seen in **Figure 2**. In addition, it has residues of D-mannose, D-arabinose and uranic acids and a small percentage of proteins [23, 27]. These findings suggest the presence of pectic polysaccharides.

Figure 2. Molecular structure of the heteropolysaccharide extracted from the chia seed (*Salvia hispanica* L.) in the 2: 1: 1 ratio of a) Xylose. b) Glucose. c) 4-O-methyl-α-D-glucouronic acid.



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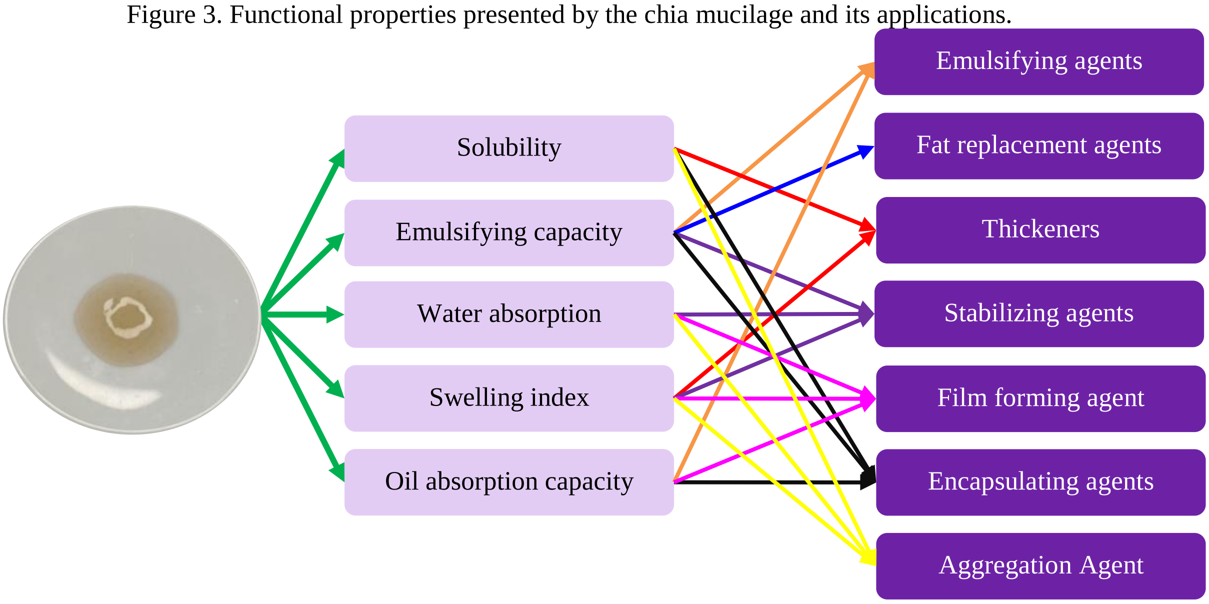
This polysaccharide is composed of glycosyl units that contain an average of three hydroxyl groups. Each of these groups is able to connect to water through hydrogen bonds [28]. According to Velazquez-gutierrez et al. [27] chia, mucilage has a low glass transition temperature (Tg, 42 °C to 57 °C). This parameter is related to the structure and stiffness of the polymeric chain and is directly proportional to the crosslink density. Thus, low Tg values result from high hygroscopicity due to the increase in free chains and hydrophilic groups [29].

Some research has focused on the study of the intrinsic properties and applications of chia mucilage. Aspects such as chemical and proximal composition and chemical properties such as thermal stability are significant factors that influence the degree of adaptation of these biomaterials in the food and pharmaceutical fields. This material also had an anionic character, due to the significant content of uronic acid, in a wide pH range. Its structural arrangement, as well as that of several vegetable gums and mucilages, is semi-crystalline and has good thermal stability, starting to decompose at 280 °C [23, 31, 31].

Through the evaluation of technological properties, it becomes possible to determine the applications of a given biopolymer, thus being parameters of interest to the industrial field. Chia mucilage has excellent water solubility (86.96 %) [32], in addition to exhibiting excellent water retention properties (95.6 g H2O. g^{-1}) and oil (22.3 g oil. g^{-}

[1]) [33], and, formation (53.26 mL. 100 mL^{-1}) and stabilization of emulsions (94.84 mL. 100 mL^{-1}) [34, 21]. **Figure 3** shows the main technological properties presented by the chia mucilage and its applications.

Figure 3. Functional properties presented by the chia mucilage and its applications.



Source: Prepared by the authors.

MChS still showed excellent photostability, with only 6.6% degradation after 120 min of exposure to UV light. The same study also verified, through the MTT method on the fibroblast L929 cell line, that the polymer has excellent cytocompatibility. Furthermore, chia mucilage showed promising mucoadhesive activity (0.390 ± 0.007 N.cm^{-2}) [35].

4 APPLICATIONS OF CHIA MUCILAGE IN THE FOOD INDUSTRY

Currently, there is a notable increase in the demand for alternative products and / or directed to people with restrictions, such as those who are allergic or do not consume gluten, which make it possible and even desirable to use natural gums such as chia mucilage. These biomaterials are used in the food industry as dietary fibers, thickeners, gelling agents, emulsifiers, stabilizers, fat substitutes, clarifying agents and flocculants. They can still be applied in the development of edible films, in the encapsulation of flavorings and food dyes, as well as being applied in the inhibition of crystallization [36,37].

4.1 FOOD SUBSTITUTE - "FOOD REPLACER"

For the consumer, sensory characteristics are, at first sight, the main determinants for the acquisition or not of the finished food product. In this way, the aggregation of natural hydrocolloids strengthens the "eco-friendly" appeal, in addition to improving and even adding new properties to the food [38]. Currently, there has been a commercial demand for the consumption of healthy foods, both through functional aggregation or by reducing caloric load. Li & Nie [39], describe "fat replacers" as ingredients that, when used in foods, completely or partially replace fat. The "fitness" appeal of these ingredients is related to their caloric load, which can be reduced or even close to zero.

The mucilage extracted from the chia seed is mainly composed of dietary fiber, thus presenting little digestibility and reduced caloric content. Associated with these characteristics, mucilage still has an enormous capacity for water retention. In this way, this biomaterial is attractive to the industrial field, as an emulsifying agent and fat substitute, adding nutritional value to food [34,40].

A study by Câmara et al. [41] developed a sausage without phosphates and with 50% less fat. For this purpose, the chia's mucilage was added in concentrations of 2% and 4% on the final formulation. The sensory analysis revealed that the sample with 2% mucilage was better evaluated than the one with 4% in all the analyzed parameters (aroma, flavor and texture) when compared to the control (sausage with 100% fat and phosphates). The role of MChS goes beyond reducing the levels of fat and phosphate that in excess are harmful to human health, but also delaying digestion, increasing satiety, prolonging the release of glucose from the food matrix and reducing the absorption of fatty acids and cholesterol [42].

Fernandes & Salas-Mellado [11] obtained preparations of cakes and breads with substitution of 25, 50, 75 and 100% of the oil for chia mucilage. For both products, the formulation with the best consumer acceptance index for bread (89%) and cake (86.2%) was with the substitution of 75% of the oil by MChS. The percentage of lipid reduction in relation to the control for the bread formulation was 36.7%, while for the cake the reduction was 51.6%.

The substitution of fat in processed hamburgers is considered a challenge, due to the quality and acceptance parameters well established by the market. This obstacle was overcome by Paula et al. [43], who added MChS in hamburger preparations, improving the fiber content parameter (1400% increase), reducing the lipid content by 28.99% and keeping the other hamburger proximal parameters stable. As for the organoleptic characteristics, the presence of mucilage, in addition to reducing fat levels, improved appearance and contributed to the induction of the fibrous and crunchy texture of the food. After the sensory analysis, it was found that the global acceptance of the product ranged from 7.6 to 8.1.

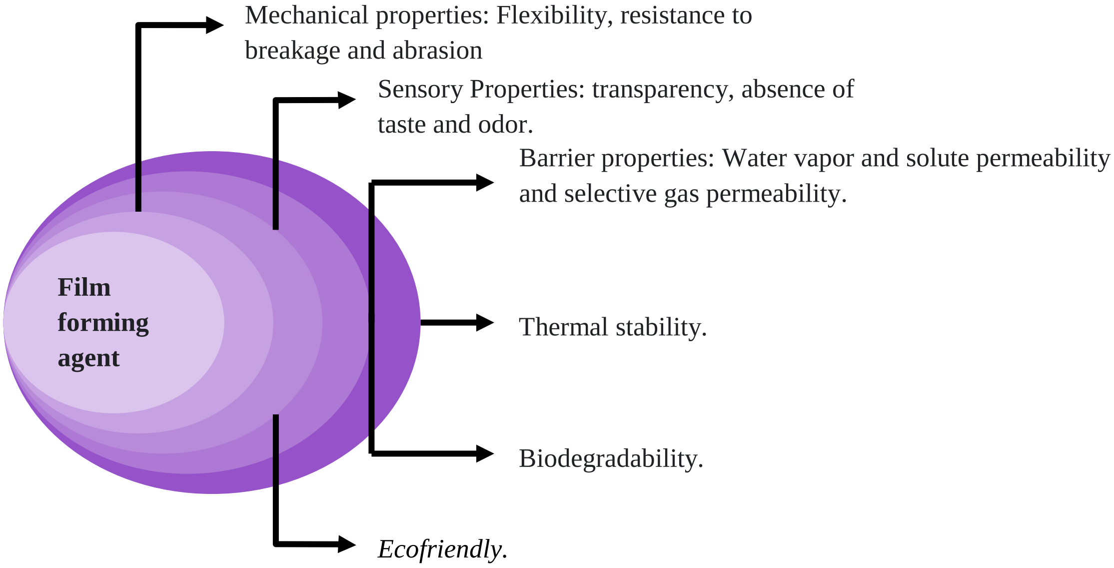
Due to its wide range of functional properties, chia mucilage is able to modify more than one sensory characteristic of food. The study by Darwish, Khalifa & El Sohaimy [44] evaluated the stabilizing and thickening action of MChS in yoghurts. It was observed that the addition of 2% MChS, improved the texture of the food by increasing the elasticity and reducing the hardness, consequently, increasing the acceptance of the product.

In the case of ice cream, sudden changes in temperature can contribute to the phenomenon of recrystallization. When it occurs, the texture characteristics of the product are compromised due to the development of ice crystals [45,46]. To solve this problem Chavan et al. [10] used MChS as a stabilizer in concentrations ranging from 0.1% to 0.4%. The addition of this input in concentrations up to 0.3% in addition to adding nutritional value to the product maintained the expected sensory characteristics, obtaining a high rate of acceptance by the testers (score of 8.4 to 8.8).

4.2 EDIBLE AND / OR BIODEGRADABLE PACKAGING AND FILMS

The search for sustainable development has increased the demand for the use of biodegradable packaging for the storage and conservation of food and beverages. It is expected that the materials used in the coating of foodstuffs will make it possible to extend the useful life of the goods [47]. Food films are solid and flexible membranes with well-defined dimensions consisting of an active substance incorporated into a matrix capable of controlling its release [48, 49, 50]. **Figure 4** presents important characteristics that a biopolymer must have for the development of a film.

Figure 4. Important characteristics of a good film-forming agent.



Source: Prepared by the authors.

Natural gums and mucilages have called the attention of researchers to the development of edible food coatings due to their constitution, rich in carbohydrates. Because of this characteristic, most polysaccharides have good barrier properties, especially when in conditions of low or moderate relative humidity [51, 52]. In addition, intermolecular forces such as ionic, electrostatic, hydrophobic and reticular interactions or through intra and intermolecular hydrogen bonds are also able to modulate this property [53].

The use of biopolymers for food coating has many advantages, it is easy to obtain and from renewable sources, it has low production costs, excellent barrier properties and, due to its easy handling, allows the incorporation of bioactive agents. It is still more widely accepted by consumers when compared to other methods of conservation, such as the addition of chemical preservatives and irradiation [54, 55, 56].

Charles-rodriguez et al. [57], used MChS to develop a food film associated with the phenolic extract of *Rhus microphylla*. The extract of *R. microphylla* showed good antioxidant and antifungal activities. The association between the two ingredients was responsible for the formation of a resistant, thick, opaque and dark film with proven biological activities. In addition, the association promoted the reduction of humidity, although there was no change in water vapor permeability and solubility, which demonstrates its high potential for biodegradability.

The film produced by Capitani et al. [58] consisted of a mucilage-chia protein conjugate and glycerol (plasticizer, 2: 1). Clove oil (CEO) was added to the formulation as an antibacterial agent. There was a wide variation in the mechanical parameters of tensile strength (TS, 0.47 to 2.77 kgf), elongation at break (EB, 1.51 to 6.12%) and modulus of elasticity (e, 0.48 to 6.02 kgf. mm^{-1}). According to the authors, the samples with the highest concentration of CEO were the most affected, with the parameters decreased. The film containing 2% mucilage showed a yellowish color, maintaining transparency, flexibility, adequate thickness and without the characteristic clove's smell.

Muñoz et al. [24] produced films with the polysaccharide extracted from chia associated with Whey protein in the proportions of 1: 3 and 1: 4, using glycerin (2: 1, mixture: plasticizer) as plasticizer. The films presented good mechanical properties and low permeability to water vapor, with the ratio 1: 3 being that formed the film with the highest values of TS (4.68 ± 1.05 MPa), EB (17.32 ± 3, 82%) and puncture resistance (PR, 117.05 ± 21.76 N).

The films produced from the lyophilized mucilage had a thickness (T) of 0.047 ± 0.002 mm, TS of 12.00 ± 0.74 MPa and EB of 6.7 ± 0.2% and contact angle (CA) of 79.27 ° ± 0.61. They also showed a high degree of degradation after 30 days of contact with the soil [59]. Mujtaba et al. [52] developed a nanocomposite film of chia mucilage and 6% starch nanocrystals. Although TS (7 MPa) and AC (64.9 ° ± 0.47) have decreased, the parameters of T (0.0426 ± 0.005 mm), EB (17.5%) and soil degradation time (15 days) have been considerably improved.

Associated with good mechanical properties, the nanocomposites showed improvement in antibacterial activities (inhibition zone >15 mm in all evaluated microorganisms) and antioxidant (238.71 mg TE. g^{-1}) when compared to the control. It was also observed that the films showed prominent antiproliferative activity against HepG2 cell lines (Human liver cancer cells, 24% reduction in viability) and low inhibition of viability in cells of the Vero line (renal epithelial cells extracted from an African green monkey) [52]. In this way, chia mucilage presents itself as an excellent and practical alternative for the production of food films. And because it has excellent mechanical attributes, it can be used alone or in association with other film makers and still carry substances with biological activities.

4.3 ENCAPSULATION OF FOOD SUBSTANCES

According to Pan et al. [60] it is essential to use a good emulsifier that behaves as a preservative in the processing, transport and storage of micro and nanoparticles. The centesimal composition of MChS rich in proteins and carbohydrates adds excellent properties of encapsulation, emulsification and oil absorption, while forming gels [31, 59, 61]. In this way, MChS becomes promising for the encapsulation of substances, being considered a technological alternative for the improvement of organoleptic attributes and oil stability.

MChS, together with maltodextrin, was applied in the encapsulation of the natural food dye, betacyanin. The results showed that the encapsulation yield varied from 41% to 43%, being directly proportional to the amount of polymer used. The amount of dye carried per gram of dry powder, showed a considerable increase when compared to the control of maltodextrin (from 26% to 49%). The sample also showed good thermal stability (up to 40 ° C) and in a wide pH range [62]. When forming complexes of coacervates using MChS and gelatin Hernández-Nava et al. [63] were able to encapsulate the essential oil of *Origanum vulgare* with an encapsulation efficiency greater than 90%.

Nanoencapsulation is also a technological alternative to make it possible to incorporate oils into foods with a high-water content [64]. Da Silva Stefani et al. [65] enriched the orange juice with linseed oil encapsulated in MChS. As a result, nanoparticles were obtained with an average diameter of 356 ± 2.83 nm, homogeneously distributed, and thermoresistant that were able to protect the oil from oxidation. The enrichment of orange juice with nanoparticles did not compromise its acceptance by the evaluators (83%), in addition, the bioaccessibility of the oil was 12.80%, suggesting high stability of the encapsulation process during *in vitro* digestion.

5 APPLICATIONS OF CHIA MUCILAGE IN THE PHARMACEUTICAL INDUSTRY

Among biopolymeric materials, polysaccharides symbolize a renewable resource of high relevance for application in the industrial sector, being present in several areas [66]. Characteristics such as high-water solubility, biodegradability and biocompatibility, non-toxicity, rapid enzymatic degradation and low cost, also contribute to the interest in its use [67, 68]. In the pharmaceutical industry, they are commonly used as encapsulants, disintegrating agents, thickeners, emulsifiers and release profile controllers [69].

5.1 ENCAPSULATION OF ACTIVE SUBSTANCES

The encapsulation of active substances using biopolymers is an effective measure for improving the solubility of these agents in water, as well as the physico-chemical characteristics, making them more stable and less susceptible to harmful action in the environment [64,69]. In one study, he used chia mucilage in association with a soluble fraction of proteins and maltodextrin for the encapsulation of *Lactobacillus plantarum* and *Bifidobacterium infantil*. The encapsulation not only guaranteed the viability of the microorganisms even after 45 days of preparation (≥10 LogUFC.g-1), but also protected them from simulated gastric activity, improving the entire performance of the formulation [70].

5.2 PHARMACEUTICAL EXCIPIENTS

The chia heteropolysaccharide was applied to the development of beads for controlled drug release using the coacervation technique. The obtained beads had irregular shapes, pores in the microgel particles and good water absorption capacity. It was also found that 100% of the encapsulated substance (proanthocyanin) was released after 12 hours, with 42% being released in the first 10 min of incubation in phosphate buffer [71].

The biopolymer was also used to carry essential oil of green cardamom (OECV) in nanofibers obtained by electrospinning. The use of mucilage enabled the incorporation of high levels of OECV (up to 64 mg. mL^{-1}), contributing positively to the increase in oil's antibacterial and antioxidant dose-dependent activities [72]. Madaan et al. [73] developed indomethacin tablets using MChS as a disintegrating agent. The formulation with 6% mucilage obtained the best parameters of hardness (D, 3.2 ± 0.02 kg. cm^2), degradation time (25.2 ± 0.03 sec), percentage of encapsulation (% E, 99.5 ± 0.08%) and in vitro release (98.12% after 30 min) even after 90 days of storage.

Another study evaluated the effect of using MChS in association with mesquite gum as an encapsulating agent for lemon essential oil found that the addition of mucilage prevented the oil oxidation process. The same study also concluded that the increase in the concentration of the biopolymer in the formulations contributed to the delay in the release of the active substance, mainly in solutions with pH close to neutrality (6.5). This behavior was attributed to the increase in the size of the particles and the swelling of the material, which when in contact with water formed a robust gel [74].

5.3 BIOLOGICAL PROPERTIES

Chia mucilage has some biological activities evaluated in vitro. Rosas-Ramírez et al. [75], evaluated the potential that this biomaterial presents as a modifying agent of cancer cell resistance to vinblastine. The study revealed that, despite not having its own cytotoxic effects, the addition of MChS was able to inhibit the efflux pump of several cancer cell lines. The IC_{50} of vinblastine associated with mucilage was about 4.5 times lower than vinblastine isolated against breast carcinoma cells (MCF7).

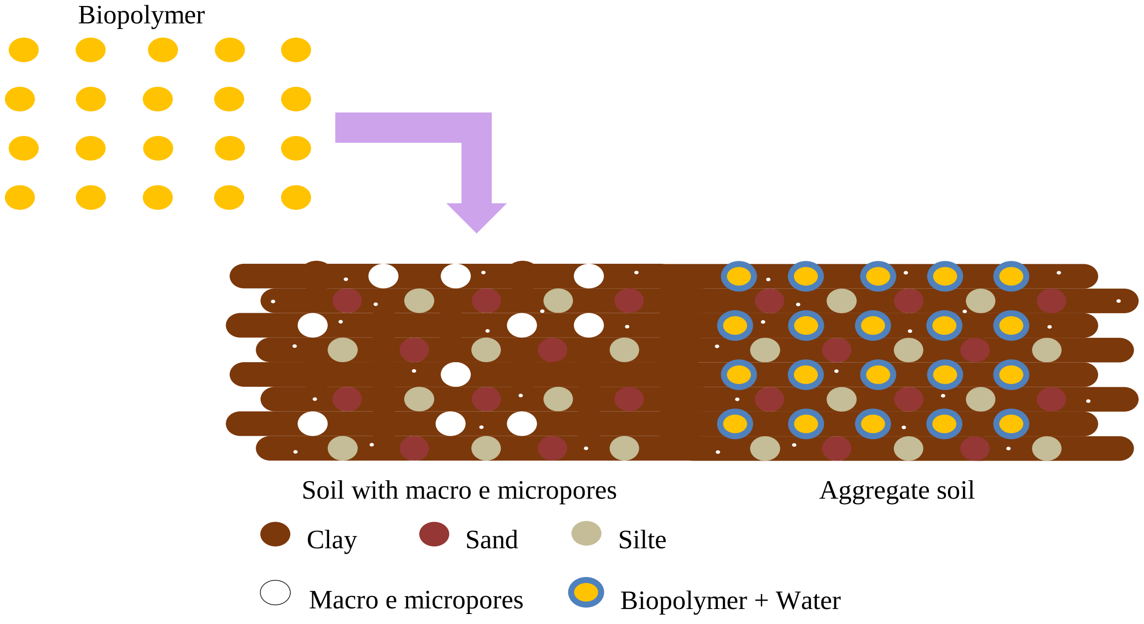
Another study found anti-inflammatory action of MChS in obese rats with rheumatoid arthritis (O-AtR) by reducing the paw volume by 25.99% and the inflammatory volume by 38.40%. While, in non-obese and arthritic rats (NO-AtR), the percentage was slightly lower, being 18.33% and 30.28% for swelling of the paw and inflammatory volume, respectively. In addition, the study suggested that MChS can be considered a natural modulator of oxidative stress and the lipid profile associated with O-AtR [76].

The role of the chia polysaccharide in the modulation of lipid and glucose profiles in vitro was studied by Tamargo et al. [77]. The use of a 0.95% mucilage dispersion led to a 66.7% reduction in bioaccessibility for glucose, 56.1% for fatty acids, 37.2% for cholesterol and 64.6% for bile salts. In addition to these biological properties, MChS had an anti-oxidant activity of 59.5 ± 0.6% over the free radical DPPH. The high antioxidative potential presented by mucilage can be attributed to the presence of catechins (8.40 ± 1.02 µg. g^{-1}), caffeic acid (557.24 ± 59.26 µg. g^{-1}), in addition to having high content of phenolic compounds (923.86 ± 75.56 µg. g^{-1}) [48.78].

6 OTHER INDUSTRIAL APPLICATIONS OF CHIA SEED MUCILAGE

Vegetable gums and mucilages play a fundamental role in stabilizing soils against erosion. Due to their adhesive properties, these biomaterials are able to form polymeric bonds, which retain water, and thus are able to aggregate soil particles (**Figure 5**) [80, 81, 82]. They also increase soil stability, by controlling the rate of water absorption in dry soils [83, 84]. In this context, chia mucilage can also be used to improve soil aggregation and conditioning.

Figure 5. Soil aggregation and conditioning process using polymers obtained from plants and seed.



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Di Marsico et al. [85, 86] evaluated the potential of MChS in sorption-desorption of soil herbicides and in improved soil stability. The studies indicated that the addition of 2% of MChS improved the structure of the clayey soil by reducing approximately 50% of the specific surface area. In addition, excellent sorption of the 4 tested herbicides (MCPA, Diuron, Clomazone and Terbutilazine) was observed. Also, an increase in the rate of aggregation of soils in a dose-dependent manner was observed, which persisted even after 30 days of application.

7 CONCLUSIONS

It was possible to conclude that the chia mucilage (*Salvia hispanica* L.) has numerous and unique physicochemical, chemical and technological properties. In addition, as it is of vegetable origin, this biopolymer is a renewable, inexpensive and non-toxic source of resources, further increasing the interest in its use in various industrial sectors. Applications in the food field are among the most used in view of the industrial perspective. However, the infinite potential that this biomaterial has for the pharmaceutical and agricultural industries is undeniable. In this way, chia mucilage contributes positively to sustainable socioeconomic development, since its use is able to reduce the environmental impact and strengthen the production chain, generating employment and income.

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