International Journal of Biological Macromolecules 107 (2018) 817–824

Contents lists available at ScienceDirect

International Journal of Biological Macromolecules

journal homepage: www.elsevier.com/locate/ijbiomac

Rheological properties of tamarind (*Tamarindus indica* L.) seed mucilage obtained by spray-drying as a novel source of hydrocolloid

Erik Alpizar-Reyes[a], Angélica Román-Guerrero[b], Raquel Gallardo-Rivera[b], Victor Varela-Guerrero[c], Julian Cruz-Olivares[a], César Pérez-Alonso[a,*]

[a] *Departamento de Ingeniería Química, Facultad de Química, Universidad Autónoma del Estado de México, Paseo Colón esq. Paseo Tollocan s/n, Col. Residencial Colón, C.P. 50120, Toluca, Estado de México, Mexico*
[b] *Departamento de Biotecnología, Universidad Autónoma Metropolitana-Iztapalapa, San Rafael Atlixco No. 186, Col. Vicentina, C.P. 09340, Ciudad de México, Mexico*
[c] *Centro Conjunto de Investigación en Química Sustentable UAEM – UNAM, Carretera Toluca-Atlacomulco, km 14.5, Unidad El Rosedal, Toluca, Estado de México, 50200, Mexico*

ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form 1 September 2017
Accepted 15 September 2017
Available online 18 September 2017

Keywords:
Tamarind seed mucilage
Rheological properties
Power law model

ABSTRACT

Tamarind seed mucilage (TSM) was extracted and obtained by spray drying. The power law model well described the rheological behavior of the TSM dispersions with determination coefficients R^2 higher than 0.93. According to power law model, non-Newtonian shear thinning behavior was observed at all concentrations (0.5%, 1%, 1.5% and 2%) and temperatures (25, 30, 40, and 60 °C) studied. Increasing temperature decreased the viscosity and increased the flow behavior index, opposite effect was observed when increasing the concentration. The temperature effect was more pronounced at 2.0% TSM concentration with an activation energy of 20.25 kJ/mol. A clear dependence of viscosity on pH was observed, as pH increased from acidic to alkaline conditions, the viscosity increased. It was found that the rheological properties of TSM were affected by the sucrose and salts and their concentrations as well due to the addition of ions (or sucrose) decreases repulsion and allows molecule expansion promoting a significant reduction in viscosity. These results suggest that TMS could be applied in the production of foods that require additives with thickening capacity.

1. Introduction

Hydrocolloids as biological macromolecules are widely used in the pharmaceutical, cosmetic, textile, paper and food industries as thickeners, water retention agents, emulsion stabilizers, suspending agents, binders, etc. [1–4]. In recent years, the mucilages are the preferred hydrocolloids since these are cheap, nontoxic, ecofriendly and nonpolluting during production and application, because they are able to bind and immobilize a large amount of water [5–7]. Therefore, the rheological behavior of hydrocolloids is of special importance since they are applied looking to modify the textural attributes of food. Rheological behavior of every biological macromolecule is unique and this information is very useful in a large number of industrial applications and should be carefully taken into account for designing and modelling purposes [8–10]. Shear-thinning or pseudoplastic non-Newtonian behavior has been reported in gums and mucilages; this property depends on many factors like concentration of the active compound, temperature, degree of dispersion, dissolution, electrical charge, previous thermal and mechanical treatment, presence or absence of other lyophilic colloids, and the presence of electrolytes or non-electrolytes [5,9,11–13]. Also, the chemical structures of the hydrocolloids and its conformation, particle size distribution, and particle shape, as well as the interactions between suspended particles, are known to affect flow behavior [10–14]. Mucilage extracted from the tamarind seed (TSM, up to 72%), is a natural polysaccharide available as a by-product of tamarind pulp industry mucilage [12]. TSM is composed of β-(1,4)-D-glucan backbone substituted with side chains of α-(1,4)-D-xylopyranose and (1,6) linked [β-D-galactopyranosyl-(1,2)-α-D-xylopyranosyl] to glucose residues, where glucose, xylose and galactose units are present in the ratio of 2.8:2.25:1.0, as the monomer units [15] and with a molecular weight of 720–880 kDa [12]. The mucilage dispersed in water has the ability of forming viscous solutions, with high thermal and chemical stability, edible, biodegradable, non-carcinogenic,

---

* Corresponding author.
E-mail addresses: cpereza@uaemex.mx, cesar_perezalonso@yahoo.com.mx (C. Pérez-Alonso).

https://doi.org/10.1016/j.ijbiomac.2017.09.048
0141-8130/

biocompatible and nontoxic properties [15]. TSM contains high amounts of many essential amino acids, like isoleucine, leucine, lycine, methionine, phenylalanine and valine [16], making the mucilage affordable as food additive. However, detailed data about the rheological behaviour of TSM spray dried at different environments is not available. This information is valuable to establish possible industrial applications, particularly for food products. TSM has the added benefit of employing a plant-based resource from a by-product of tamarind pulp industry, which is not been exploited yet, and could have a positive impact on the development of producer economies. Therefore, the aim of the present study was to characterize the rheological properties of aqueous dispersions of TSM spray dried obtained from tamarind seeds grown in Mexico, evaluating the effect of some conditions of the medium such as mucilage concentration, temperature, pH, type of salt, and sucrose concentrations.

2. Materials and methods

2.1. Materials

Tamarind dried pods were purchased at a local market of Toluca City, Mexico. The initial moisture content of tamarind seeds was ~2.5 kg water/kg dried solid. Chemical reagents were purchased from Sigma Aldrich S.A. de C.V. (Toluca, Mexico). All the water used in the experiments was deionized.

2.2. Tamarind seed mucilage extraction

Mucilage extraction was performed taking as basis the method proposed by Khounvilay and Sittikijyothin [12] with some modifications. The seeds were extracted manually from mature pods of tamarind, milled and grounded through a 355 μm mesh using a hammermill Pulvex 100 Mini 2HP (Mexico City, Mexico). 20.0 g of milled tamarind seeds were placed in 1.0 L beaker and deionized water was added in a 1:10 wt. ratio. The resulting mixture was stirred in a hot plate stirrer (Thermo scientific SP131325, China) adjusted at level 8 for 10 min to achieve a homogenous mixture. Deionized water was added in a 1:40 wt. ratio in relation with the initial weight of seeds and kept with constant stirring. The mixture was heated and kept at a constant temperature of 80 °C for 60 min. The mixture was put aside at 20 °C for 24 h to assure the release of the mucilage, and then was centrifuged with a Hermle Z323 K highspeed centrifuge (Hermle, Labortechnic, Germany) for 8 min at 524*g*. The supernatant represents the mucilage fraction, which was decanted and stored at ~4 °C for subsequent analysis.

2.3. Spray drying of tamarind seed mucilage

The extracted mucilage was feed at a rate of 40 mL/min to a Nichols/Niro spray-drier (Turbo Spray PLA, NY, USA) operated with an inlet temperature of 135 ± 5 °C, outlet temperature at 80 ± 5 °C and injecting compressed air at 4.0 bar. The spray-dried mucilage was stored in desiccators containing P_2O_5 to prevent increases in absorbed moisture.

2.4. Proximal analysis

Moisture, lipid and ash content of tamarind seed mucilage was determined according to the AOAC standard methods, 925.10, 920.85 and 923.03, respectively [17]. The total protein content of the mucilage was determined by Kjeldahl procedure (N × 6.25) as described in AOAC official method 981.10. Total carbohydrate content was evaluated by difference.

2.5. Rheological measurements

Rheological characterization was carried out using steady shear tests using a Physica MCR 300 (Physica Meβtechnik GmbH, Stuttgart, Germany) modular compact rheometer, with a cone-plate geometry, with cone diameter of 50 mm in diameter and cone angle of 2° in all the cases. The viscosity of mucilage dispersions were carefully poured in the measuring system, and left to rest for 5 min for structure recovery and temperature equilibration. The apparent viscosity (η_{app}) – shear rate ($\dot{\gamma}$) behaviour of the mucilage dispersions was determined by applying an increasing shear rate from 0.1 to 100 s^{-1}. Three replicates of each sample were made. The flow behavior index (n) and consistency index (k) values were computed by fitting to the Ostwald-de-Waele or Power Law model (Eq. (1)):

$$\tau = k\dot{\gamma}^n \tag{1}$$

where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), k is the consistency coefficient (Pa s^n) and n is the flow behavior index (dimensionless).

2.6. Evaluation of the temperature dependence of mucilage dispersions

TSM dispersions were prepared with deionized water at concentrations of 0.5%, 1.0%, 1.5% and 2% (w/w), under slow stirring at room temperature. Then the dispersion was kept at 4 °C for 24 h to complete hydration prior to assessment. Prepared samples were loaded into the plate and maintained for 5 min at measurement temperatures of 25, 30, 40 and 60 °C. A solvent trap was used in order to minimize the solvent loss due to evaporation. Optical microscopy images were obtained in a microscopy MOTIC BA-400 Xiamen, China, at resolution of 100 x for concentrations of 0.5%, 1.0%, 1.5% and 2% (w/w) of TSM at room temperature. Three replicates of each sample were made.

The temperature dependency of consistency coefficient (indicator of the viscous nature of the sample) was assessed by fitting to the Arrhenius model (Eq. (2)) as was suggested by Sengul et al. [18]:

$$k = k_0 e^{(Ea/RT)} \tag{2}$$

where k_0 is the proportionality constant (or consistency coefficient at a reference temperature, $Pa^* s^n$), *Ea* the activation energy (J/mol), *R* the universal law gas constant (8.314 J/mol K), and *T* the absolute temperature (K).

2.7. Determination of flow properties at different pH

Dispersions of TSM at 1.0% (w/w) were used to measure the flow properties with different pH values of 4.0, 7.0 and 10.0 (adjusted using 0.1 mol/L of NaOH and HCl) at shear rates from 0.1 to 100 s^{-1} and constant temperature of 25 °C. Optical microscopy images were obtained in a microscopy MOTIC BA-400 Xiamen, China, at resolution of 100× for this dispersions of TSM at room temperature. Three replicates of each sample were done.

2.8. Flow properties at different salts concentrations

Dispersions of TSM at 1.0% (w/w) were prepared. Monovalent (NaCl and KCl) and divalent ($CaCl_2$) salts were added to dispersions to give final concentrations of 0.01 M, 0.02 M and 0.03 M, respectively. Viscosity measurements were performed at a shear rate from 0.1 to 100 s^{-1} and keeping constant temperature at 25 °C. Three replicates of each sample were made.

Table 1
Power law parameters for TSM at different concentrations and temperatures.

Temperature (°C)	k (Pa s^n)	n	R^2
0.5% (w/w)			
25	0.058	0.698	0.983
30	0.050	0.704	0.994
40	0.034	0.724	0.992
60	0.016	0.750	0.991
1.0% (w/w)			
25	0.317	0.826	0.996
30	0.242	0.826	0.994
40	0.087	0.841	0.991
60	0.029	0.846	0.985
1.5% (w/w)			
25	0.322	0.811	0.987
30	0.277	0.817	0.994
40	0.181	0.849	0.991
60	0.099	0.886	0.993
2.0% (w/w)			
25	1.486	0.784	0.989
30	1.380	0.798	0.992
40	1.072	0.804	0.990
60	0.642	0.818	0.994

2.9. *Assessment of flow properties at selected sugar concentrations*

Sucrose was dissolved into the 1.0% (w/w) dispersions of TSM to give final sucrose concentrations of 0.0%, 2.5%, 5.0%, and 10% (w/v). The flow properties were measured at shear rates from 0.1 to 100 s^{-1} and constant temperature of 25 °C. Three tests of each sample were done.

3. Results and discussion

3.1. *Proximate composition of tamarind seed mucilage*

The proximal analysis of spray dried tamarind seed mucilage gave the resulting fractions on a dry basis: 12.96 ± 0.09% of proteins, 82.17 ± 0.21% of total carbohydrates, 4.28 ± 0.17% of fats and 0.59 ± 0.07% of ashes. These values are consistent with other reported previously by Khounvilay and Sittikijyothin [12] and Alpizar-Reyes et al. [19] with ranges of 12.77–15.40% of protein, 61.00–80.66% of total carbohydrates, 3.00–7.50% of fats and 0.07–3.30% of ashes. The small difference in composition of tamarind seed mucilage with other studies may be attributed to the difference in geographical origin, variety and growing and harvesting conditions.

3.2. *Effect of concentration and temperature on flow properties*

The influence of TSM concentration and temperature on the flow properties displayed a well-fitting data of shear rate versus shear stress to Ostwald-de-Waele or Power law model, it showed a typical non-Newtonian behavior at different conditions of concentrations and temperatures. The consistency coefficient (k), flow behavior index (n) and coefficients of determination (R^2) obtained by fitting data to power law model are shown in Table 1. The coefficients of determination (R^2) were higher than 0.906 for all tested samples indicating the suitability of the power law model to describe the flow properties of TSM.

Power law model designated that for low n values the pseudoplasticity of the fluid is increased tending not to be a Newtonian fluid, therefore, when n increases tending to be equal to one, the fluid becomes Newtonian showing slime like appearance. Pseudoplastic or shear-thinning fluids have a lower apparent viscosity at higher shear rates, and are usually solutions of large, polymeric molecules in a solvent with smaller molecules. It is generally supposed that the large molecular chains tumble at random and affect large volumes of fluid under low shear, but that they gradually align themselves in the direction of increasing shear and produce less resistance. The values of flow behavior index, n, were less than one, indicating the pseudoplastic (shear thinning) nature of the TSM at different measuring conditions. The low values of flow behavior indexes represent the great departure of flow from the Newtonian behavior and like many other shear-thinning hydrocolloids, they have a high viscosity at low shear rates which decreases dramatically as the shear is increased [8]. When the TSM concentration was increased from 1.0% to 2.0% (w/w) the values for flow behavior index decreased, nevertheless, in the special case of 0.5% (w/w) dispersion of TSM, n did not follow the general tendency. This could be attributed to the low concentration of TSM and the influence on flow behavior index by the predominance of hydrogen bonds from water medium on the dispersion which acts as a plasticizer and enhances the molecular motion and reduces the torsion [13].

Table 2
Activation energy from Arrhenius equation for TSM at different concentrations.

TSM concentration % (w/w)	k_0 (Pa*s^n)	Ea (kJ/mol)	R^2
0.5	0.711	0.98	0.975
1.0	0.163	5.27	0.948
1.5	0.089	6.69	0.918
2.0	0.001	20.25	0.995

On the other hand, when temperature was increased for the all concentrations studied, flow behavior index increased, indicating that the degree of pseudoplasticity was reduced when the temperature was increased. This phenomena could be attained to the energy dissipation movement of the molecules and decrease in intermolecular interactions, which in turn decrease the energy needed for the flow, thus decreasing the interference of the hydrodynamic domains [20,21]. Values of n were in the range of 0.698–0.886; in a comparative way, the values of n obtained for TSM are in agreement with those reported for flaxseed mucilage [22], welan and xanthan gum [23], acacia senegal gum [24], and a hydrocolloid from *Ziziphus lotus* fruit [25].

The values for consistency coefficient (Table 1) increasing when the TSM concentration was increased, this increase of k values may be attributed to the increase of water binding capacity when concentration was increased [26] due to an increase in the intermolecular interaction. In addition, consistency coefficient decreased when temperature was increased for the all concentrations studied, indicating a decrease in viscosity at higher temperatures. Wanchoo et al. [27] reported that the coefficient k is a strong function of the concentration of the solution and the temperature, whereas index n does not have a strong dependency on the concentration and temperature of the polymeric solutions. The same effect of temperature and concentration on the consistency coefficient was reported for flaxseed mucilage [22], chia mucilage [8], nopal mucilage [13], basil seed gum [28], xanthan gum, guar gum [29], and welan gum [23], at similar temperature and concentration conditions, corroborating the shear thinning nature of TSM.

Natural logarithm of consistency coefficients for all concentrations studied *versus* 1000/T were plotted (Fig. 1) in order to fit to the Arrhenius model for studying the temperature dependence of the viscosity (Table 2). Activation energy (Ea) for the flow process is related to chain flexibility [26] and the values higher than 0.92 of R^2 indicate that the dispersions in relation with temperature followed the Arrhenius type equation. A higher Ea value means a more rapid change in viscosity with temperature and the microstructure is more prone to change. Activation energy increased when TSM concentration in dispersions increased from 0.5 to 2.0%, indi-

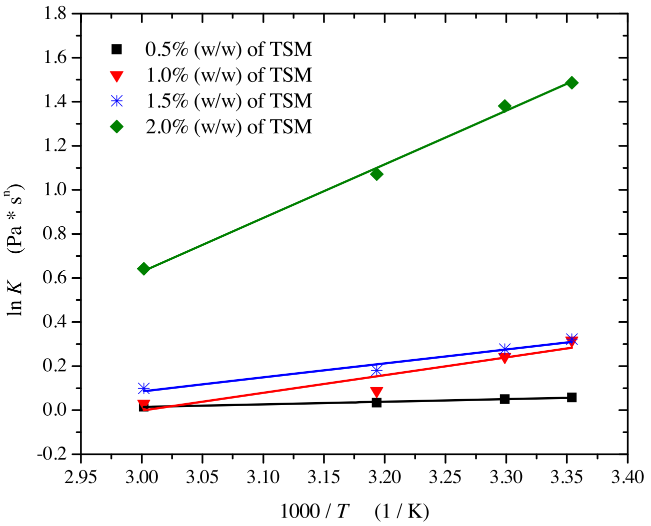

Fig. 1. Consistency index as function of temperature of TSM at different concentrations.

cating higher viscosity values when the concentration was higher, and subsequently, greater viscosity dependency to the temperature [10,13]. A higher value of *Ea* suggests that a large amount of external energy is required to initiate the motion of molecules in aqueous solutions. High activation energy is correlated with strong interaction between polymer chains, with the microstructure being less prone to alteration during thermal processing [23].

The variation in apparent viscosity with shear rate for the different temperatures and concentrations studied is shown in Fig. 2. For all dispersions, the viscosity decreased when the shear rate increased from 0.1 to 100 s^{-1}. This general tendency confirms the pseudoplastic behavior of the TSM dispersions, since as shear rate increases, the randomly positioned chains of polymer molecules become aligned in the direction of the flow, generating solutions with lower viscosity, resulting in less interaction among adjacent polymer chains [30]. In the low shear rate, the stretching polysaccharide molecules intertwined to form aggregates, the high viscosity is due to the large fluids flow resistance. Increasing shear rate the molecules are dispersed along the flow direction, as well as fluids flow resistance declines, resulting in the decrease of apparent viscosity [31]. A similar behavior was observed for other hydrocolloids [27,29,32,33].

The apparent viscosity of the dispersions (Fig. 2a) increased with the increase in mucilage concentration from 0.5% to 2.0% (w/w). According to Fig. 3, this attributed to the higher content of total solids in the dispersion, which causes an increase in viscosity due mainly to an increased restriction of intermolecular motion caused by hydrodynamic forces and the formation of an interfacial film as a result of highly branched structure in the TSM and multiple association points existing among the TSM molecules [33,34] (Fig. 3). On the other hand, Fig. 2b shows the decrease of viscosity with the increase of temperature. This effect may be attributed to the separation of the TSM molecules in solution, which become higher at higher temperature, promoting the decrease on viscosity. This phenomenon was observed in dispersions of chia mucilage [8], xanthan gum [34], flaxseed gum [35].

Shear-thinning hydrocolloids are extensively used to improve or modify food texture. The reduction in solution viscosity provides processing advantage during high-shear processing operations like pumping and filling, whereas high viscosity provides a desirable mouth feel during mastication, while the values of viscosity at the high shear rate allow understanding the viscosity of the product during certain processing operations such as pumping and spray drying. Accordingly, as the viscosity of solution decreases as shear rate increases, pumping efficiency increases as pump flow rate increases [36].

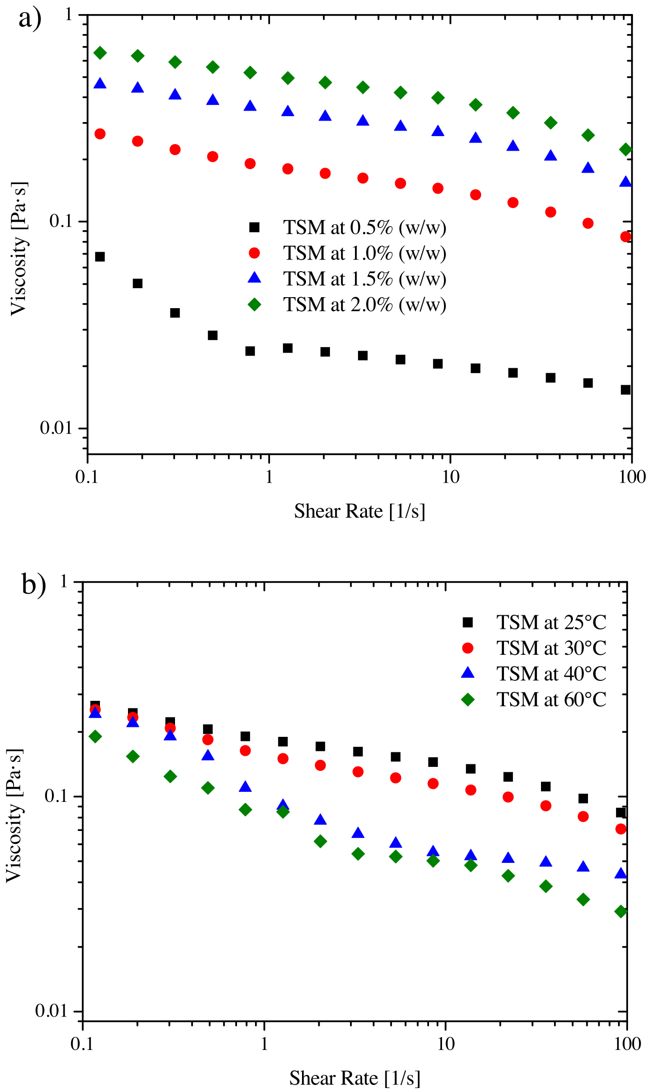

Fig. 2. Apparent viscosity dependence of concentrations (a) (temperature of 25 °C) and temperatures (b) (concentration of 1.0% (w/w)) of TSM.

Table 3
Power law parameters for TSM dispersions (1.0% w/w) at 25 °C and different pH conditions.

pH	k (Pa s^n)	n	R^2
4	0.048	0.884	0.971
7	0.317	0.826	0.964
10	0.538	0.815	0.937

3.3. *Effect of pH*

The rheological behavior in terms of shear stress versus shear rate of TSM dispersions at 25 °C and 1.0% (w/w) at different conditions of pH was adjusted to power law model, the parameters are shown in Table 3. The coefficients of determination (R^2) were higher than 0.99 for all tested samples indicating the suitability of the power law model to describe the flow properties of TSM. The influence of pH on the apparent viscosity of TSM dispersions is shown in Fig. 4, and as expected, a shear-thinning behavior varying shear rate values was observed for all dispersions. When the pH

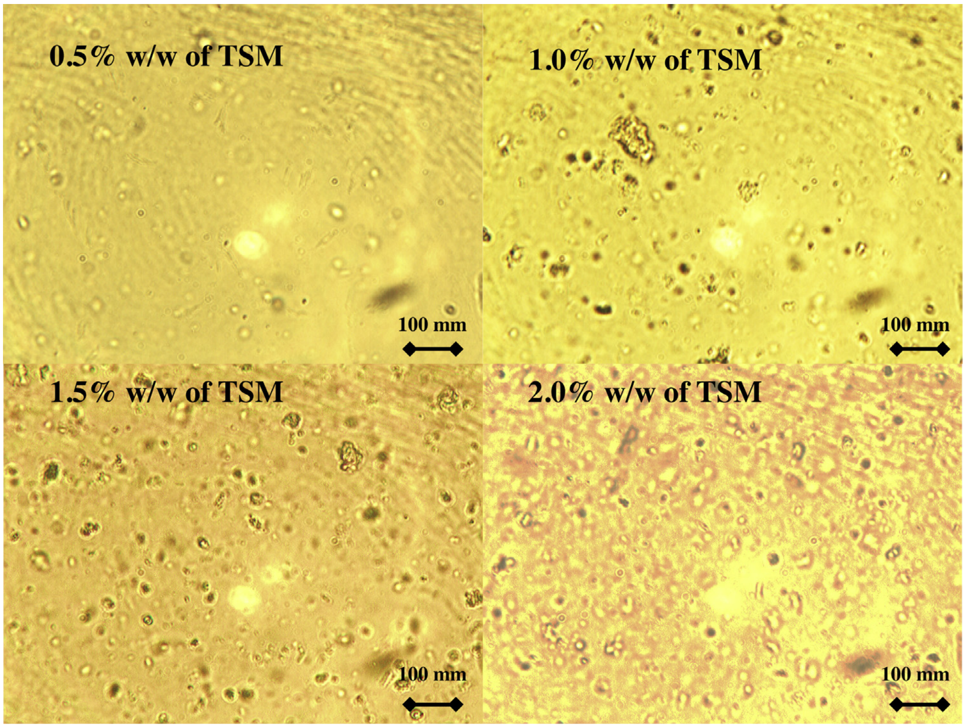

Fig. 3. Optical microscopy images for 0.5, 1.0, 1.5 and 2.0% (w/w) TSM dispersions.

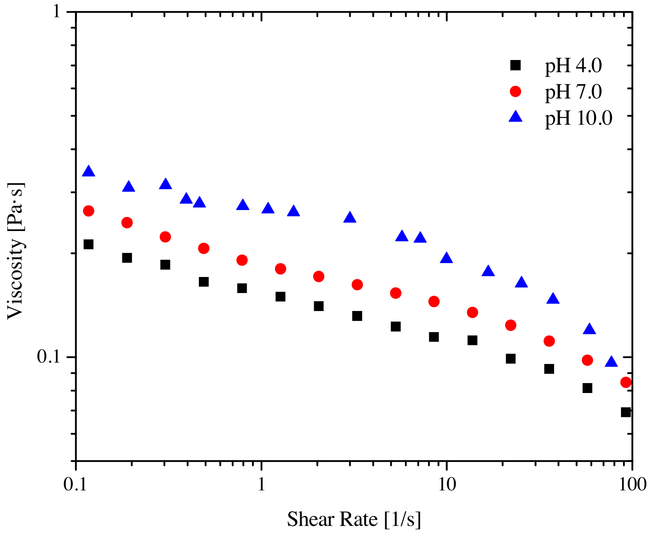

Fig. 4. pH effect upon viscosity of TSM (concentration of 1.0% (w/w) and 25 °C).

of the dispersion was increased from 4.0 to 10.0, the consistency coefficient (k) increased and flow behavior index (n) decreased; the general behavior of both parameters may be associated with an increase in charge density [37] promoting a contraction of the TSM molecules, and thus viscosity decreases (Figs. 4 and 5).

3.4. Effect of salts

The effect of ion concentration on the mucilage viscosity is important not only to determine whether the TSM performs as polyelectrolyte as well to estimate functional rheological properties [38–40]. Charged molecules show a strong dependence on ionic strength [13]. The flow behavior is represented by fitting experimental data to power law model with R^2 values higher than 0.99. For all salts, NaCl, KCl y $CaCl_2$, the flow behavior parameter increased progressively when the salts concentration was increased from 0.01 to 0.03 M indicating that the addition of salts reduced the pseudoplastic nature of the TSM dispersions. The highest values for n were observed in NaCl, indicating that the addition of this salt have the most important effect on the pseudoplasticity of TSM dispersions, even though, at 0.03 M of this salt on TSM dispersion, the fluid showed a n value so closely to 1, indicating that this dispersion may behave as Newtonian fluid.

The values of k were lower when a monovalent salt (NaCl and KCl) was added, compared with a divalent salt ($CaCl_2$) was added, in the dispersions prepared. These results suggest that the molecular structure of the TSM is negatively charged [41], behaving like a polyelectrolyte, and thus the addition of positive ions reduces the repulsion and molecular expansion, causing a significant decrease in viscosity [13]. On the other hand, the decrease of k in a medium with the presence of salts could be associated with the presence of sulfate groups and carboxylic acids in the structure of the polysaccharide [42]. The salts cause the contraction of the polysaccharide molecules, and thus viscosity decreases. A similar behavior was observed in dispersions of chia mucilage [29], and Balangu gum [43].

It has been reported that the electrostatic forces could change the arrangement of ionic polysaccharides and their physicochemical properties like viscosity as well [38]. Viscosity-shear rate curves for TSM (1% w/w) in the presence of different levels of NaCl, KCl and $CaCl_2$ (0, 0.1, 0.2 and 0.03 M) at 25 °C were obtained and in Fig. 6 is depicted the general trend for 0.03 M, applicable for the other salt concentrations. Regardless of salts concentration, the apparent viscosity was decreased as the shear rate increased from 0.001 to 1000 s^{-1}. Moreover, the addition of NaCl, KCl and $CaCl_2$ salts to the TSM dispersions at higher concentrations decreased the viscosity to a greater degree. For all the solutions, within the shear rates used, the shear-thinning behavior was observed. Rao [44] declared that this flow denotes the typical behavior of many biopolymer solutions. In the absence of salts, the inherent negative charge of TSM molecule produces strong intermolecular electrostatic repulsion and thus a more expanded molecule [41]. Hence,

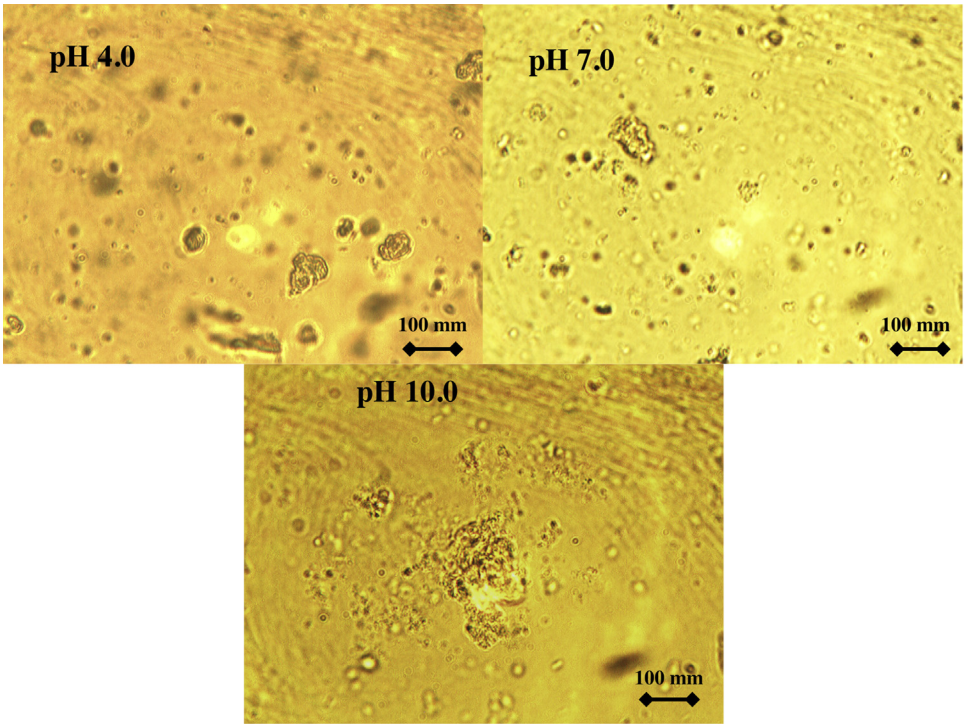

Fig. 5. Optical microscopy images at pH's of 4.0, 7.0 and 10.0 for 1.0 (w/w) TSM dispersions.

the higher viscosity of TSM with deionized water than salt solutions becomes clear. In the presence of NaCl, the viscosity showed a higher decrease, thus, this decrease was bigger at higher concentrations. Mazza and Biliaderis [35] stated that the reduction detected in viscosity of flax seed mucilage after NaCl addition was induced by increasing association of counter ions with the polymer molecules, which resulted in a reduction in electrostatic repulsion of charged groups on the polymer chain. Achi and Okolo [45] results demonstrated that the *Prosopis africana* seed gum had a slight reduction in viscosity affected by addition of 0.01 M NaCl. They concluded that salt addition enhanced the flexibility of the molecules, which forced a conformational change that led to a decrease in viscosity.

According to Razavi et al. [46], at high salt concentration, a portion of the ionized groups on the polymer will turn out to be neutralized (due to ion pair formation), causing a more compact formation. Besides, divalent cations are able to form salt bridges between acid groups and most of them are intramolecular bonds, thus causing a further reduction of the volume occupied by the gum. These results suggest that TSM is a negatively charged polyelectrolyte molecule, therefore, the addition of positive ions decreases repulsion and molecule expansion promoting a significant reduction in viscosity. These results are in agreement with results reported by Medina-Torres et al. [13] for nopal mucilage, by Razavi et al. [47] for wild sage mucilage (Table 4).

Table 4
Power law parameters for TSM (1.0% w/w at 25 °C) with different salt concentrations.

Salt	K (Pa s^n)	n	R^2
NaCl (M)			
0	0.317	0.826	0.977
0.01	0.165	0.847	0.984
0.02	0.043	0.882	0.960
0.03	0.034	0.996	0.997
KCl (M)			
0	0.317	0.826	0.986
0.01	0.094	0.839	0.984
0.02	0.072	0.849	0.981
0.03	0.047	0.856	0.971
$CaCl_2$ (M)			
0	0.317	0.826	0.979
0.01	0.195	0.820	0.985
0.02	0.062	0.881	0.974
0.03	0.039	0.925	0.966

Table 5
Power law parameters for TSM (1.0% w/w at 25 °C) with different sucrose concentrations.

Sucrose concentration (%)	k (Pa s^n)	n	R^2
0	0.317	0.826	0.996
2.5	0.157	0.793	0.987
5.0	0.138	0.779	0.989
10.0	0.068	0.759	0.973

3.5. *Effect of sucrose*

The typical shear rate-shear stress curves for TSM (1.0% w/w and at 25 °C) where studied as a function of sucrose concentrations of 0.0%, 2.5%, 5.0%, and 10.0% (w/v) and well fitted to the power law model with correlation factors (R^2) higher than 0.99 for all cases. Changes in consistency coefficient (k) and flow behavior index (n) as a function of sucrose concentration are presented in Table 5. It can be found that increase in the sucrose concentration had an amplifying influence on all power law parameters. Both parameters were influenced by sucrose concentration. The k value decreased from 0.317 ± 0.002 Pa*s^{n} to 0.068 ± 0.004 Pa*s^{n} whereas the n value decreased from 0.826 ± 0.007 to 0.759 ± 0.018. The higher flow behavior index indicated that at higher concentration of sucrose, the dispersions exhibited less pseudoplastic behavior and lean towards to be Newtonian fluid. Furthermore, for all concentrations of sucrose studied, a shear thinning behavior was evidently observed according to power law parameters, this type of flow behavior also has been reported for many hydrocolloids solutions [48–51]. This property is particularly substantial in formulation of oil in water emulsion, to prevent the drop separation and to allow

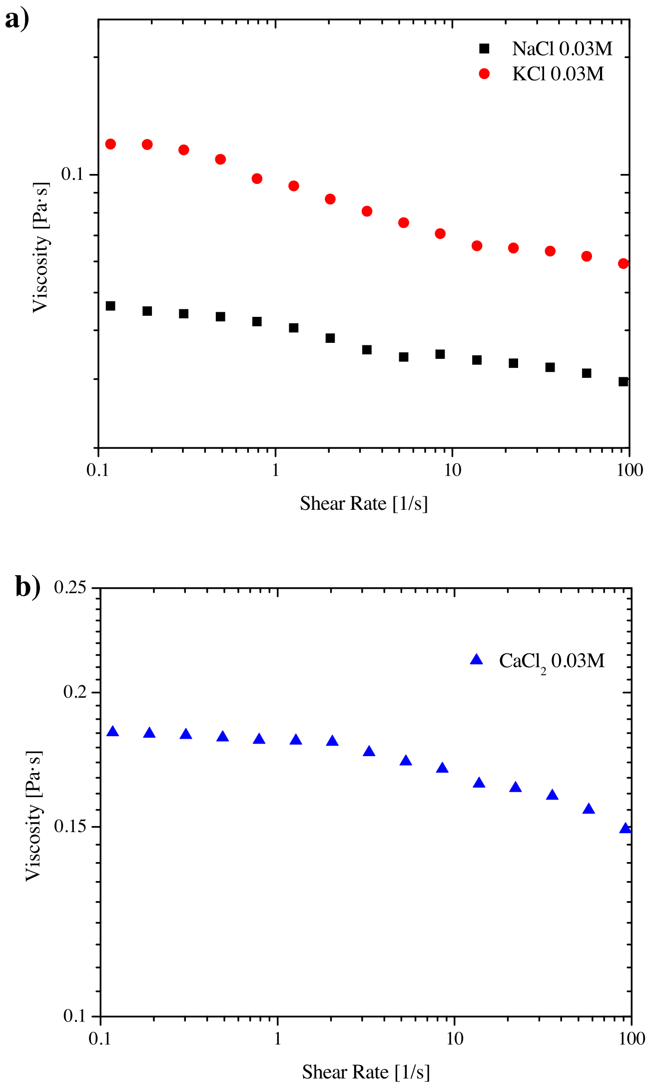

Fig. 6. a) Effect of different monovalent and b) divalent salt on TSM viscosity (concentration of 1.0% (w/w) and 25 °C).

an easy flow when poured [52]. Numerous authors who studied the effect of sucrose concentration on the rheological behavior are in agreement with this study reporting similar effects for oat gum [53], cress seed gum [48] and Balangu seed gum [54].

Fig. 7 shows rheological behavior of TSM dispersion at different sucrose concentrations. Previous studies had concluded that the existence of sucrose in the aqueous phase of liquid food systems containing hydrocolloids can change final rheological characteristics obtained over increasing or decreasing the system viscosity. Hence, enhancing aqueous phase viscosity results in a viscosity increment, instead, may reduce the hydration of hydrocolloid molecules which results in a decrement in viscosity, it can be concluded that the viscosity obtained maybe close to the viscosity which can be felt in the mouth. It has been reported that higher viscosity of food stuffs created a better mouthfeel [50]. Consequently, addition of the sugars to the TSM dispersion solution can make a good mouth feeling solution rather than a slimy feel in gone.

4. Conclusions

The analyzed Tamarind seed mucilage dispersions presented a Non-Newtonian shear thinning behavior ($n < 1$). The power law model well described the flow properties of the dispersions. Increasing the solution concentrations increased the viscosity and pseudoplasticity while increasing temperature resulted in a decrease in viscosity and pseudoplasticity. In addition, temperature dependency of the consistency index for the gum solutions was well described by the Arrhenius model. The influence of pH was the variable with the most significant effect on the flow behavior and rheological properties of TSM, when pH increases, apparent viscosity increased, this may be associated with an increase in charge density promoting a contraction of the TSM molecules. Addition of salts to TSM dispersions resulted in a diminution of k and an increment of n, promoting a decrease on apparent viscosity, suggesting that the molecular structure of the TSM is negatively charged, behaving like a polyelectrolyte. Addition of sucrose did not influence significantly apparent viscosity. According to the results of this study, it can be concluded that TSM could be potentially applied as hydrocolloid in order to achieve a superior quality for new and existing hydrocolloid added products.

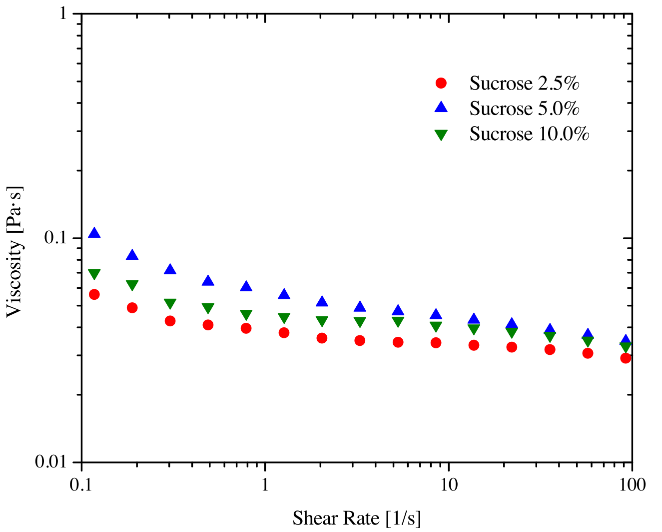

Fig. 7. Apparent viscosity dependence of sucrose concentrations TSM dispersions of 1.0% w/w.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgements

The authors wish to acknowledge the partial financial support of this research to the Universidad Autónoma del Estado de México through grant 4371/2017/CI. Also the authors wish to thank the financial support provided to the author E. Alpizar-Reyes who received a scholarship with number 331443 through the Consejo Nacional de Ciencia y Tecnología (CONACyT) of Mexico.

References

[1] R.R. Bhosale, R.A.M. Osmani, A. Moin, Natural gums and mucilages: a review on multifaceted excipients in pharmaceutical science and research, Int. J. Pharmacogn. Phytochem. Res. 6 (2014) 901–912.
[2] T. Kaewmanee, L. Bagnasco, S. Benjakul, S. Lanteri, C.F. Morelli, G. Speranza, M.E. Cosulich, Characterisation of mucilages extracted from seven Italian cultivars of flax, Food Chem. 148 (2014) 60–609.
[3] G. Archana, K. Sabina, S. Babuskin, K. Radhakrishnan, M.A. Fayidh, P. Azhag Saravana Babu, M. Sivarajan, M. Sukumar, Preparation and characterization of mucilage, Carbohydr. Polym. 98 (2013) 89–94.
[4] V.D. Prajapati, G.K. Jani, N.G. Moradiya, N.P. Randeria, Pharmaceutical applications of various natural gums, mucilages and their modified forms, Carbohydr. Polym. 92 (2013) 1685–1699.

[5] K.K.T. Goh, L. Matia-Merino, J.H. Chiang, R. Quek, S.J.B. Soh, R.G. Lentle, The physico-chemical properties of chia seed polysaccharide and its microgel dispersion rheology, Carbohydr. Polym. 149 (2016) 297–307.

[6] M.R. Segura-Campos, N. Ciau-Solís, G. Rosado-Rubio, L. Chel-Guerrero, D. Betancur-Ancona, Chemical and functional properties of chia seed (*Salvia hispanica* L.) gum, Int. J. Food Sci. 2014 (2014) 1–5.

[7] M. Soleimanpour, A. Koocheki, R. Kadkhodaee, Influence of main emulsion components on the physical properties of corn oil in water emulsion: effect of oil volume fraction, whey protein concentrate and *Lepidium perfoliatum* seed gum, Food Res. Int. 50 (2013) 457–466.

[8] M.I. Capitani, L.J. Corzo-Rios, L.A. Chel-Guerrero, D.A. Betancur-Ancona, S.M. Nolasco, M.C. Tomás, Rheological properties of aqueous dispersions of chia (*Salvia hispanica* L.) mucilage, J. Food Eng. 149 (2015) 70–77.

[9] C.V. Cervantes-Martínez, L. Medina-Torres, R.F. González-Laredo, F. Calderas, G. Sánchez-Olivares, E.E. Herrera-Valencia, J.A. Gallegos Infante, N.E. Rocha-Guzman, J. Rodríguez-Ramírez, Study of spray drying of the Aloe vera mucilage (*Aloe vera barbadensis* Miller) as a function of its rheological properties, LWT–Food Sci. Technol. 55 (2014) 426–435.

[10] E.E. García-Cruz, J. Rodríguez-Ramírez, L.L. Méndez Lagunas, L. Medina-Torres, Rheological and physical properties of spray-dried mucilage obtained from *Hylocereus undatus* cladodes, Carbohydr. Polym. 91 (2013) 394–402.

[11] G. Avila-de la Rosa, J. Alvarez-Ramirez, E.J. Vernon-Carter, H. Carrillo-Navas, C. Pérez-Alonso, Viscoelasticity of chia (*Salvia hispanica* L.) seed mucilage dispersion in the vicinity of an oil-water interface, Food Hydrocoll. 49 (2015) 200–207.

[12] K. Khounvilay, W. Sittikijyothin, Rheological behaviour of tamarind seed gum in aqueous solutions, Food Hydrocoll. 26 (2012) 334–338.

[13] L. Medina-Torres, E. Brito-De La Fuente, B. Torrestiana-Sanchez, R. Katthain, Rheological properties of the mucilage gum (*Opuntia ficus* indica), Food Hydrocoll. 14 (2000) 417–424.

[14] L. Matia-Merino, K.K.T. Goh, H. Singh, A natural shear-thickening water-soluble polymer from the fronds of the black tree fern, *Cyathea medullaris*: influence of salt, pH and temperature, Carbohydr. Polym. 87 (2012) 131–138.

[15] M. Sharma, D. Mondal, C. Mukesh, K. Prasad, Preparation of tamarind gum based soft ion gels having thixotropic properties, Carbohydr. Polym. 102 (2014) 467–471.

[16] S. Panigrahi, B. Bland, P.M. Carlaw, A.F. Science, The nutritive value of tamarind seeds for broiler chicks, Anim. Feed Sci. Technol. 22 (1989) 285–293.

[17] AOAC, Association of Official Analytical Chemists Official Methods of Analysis of AOAC International, vol. 534, Association of Official Analytical Chemists, Washington, DC, USA, 2006.

[18] M. Sengül, M. Fatih Ertugay, M. Sengül, Rheological, physical and chemical characteristics of mulberry pekmez, Food Control 16 (2005) 73–76.

[19] E. Alpizar-Reyes, H. Carrillo-Navas, R. Romero-Romero, V. Varela-Guerrero, J. Alvarez-Ramírez, C. Pérez-Alonso, Thermodynamic sorption properties and glass transition temperature of tamarind seed mucilage (*Tamarindus indica* L.), Food Bioprod. Process 101 (2017) 166–176.

[20] M. Bohdanecky, J. Kovar, Viscosity of Polymer Solutions, Elsevier Scientific Pub. Co., 1982.

[21] R. Lapasin, S. Pricl, Rheology, in Rheology of Industrial Polysaccharides: Theory and Applications, Springer, 1995, pp. 162–249.

[22] M. Wu, D. Li, L. Wang, Y. Zhou, Z. Mao, Rheological property of extruded and enzyme treated flaxseed mucilage, Carbohydr. Polym. 80 (2010) 460–466.

[23] L. Xu, G. Xu, T. Liu, Y. Chen, H. Gong, The comparison of rheological properties of aqueous welan gum and xanthan gum solutions, Carbohydr. Polym. 92 (2013) 516–522.

[24] R. Sibaja-Hernández, A. Román-Guerrero, G. Sepúlveda-Jiménez, M. Rodríguez-Monroy, Physicochemical, shear flow behaviour and emulsifying properties of *Acacia cochliacantha* and *Acacia farnesiana* gums, Ind. Crops Prod. 67 (2015) 161–168.

[25] M. Adeli, V. Samavati, Studies on the steady shear flow behavior and chemical properties of water-soluble polysaccharide from *Ziziphus lotus* fruit, Int. J. Biol. Macromol. 72 (2015) 580–587.

[26] A. Koocheki, A.R. Taherian, A. Bostan, Studies on the steady shear flow behavior and functional properties of *Lepidium perfoliatum* seed gum, Food Res. Int. 50 (2013) 446–456.

[27] F. Chenlo, R. Moreira, C. Silva, Rheological properties of aqueous dispersions of tragacanth and guar gums at different concentrations, J. Texture Stud. 41 (2010) 396–415.

[28] S. Naji-Tabasi, S.M.A. Razavi, New studies on basil (*Ocimum bacilicum* L.) seed gum: part III –steady and dynamic shear rheology, Food Hydrocoll. 67 (2017) 243–250.

[29] S.K. Velázquez-Gutiérrez, A.C. Figueira, M.E. Rodríguez-Huezo, A. Román-Guerrero, H. Carrillo-Navas, C. Pérez-Alonso, Sorption isotherms, thermodynamic properties and glass transition temperature of mucilage extracted from chia seeds (*Salvia hispanica* L.), Carbohydr. Polym. 121 (2015) 411–419.

[30] B.S. Chagas, D.L.P. Machad Jr., R.B. Haag, C.R. de Sousa, E.F. Lucas, Evaluation of hydrophobically associated polyacrylamide-containing aqueous fluids and their potential use in petroleum recovery, J. Appl. 91 (2004) 3686–3692.

[31] M. Oh, J. So, S. Yang, Rheological evidence for the silica-mediated gelation of xanthan gum, J. Colloid Interface Sci. 216 (1999) 320–328.

[32] S. Naji-Tabasi, S.M.A. Razavi, New studies on basil (*Ocimum bacilicum* L.) seed gum: part II–emulsifying and foaming characterization, Carbohydr. Polym. 149 (2016) 140–150.

[33] A.-I. Yeh, T.-Y. Chan, G.C.-C. Chuang, Effect of water content and mucilage on physico-chemical characteristics of Yam (*Discorea alata* Purpurea) starch, J. Food Eng. 95 (2009) 106–114.

[34] R.A. Speers, M.A. Tung, Concentration and temperature dependence of flow behavior of xanthan gum dispersions, J. Food Sci. 51 (1986) 96–98.

[35] G. Mazza, C.G. Biliaderis, Functional properties of flax seed mucilage, J. Food Sci. 54 (1989) 1302–1305.

[36] D.J. McClements, Emulsion rheology 8.1, in: Food Emulsions: Principles, Practice, and Techniques, 2005.

[37] R.H. Chen, W.Y. Chen, Rheological properties of the water-soluble mucilage of a green laver, *Monostroma nitidium*, J. Appl. Phycol. 13 (2001) 481–488.

[38] A.R.R. Yousefi, S.M.A.A. Razavi, S.H.H. Khodabakhsh Aghdam, Influence of temperature, mono- and divalent cations on dilute solution properties of sage seed gum, Int. J. Biol. Macromol. 67 (2014) 246–253.

[39] A.R. Yousefi, S.M.A. Razavi, A. Norouzy, In vitro gastrointestinal digestibility of native, hydroxypropylated and cross-linked wheat starches, Food Funct. 6 (2015) 3126–3134.

[40] Y. Yan, M. Takemasa, C. Zhao, L. Yu, K. Nishinari, Structure-gelation research on gallate analogs and xyloglucan by rheology, thermal analysis and NMR, Food Hydrocoll. 52 (2016) 447–459.

[41] E. Alpizar-Reyes, H. Carrillo-Navas, R. Gallardo-Rivera, V. Varela-Guerrero, J. Alvarez-Ramirez, C. Pérez-Alonso, Functional properties and physicochemical characteristics of tamarind (*Tamarindus indica* L.) seed mucilage powder as a novel hydrocolloid, J. Food Eng. 209 (2017) 68–75.

[42] K.-Y. Lin, J.R. Daniel, R.L. Whistler, Structure of chia seed polysaccharide exudate, Carbohydr. Polym. 23 (1994) 13–18.

[43] S.M.A. Razavi, S.W. Cui, H. Ding, Structural and physicochemical characteristics of a novel water-soluble gum from *Lallemantia royleana* seed, Int. J. Biol. Macromol. 83 (2016) 142–151.

[44] M.A. Rao, J.A. Lopes da Silva, Rheological Behavior of Food Gels, in Rheology of Fluid and Semisolid Foods, Principles and Applications, Springer, 2007, pp. 367–369.

[45] O.K. Achi, N.I. Okolo, The chemical composition and some physical properties of a water-soluble gum from *Prosopis africana* seeds, Int. J. Food Sci. Technol. 39 (2004) 431–436.

[46] S.M.A. Razavi, H. Taheri, L.A. Quinchia, Steady shear flow properties of wild sage (*Salvia macrosiphon*) seed gum as a function of concentration and temperature, Food Hydrocoll. 25 (2011) 451–458.

[47] B. Alizadeh Behbahani, F. Tabatabaei Yazdi, F. Shahidi, M.A. Hesarinejad, S.A. Mortazavi, M. Mohebbi, Plantago major seed mucilage: optimization of extraction and some physicochemical and rheological aspects, Carbohydr. Polym. 155 (2017) 68–77.

[48] F. Behrouzian, S.M.A. Razavi, H. Karazhiyan, The effect of pH, salts and sugars on the rheological properties of cress seed (*Lepidium sativum*) gum, Int. J. Food Sci. Technol. 48 (2013) 2506–2513.

[49] M. Maskan, F. Göğüş, Effect of sugar on the rheological properties of sunflower oil water emulsions, J. Food Eng. 43 (2000) 173–177.

[50] A.R. Yousefi, R. Eivazlou, S.M.A. Razavi, Steady shear flow behavior of sage seed gum affected by various salts and sugars: time-independent properties, Int. J. Biol. Macromol. 91 (2016) 1018–1024.

[51] K. Al-Malah, Effect of glucose concentration on the rheological properties of wheat-starch dispersions, Food Hydrocoll. 14 (2000) 491–496.

[52] A.R. Taherian, P. Fustier, H.S. Ramaswamy, Effects of added weighting agent and xanthan gum on stability and rheological properties of beverage cloud emulsions formulated using modified starch, J. Food Process Eng. 30 (2007) 204–224.

[53] N.L. Dawkins, I.A. Nnanna, Studies on oat gum [$(1 \rightarrow 3, 1 \rightarrow 4)$-β-D-glucan]: composition, molecular weight estimation and rheological properties, Food Hydrocoll. 9 (1995) 1–7.

[54] F. Salehi, M. Kashaninejad, V. Behshad, Effect of sugars and salts on rheological properties of Balangu seed (*Lallemantia royleana*) gum, Int. J. Biol. Macromol. 67 (2014) 16–21.