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Studies on the steady shear flow behavior and functional properties of *Lepidium perfoliatum* seed gum

Arash Koocheki [a,]*, Ali Reza Taherian [b], Aram Bostan [a]

[a] Department of Food Science and Technology, Ferdowsi University of Mashhad (FUM), PO Box: 91775-1163, Mashhad, Iran
[b] Food Research and Development Centre, Agriculture & Agri-Food Canada, 3600 Casavant West, St-Hyacinthe, Quebec, Canada, J2S-8E3

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Flow properties of *Lepidium perfoliatum* gum, extracted from Qodume shahri seeds, as influences of concentrations (0.5%, 1%, 1.5% and 2%), temperatures (5, 25, 45, and 65 °C), salts and pHs were investigated. Among the selected models, power law model well described the rheological behavior of the *L. perfoliatum* seed mucilage solutions with high determination coefficients, R^2 and low root mean square error (RMSE). Non-Newtonian shear thinning behavior was observed at all temperatures and concentrations. While increase in temperature decreased the viscosity and increased the flow behavior indices, adverse effect was obtained by increasing the concentration. The temperature effect was more pronounced at 0.5% *L. perfoliatum* seed gum concentration and indicated the higher activation energy (E_a: 31614.56 J/mol). The viscosity was dependent on type of salt addition, and decreased with salt concentration. This behavior was more evident when using divalent salt. A marked dependence of viscosity on pH was also observed, as pH increased from acidic to alkaline conditions, the viscosity increased until pH of 9 and afterward decreased. The hydrocolloid showed good water absorption capacity (WAC) and imparted relatively high stability to foam and oil-in-water emulsion. However, the gum solubility was low at all temperatures studied (30, 60 and 90 °C).

1. Introduction

There are a variety of hydrocolloids on the market, including plants or seaweed derived and those produced by microorganisms. Plant hydrocolloids, which naturally occur in plants seed, can be used to diverse physical, mechanical and sensorial functions of food. These gums have been exploited as thickeners, stabilizers, gelling agents and emulsifiers in food systems (Anderson & Andon, 1998; Koocheki, Ghandi, Razavi, Mortazavi, & Vasiljevic, 2009; Koocheki & Kadkhodaee, 2011; Koocheki, Kadkhodaee, Mortazavi, Shahidi, & Taherian, 2009). Their caloric value is quite low, making them useful particularly in the development of diet foods. Generally, hydrocolloids do not have direct influence on the taste and flavor of foodstuffs (Cancela, Alvarez, & Maceiras, 2005).

Recently, the demand for new source of hydrocolloid gums and interest in the functional properties of seed gums from local sources have been increased (Koocheki, Mortazavi, Shahidi, Razavi, Kadkhodaee, & Milani, 2010; Williams & Phillips, 2000) owing to the advantages of being naturally derived ingredients (Lai, Tung, & Lin, 2000). Many plants have been analyzed for their potential as sources of seed gums such as locust been and guar (Glicksman, 1982), Flaxseed (Cui, Mazza, Oomah, & Billiaderis, 1994) and white mustard (Balke & Diosady, 2000).

The volume share of the ingredients depends on the security of their supply, quality and price. *Lepidium*, of the Cruciferae family, is a genus of 230 species and is distributed throughout the world. *Lepidium perfoliatum* is native to Egypt, Arabia, Iraq, Iran and Pakistan and locally called Qodume shahri. In traditional medicine, Qodume shahri seeds are soaked in water and the mucilage extracted are widely employed for the treatment of dry coughs, whooping cough, lung infections and demulcent (Amin, 2005). There is no published information about the rheological and functional properties of this gum. Therefore, the main aims of the present work were to 1) determine the flow behavior of *L. perfoliatum* seed gum solutions and define it with suitable rheological model; 2) find out the changes of flow properties while changing the concentration, temperature and environmental stresses (pH and salts); and 3) evaluate solubility, water absorption capacity (WAC), emulsion and foam stabilizing effect of *L. perfoliatum* seed gum.

2. Materials and methods

2.1. Materials

The Qodume shahri (*L. perfoliatum*) seed was obtained from the local medical plant market, Mashhad, Iran. The seeds were manually cleaned to remove all foreign matter such as dust, dirt, stones, chaff, immature and broken seeds. Three different commercial hydrocolloids used in this study were guar, xanthan and locust bean gums

* Corresponding author. Tel.: +98 915 313 9459; fax: +98 511 8787430.
E-mail address: koocheki@um.ac.ir (A. Koocheki).

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(Food grade gum, Sigma-Aldrich Co., St. Louis Mo., USA). All other chemicals used in this study were of analytical grade and purchased from Merck (Darmstadt, Germany) company.

2.2. Gum extraction

Qodume shahri seed gum was prepared according to the method of our previous work (Koocheki, Taherian, Razavi, & Bostan, 2009). In brief, Qodume shahri seed gum was dispersed in preheated deionized water (Milli-Q, Millipore, Bedford, USA) at a water/seed ratio of 30:1. The pH was monitored continuously and adjusted at 8 using 0.1 mol/L NaOH and/or HCl at a constant temperature of 48 ± 1.0 °C. The seed-water slurry was stirred continuously with a mechanical mixing paddle throughout the entire extraction period (1.5 h). The seeds were discarded, and ultimately, the slurry was dried in a conventional oven (45 °C), milled and sieved using a mesh 18 sifter.

2.3. Chemical analysis

Ash, moisture and total fat contents in *L. perfoliatum* seed gum were determined according to AOAC methods (2005). Crude protein content was measured using Kjeldahl method and considering 6.25 as the conversion rate of nitrogen to crude protein (Kjeldahl, 1883). Total carbohydrate content was measured based on the method described by Karazhiyan, Razavi and Philips (2011).

2.4. Rheological measurement

Rheological measurements were carried out using a rotational viscometer (Bohlin Model Visco 88, Bohlin Instruments, UK) equipped with C25 or C30 measuring bob and cup (based on viscosity of dispersion) and a heating circulator (Julabo, Model F12-MC, Julabo Labortechnik, Germany). Different concentrations of *L. perfoliatum* seed gum were prepared by hydrating dried hydrocolloid powder in deionized water while stirring for 2 h using a magnetic stirrer. The dispersions were then left overnight at 4 °C to ensure a complete hydration.

For each test, approximately 15–25 ml of hydrated sample was loaded into the cup and allowed to equilibrate for 10 min at desired temperature (5, 25, 45 and 65 °C) and were subjected to a programmed shear rate increasing from 0 to 300 s^{-1} in 3 min followed by a logarithmically decreasing from 300 to 0 s^{-1} in 3 min.

2.5. Rheological models

Numerous factors influence the selection of a rheological model to describe the flow behavior of a particular fluid. Many models have been used to represent the flow behavior of non-Newtonian fluids (Steffe, 1996). Some of the most widely used rheological models are the Power Law (Eq. (1)), with two parameters (consistency coefficient and flow behavior index); Casson (Eq. (2)), with two parameters (consistency coefficient and yield stress); the Heinz-Casson (Eq. (3)), Herschel-Bulkley (Eq. (4)), Vocadlo (Eq. (5)) and Mizrahi-Berk (Eq. (6)) models, with three parameters (consistency coefficient, flow behavior index and yield stress); and Generalized Herschel-Bulkley (Eq. (7)), with four parameters (Germain, Dufresne, & Ramaswamy, 2006; Holdsworth, 1993; Steele, van Lieshout, & Goff, 2003). In this work, the experimental data were fitted according to these models:

$$\text{Power-law}: \tau = k\gamma^n \quad (1)$$

$$\text{Casson}: \tau^{1/2} = \tau_0^{1/2} + k\gamma^{1/2} \quad (2)$$

$$\text{Heinz-Casson}: \tau^n = \tau_0 + k\gamma^n \quad (3)$$

$$\text{Herschel-Bulkley}: \tau = \tau_0 + k\gamma^n \quad (4)$$

$$\text{Vocadlo}: \tau^{1/n} = \tau_0^{1/n} + k\gamma \quad (5)$$

$$\text{Mizrahi-Berk}: \tau^{1/2} = \tau_0^{1/2} + k\gamma^n \quad (6)$$

$$\text{Generalized Herschel-Bulkley}: \tau^n = \tau_0^n + k\gamma^m \quad (7)$$

where, τ is shear stress, (Pa), γ is shear rate (s^{-1}), k is consistency coefficient (Pa s^n), n is flow behavior index (dimensionless), τ_0 is yield stress (Pa) and m is a form of flow behavior index.

The suitability of these models was investigated with a view to choose the most suitable model for prediction of flow behavior of *L. perfoliatum* seed gum. The choice of the most appropriate model was based on the statistical parameters of the determination coefficient (R^2) and root mean square error (Eq. (8)). With this regard, the model that showed the best fit to the data, derived from the highest values for the determination coefficient (R^2) and lowest values for root mean square error (RMSE), was considered.

$$\text{RMSE} = \sqrt{\frac{\sum_{n=1}^{N}\left(W_{experimental} - W_{calculated}\right)^2}{N}} \times 100 \quad (8)$$

where N is the number of data points and W indicates shear stress.

2.6. Effect of temperature and concentration on gum solutions

For flow measurement, gum solutions were prepared at concentrations of 0.5%, 1%, 1.5% and 2% (w/w) by dispersing the required amount of gum in deionized water (Milli-Q, Millipore, Bedford, USA), under slow stirring at room temperature, and stored for 18 h at 4 °C for complete hydration prior to assessment. Further, the effect of concentration on consistency index could be represented by a power equation (Eq. (9)):

$$k = aC^b \quad (9)$$

where a and b are constants, C is concentration.

Temperature effects were evaluated at four levels (5, 25, 45 and 65 °C). The temperature dependency of consistency coefficient (indicator of the viscous nature of the sample) was assessed by fitting the Arrhenius model (Eq. (10)) as was suggested by Sengul et al. (2005):

$$k = k_0 \cdot \exp(E_a / RT) \quad (10)$$

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

The effect of temperature on the consistency coefficient (k) and flow behavior index (n) was also evaluated using a modified Turial approach (Turian, 1964) through a regression analysis (Eqs. (11) and (12)):

$$\log k = \log k_0 - A_1 T \quad (11)$$

$$n = n_0 + A_2 T \quad (12)$$

where A_1 and A_2 are the slopes for Turian models. Higher A_1 and A_2 represent more dependency of n and k to the temperature.

2.7. Effect of salts on gum solutions

Concentrations of 0.2–1% of monovalents (NaCl and KCl) and divalents ($CaCl_2$ and $MgCl_2$) salts were added to 1% hydrated gum