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Steady shear flow behavior of gum extracted from *Ocimum basilicum* L. seed: Effect of concentration and temperature

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ABSTRACT

Steady shear flow behavior of basil seed gum (BSG) was investigated between 0.5% and 2% (wt/wt) concentration and temperatures of 5–85 °C. BSG showed shear thinning behavior at all concentrations and temperatures. The Herschel–Bulkley model was employed to characterize flow behavior of BSG solutions at 0.1–1000 s^{-1} shear rate. The pseudoplasticity of BSG increased markedly with concentration. Flow behavior of 1% BSG indicated a higher viscosity of this gum at low shear rates compared to xanthan, konjac and guar gum at similar concentration. The activation energy of BSG quantified using an Arrhenius equation increased from 4.9×10^3 to 8.0×10^3 J mol^{-1} as concentration changed from 0.5% to 2% wt/wt. This indicated a heat-resistant nature of BSG. Increasing the apparent viscosity of BSG as temperature increase from 60 °C showed a sol–gel behavior of BSG based on dynamic oscillatory measurements. The static yield stress was obvious between shear rates 0.001–0.1 s^{-1} (9.98 Pa for 1% BSG at 20 °C). The existence of the yield stress, high viscosity at low shear rates and pseudoplastic behavior of BSG make it a good stabilizer in some food formulations such as mayonnaise and salad dressing.

1. Introduction

Ocimum basilicum L. also known as basil (or "*Reyhan*" in Iran) is a common herb plant grown in Iran. It is a culinary herb consumed in high quantity due to the characteristic flavors it imparts (Naghibi et al., 2005). This plant is found in many parts of the world especially in the tropical regions of Asia, Africa and Central and South America (Simon et al., 1999; Paton et al., 1999). Basil seeds have been used in traditional medicine for a long time to treat colic ulcer, dyspepsia, diarrhoea and inflammations, among others ailments. In Iran and in many parts of Asia, basil seeds are frequently included in beverages (*Sharbat*) and ice desserts (*Faloodeh*) for aesthetic purposes as well as a source of dietary fibre. Basil seed is black in color and oval in shape with mean dimensions of 3.11 ± 0.29 mm (length), 1.82 ± 0.26 mm (width) and 1.34 ± 0.19 mm (height) (Hosseini-Parvar, 2007).

When the seed of *O. basilicum* L. is soaked in water, the outer pericarp swells into a gelatinous mass (Azoma and Sakamoto, 2003) due to the presence of a polysaccharide layer. In several earlier studies (Anjaneyalu and Tharanathan, 1972; Tharanathan and Anjaneyalu, 1974; Tharanathan and Anjaneyalu, 1975; Anjaneyalu and Channe Gowda, 1979) the polysaccharides extracted from *O. basilicum* L. seed (basil seed) have been reported to comprise of two major fractions of glucomannan (43%) and (1 → 4)-linked xylan (24.29%) and a minor fraction of glucan (2.31%). Azoma and Sakamoto (2003) also reported the presence of highly branched arabinogalactan in addition to glucomannan and (1 → 4)-linked xylan.

In our recent publication, we reported the optimized conditions for gum extraction from basil seeds in terms of temperature, pH and water/seed ratio (Razavi et al., 2009). The yield of gum extracted from basil seeds was about 20% wt/wt (wet basis). The gum is non-gelling and has shear-thinning properties. Since basil seeds are available in abundance, there is a great potential to utilize the gum of basil seeds as a functional ingredient in the food industry due to its potential uses as a thickening and stabilizing ingredient. Polysaccharides are usually used as gelling, thickening and stabilizing agents to improve stability and textural properties of many food products such as jellies, salad dressings and desserts. The rheological properties of hydrocolloids in solution depend on factors such as: shear rate, the duration of shear rate as well as the previous shear history, concentration, temperature, pH, ionic strength, electrical charge, and previous thermal and mechanical treatment (Rao, 1986; Rao and Anantheswaran, 1982; Rao and Kenny, 1975).

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Many researchers have studied the rheological properties of common seed gums such as guar gum and locust bean gum (Morris et al., 1981; Doublier and Launay, 1981). There are a few reports about rheological properties of new sources of seed gums such as yellow mustard seed (Cui et al., 1993), flaxseed (Cui et al., 1994), white mustard seed (Balke and Diosady, 2000), fenugreek seed (Brummer et al., 2003), *Prosopis flexuosa* DC seed (Ibanez and Ferrero, 2003), *Ipomoea turpethum* seed (Singh et al., 2003), *Lallemania royleana* seed (Razavi and Karazhiyan, 2009) and *Mucuna flagellipes* seed (Nwokocha and Williams, 2009). However, there is no published report related to rheological properties of BSG. In addition, no study to date has reported on the physico-chemical characteristics of this gum. Understanding the rheological and molecular characteristics of BSG is essential to allow food product developers to exploit the functionality of this gum in different food systems.

The purpose of this study was to characterize steady shear flow properties of BSG solution as well as to study the effect of concentration and temperature on rheological behavior of BSG solution. The rheological behavior of BSG was also compared with xanthan, konjac and guar gum.

2. Materials and methods

2.1. Materials

Basil seeds used in this study were purchased from the local market at Isfahan in Iran. Chemicals of analytical grade were purchased from Merck Company (Merck KgaA, Darmstadt, Germany). Xanthan and guar gum were purchased from Sigma (Sigma Aldrich Co., St. Louis, MO, USA) and konjac gum from FMC biopolymer (Nutricol® GP 6220, Philadelphia, PA, USA).

2.2. Gum extraction from basil seeds

The extraction of gum from basil seeds was performed using a modified method based on our previous study (Razavi et al., 2009; Hosseini-Parvar, 2009). The basil seeds were soaked and swelled in distilled water at 68 ± 1 °C and a water/seed ratio of 65:1. The distilled water was adjusted to pH 8 using 0.01 mol/L NaOH solutions. The mixture was stirred with a rod paddle mixer until the seeds were completely swelled (20 min agitation, 1000 rpm). The swelled seeds were passed through an extractor with a rotating rough plate to scrape the gum layer off the seed surface (Pars Khazar 700P, Rasht, Iran).

The separated BSG was passed through a 20 μm filter (AMIAD Australia Pty Ltd., Victoria, Australia) and then centrifuged at 12,800 g for 30 min at 20 °C (Himac CR22GII, Hitachi Koki Co. Ltd., Takeda, Hitachinaka city, Japan) to remove all likely seed residuals. BSG was finally freeze-dried and stored in tightly containers under dry and cool conditions.

2.3. Chemical analysis

Ash, moisture, total fats and protein (derived from nitrogen) content in BSG were determined based on AOAC 942.05, AOAC 930.15 and 925.10, AOAC 991.36, AOAC 968.06, respectively. Total carbohydrate and soluble sugar content were measured using the phenol sulfuric acid method (Dubois et al., 1956). Starch content was determined by α-amylase method (AOAC 996.11). All chemical analysis was made in triplicate.

2.4. Sample preparation

Different concentrations of BSG were prepared with Milli-Q water containing 0.01 M sodium chloride to eliminate any ionic strength effect on the rheological measurements as BSG concentration was varied. BSG solutions were prepared by hydrating freeze-dried BSG in Milli-Q water, and mixing with a high speed rod mixer (IKA LABORTECHNIK, IKA works, Malaysia) overnight at 20 °C. All rheological measurements were performed the following day in duplicates, and the samples were replicated twice. Sodium azide (0.02% wt/wt) was added as preservative. The solutions containing 1% of xanthan, konjac and guar gum were prepared like BSG solutions.

Heat stability of BSG solutions was evaluated by measuring apparent viscosity of 1% BSG after heat treatment of the samples in a capped glass container at 40, 60, 85 and 100 °C for 30 min as well as at 121 °C for 16 min (sterilization treatment). Furthermore, the effect of freezing on the rheological properties of 1% BSG was also evaluated by storing BSG samples at −18 °C for 24 h in Eppendorf micro test tubes (Eppendorf AG, Germany). The frozen samples were thawed over approximately 2 h at room temperature.

2.5. Rheological measurements

The steady shear rheological measurements were conducted using a controlled-stress rheometer (Physica MCR 301, Anton Paar GmbH, Stuttgart, Germany) equipped with a cone and plate geometry (CP40–4, 39.958 mm in diameter, angle 4° and gap size of 49 μm). The samples were loaded onto the lower plate of the rheometer equilibrated at 20 °C and a thin layer of low-density silicone oil was used around the plate to prevent evaporation. All samples were allowed to equilibrate at the measuring temperature for 10 min before the start of the test. Data were recorded with the Rheoplus software, version 2.65 (Anton Paar Germany GmbH). Linear steady shear stress sweeps were obtained over a range of shear rates (10^{-1}–10^{3} s^{-1}) at 20 ± 0.1 °C. A temperature sweep test (5–85 °C) was performed also on 1% BSG using oscillatory dynamic mode of rheometer at 0.5% strain and frequency of 1 Hz. Rheological measurements were made in triplicate and the average reported. The data were plotted in the logarithmic scale based on viscosity as a function of shear rate. Rheological behavior of BSG was compared with xanthan, konjac and guar gum.

2.6. Data analysis

The shear rate dependency of steady shear rheological properties of BSG solutions may be described by different flow models such as Power law, Herschel–Bulkley, Casson, Heinz-Casson and Mizrahi-Berk models (Rao and Kenny, 1975; Marcotte et al., 2001; Song et al., 2006). As the Herschel-Bulkely model gave the best fit with BSG solutions (data not shown) it was used to describe their flow behavior:

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{1}$$

where, τ is shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), K is the consistency coefficient (Pa.s^n), n is the flow behavior index (dimensionless) and τ_0 is the yield stress.

The effect of temperature on viscosity of BSG solutions was studied by an Arrhenius-type equation (Rao and Kenny, 1975; Rao and Anantheswaran, 1982; Speers and Tung, 1986):

$$\eta = \eta_0 \exp(E_a/RT) \tag{2}$$

where η_0 is a constant (apparent viscosity at reference temperature, Pa.s), E_a is the activation energy (J mol^{-1}), T is the absolute temperature (K) and R is the universal gas constant (J mol^{-1} K^{-1}).

The following power, exponential and polynomial models (Rao, 1986; Speers and Tung, 1986; Marcotte et al., 2001) were used to study the effect of concentration on the apparent viscosity of BSG solutions at each temperature:

$$\eta = a_1 C^{b_1} \quad (3)$$

$$\eta = a_2 \exp(b_2 C) \quad (4)$$

$$\eta = 1 + a_3 C + b_3 C^2 \quad (5)$$

where C is the concentration of BSG solution in percentage, $a_1, a_2, a_3, b_1, b_2,$ and b_3 are constants.

The determination coefficient (R^2) and mean relative deviation (MRD) values were measured to compare fitting quality of the models. The MRD values were measured as:

$$MRD\,(\%) = \left(\sqrt{\sum((\tau_{cal} - \tau_{\exp t})/\tau_{cal})^2/N}\right) \times 100 \quad (6)$$

where τ_{cal} is the calculated value based on the fitting mode, $\tau_{\exp t}$ is the experimental value and N the total number of data points. Mean comparisons were performed by Tukey's test using Minitab 15.1.0 software (Minitab Inc., State College, PA, USA).

3. Results and discussion

3.1. Chemical composition of BSG

Table 1 shows the chemical composition of BSG based on dry matter. This analysis showed that modifying the method of separation of BSG compared to the previous study (Razavi et al., 2009) significantly increased the total carbohydrate (from 74.19% to 79.63%) and ash content (from 5.89% to 6.53%) whereas decreased the amount of fat (from 11.55% to 4.38%) and protein (from 2.01% to 1.32%). The very low starch and soluble sugar content of BSG showed its high polysaccharide concentration. In this study, the rheological behavior of the isolated native gum was characterized.

Table 1
Chemical composition of BSG.

Composition (% w/w)	
Moisture	9.1 ± 0.17
Protein[a]	1.32 ± 0.09
Fat content[a]	4.38 ± 0.14
Total carbohydrate[a]	79.63 ± 0.73
Soluble sugars[a]	0.55 ± 0.07
Starch[a]	1.53 ± 0.15
Ash[a]	6.53 ± 0.21

[a] Based on dry material.

3.2. Effect of BSG Concentration on steady shear flow behavior

Shear rate dependency of the apparent viscosity of BSG solutions at different concentrations is shown in Fig. 1. Solutions of BSG exhibited interesting pseudoplastic behavior with the viscosity decreasing rapidly with increasing shear rate (from 0.001–1.00 s^{-1}) but less rapidly at higher shear rate range (1.0–1000 s^{-1}) across all concentrations. No Newtonian region was detected at low shear rates suggesting that the zero-shear viscosity could exist at very low shear rates. In general, polysaccharide molecules with stiff conformation contribute to high zero-shear rate viscosity and possess strong shear-thinning properties. This is because stiff polymer molecules are quickly aligned in the direction of flow as shear rate increases and therefore physical interactions between adjacent polymer chains decrease. A high shear thinning behavior of polysaccharides allows liquid foods to be pumped easily and imparts a thinner consistency during swallowing (Vardhanabhuti and Ikeda, 2006). Early studies have correlated a higher degree of shear thinning with a lower degree of sliminess in the mouth produced by hydrocolloids (Szczesniak and Farkas, 1962). Consequently, the mouthfeel characteristics provided by BSG may be even better than CMC, pectin, carrageenan or monoi hydrocolloid based on the higher shear-thinning properties (Marcotte et al., 2001; Vardhanabhuti and Ikeda, 2006; Riazi and Farhoosh, 2006; Feng et al., 2007).

In order to fit the data using rheological models, Dervisoglu and Kokini (1986) suggested using two different models: one at low and another one at high shear rates. Moreover, the range of shear rate being considered in the modeling can result in different values of the rheological parameters (e.g. different n and K values). Morris (1989) stated that although the pseudoplastic behavior of many polysaccharides can be fitted by the Power Law equation and provides a reasonably linear fit on a log–log plot over several decades of shear rates, it is inadequate if a broad range of shear rates is to be explored.

For galactomannans and other random coils non-gelling polysaccharides, two Newtonian plateaus can be obtained at very low shear rates and at very high shear rates, referred to as zero-shear rate viscosity and infinite viscosity, respectively (Morris et al., 1981). For these kinds of polysaccharides, the flow curve data can be described using models like Cross (Cross, 1965; Doublier and Launay, 1981; Morris, 1989) and Carreau (Carreau, 1972). This Newtonian plateau at low shear rates (>0.01 s^{-1}) was observed for konjac and guar gum but not for BSG and xanthan gum (Fig. 2). This could suggest that BSG had a high zero-shear viscosity which could

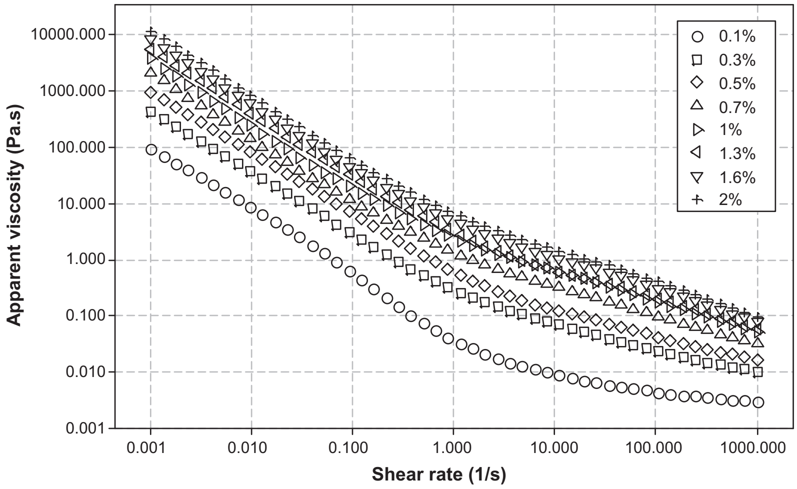

Fig. 1. Shear thinning properties of different concentrations (0.1–2%) of BSG solution.

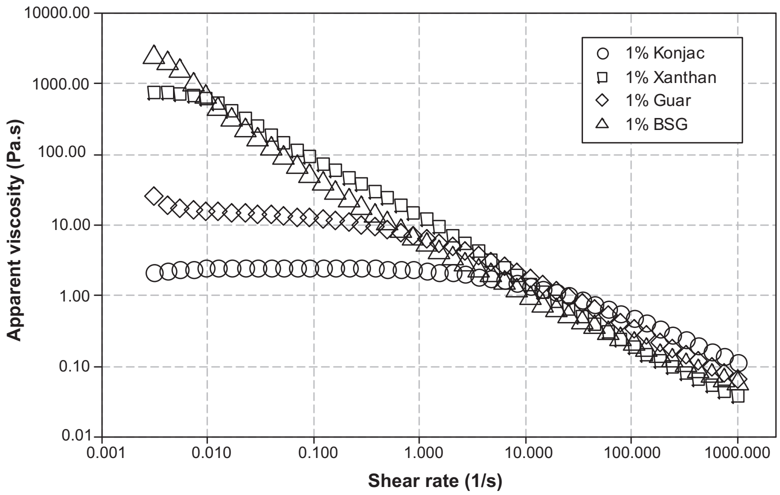

Fig. 2. High zero-shear viscosity of 1% BSG solution compare to 1% of xanthan, konjac and guar gum.

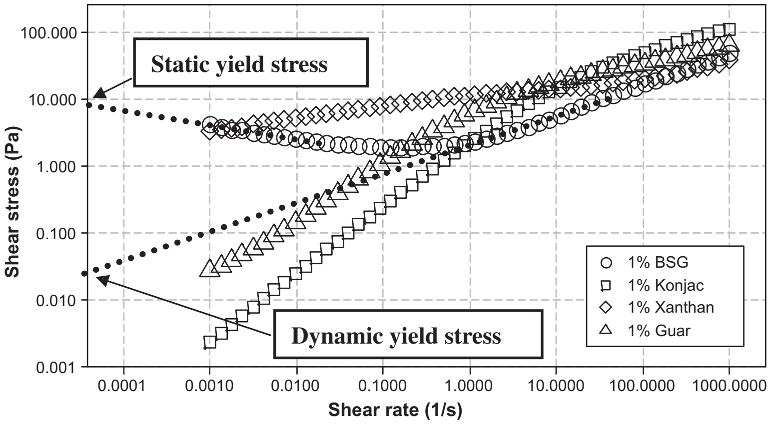

Fig. 3. Illustration of yield stress in 1% BSG solution compare to 1% of xanthan, konjac and guar gum.

not be detected by the rheometer used in this study. The zero-shear viscosity for BSG could be even higher than xanthan gum since BSG has a steeper slope at the low shear rate range (Fig. 2). Both Carreau and Cross models did not show good fitting results for the BSG flow behavior data (data not shown). From Fig. 2, the rheological behavior of BSG is quite different from konjac glucomannan, although the major fraction (43%) of BSG extract is composed of glucomannans (Anjaneyalu and Tharanathan, 1972; Azoma and Sakamoto, 2003).

For polysaccharides that exhibit yield stress such as xanthan gum (Marcotte et al., 2001; Song et al., 2006), models that include yield stress terms are more adequate. From the flow curves, both xanthan gum and BSG samples showed the presence of yield stress (Fig. 3). Observing the shape of the flow curve in the case of BSG, shear stress values diminished from very low shear rates 10^{-3}–$10^{-1}\ s^{-1}$ (Fig. 3). This phenomenon can be interpreted as the result of the existence of a static and a dynamic yield stress, as suggested previously by Cheng (1986). This author defined these two types of stresses and related them to two types of structures in a thixotropic fluid. A first structure which is responsible for the dynamic yield stress and is sensitive to shear rate associated with the equilibrium flow curve. The second structure is weak and forms over a certain period of time when the sample is at rest. The resistance to flow from the two combined structures gives rise to the static yield stress (Steffe, 1996). This may reflect the complex nature of BSG composed of more than two different polysaccharide fractions.

Among the rheological models, the Herschel–Bulkley equation gave the best fit for the flow behavior of BSG in the shear rate range of 0.1–1000 s^{-1}.

Rheological parameters obtained using Herschel–Bulkley model from various BSG concentrations (0.5–2%) at temperatures between 5 °C and 85 °C are presented in Table 2. Fitting was done for both flow curves obtained by increasing (upwards) and decreasing (downwards) the shear rate.

The values of the static yield stress obtained by extrapolation in Fig. 3 for the solutions of 0.5%, 1%, 1.5% and 2% BSG at 20 °C were 2.36, 9.98, 18.1 and 35.3 Pa, respectively. These values were significantly higher than the magnitudes of the dynamic yield stress determined by fitting the data using the Herschel–Bulkley model (Table 2). The presence of yield stress implies that BSG has high suspension ability which is a useful property when used as a stabilizer in food products such as mayonnaise and salad dressings. This is the reason for xanthan which exhibits yield stress (Marcotte et al., 2001; Song et al., 2006), to be commonly used in colloidal systems, where the long-term stability is markedly increased with its addition (Hibberd et al., 1987). From a process design point of view, the magnitude of yield stress is related to the amount of material retained on the walls of containers and transportation

Table 2
Effect of concentration and temperature on rheological parameters of BSG solutions based on Herschel–Bulkley model.

Sample/temperature (°C)	τ_0 (Pa)	Upward curve			Downward curve		
		n (−)	K (Pa.s^n)	R^2	n (−)	K (Pa.s^n)	R^2
0.5% BSG							
5	0.808 ± 0.150	0.494 ± 0.003	1.033 ± 0.044	0.974	0.566 ± 0.003	0.704 ± 0.002	0.996
20	0.929 ± 0.228	0.547 ± 0.038	0.547 ± 0.181	0.992	0.552 ± 0.018	0.541 ± 0.160	0.996
40	0.754 ± 0.021	0.509 ± 0.028	0.580 ± 0.118	0.987	0.576 ± 0.003	0.393 ± 0.022	0.998
60	0.697 ± 0.105	0.514 ± 0.041	0.491 ± 0.166	0.986	0.595 ± 0.018	0.290 ± 0.058	0.999
85	0.995 ± 0.174	0.544 ± 0.017	0.378 ± 0.046	0.986	0.625 ± 0.015	0.220 ± 0.029	0.998
1% BSG							
5	1.590 ± 0.021	0.351 ± 0.012	6.077 ± 0.067	0.978	0.431 ± 0.004	3.911 ± 0.300	0.996
20	3.469 ± 0.883	0.392 ± 0.080	3.883 ± 1.707	0.981	0.445 ± 0.007	2.975 ± 0.277	0.998
40	1.391 ± 0.057	0.341 ± 0.002	4.342 ± 0.115	0.977	0.472 ± 0.002	2.006 ± 0.054	0.996
60	1.170 ± 0.015	0.341 ± 0.008	3.833 ± 0.081	0.972	0.518 ± 0.01	1.254 ± 0.048	0.990
85	2.738 ± 0.139	0.475 ± 0.010	1.691 ± 0.036	0.951	0.559 ± 0.022	0.966 ± 0.132	0.992
1.5% BSG							
5	1.378 ± 0.345	0.295 ± 0.003	15.304 ± 0.143	0.983	0.388 ± 0.004	8.790 ± 0.212	0.997
20	4.160 ± 0.695	0.336 ± 0.058	12.302 ± 0.667	0.990	0.423 ± 0.011	5.689 ± 0.484	0.997
40	2.447 ± 1.558	0.29 ± 0.006	10.642 ± 0.403	0.978	0.449 ± 0.000	4.279 ± 0.165	0.993
60	2.667 ± 0.585	0.351 ± 0.031	6.239 ± 0.641	0.970	0.501 ± 0.003	2.459 ± 0.251	0.986
85	4.98 ± 0.317	0.413 ± 0.005	3.507 ± 0.271	0.941	0.518 ± 0.063	1.290 ± 0.086	0.974
2% BSG							
5	2.984 ± 0.785	0.276 ± 0.015	24.196 ± 2.988	0.990	0.349 ± 0.008	16.333 ± 0.962	0.998
20	11.943 ± 0.953	0.334 ± 0.024	15.982 ± 0.521	0.991	0.410 ± 0.004	10.076 ± 0.252	0.994
40	2.023 ± 1.065	0.303 ± 0.001	16.812 ± 0.679	0.992	0.418 ± 0.012	8.383 ± 1.134	0.991
60	2.365 ± 0.49	0.317 ± 0.018	13.786 ± 1.23	0.983	0.46573 ± 0.011	5.3975 ± 0.78	0.982
85	6.417 ± 1.329	0.391 ± 0.096	6.771 ± 1.606	0.948	0.501 ± 0.059	1.623 ± 0.601	0.981

Table 3
Concentration dependency of apparent viscosity (100 s^{-1}) at various temperatures using Eqs. (3)–(5).

Temperature (°C)	Power [$\eta = a_1 C^{b_1}$]			Exponential [$\eta = a_2 \exp(b_2 C)$]			Polynomial [$\eta = 1 + a_3 C + b_3 C^2$]		
	a_1 (Pa.s.%$^{-1}$)	b_1 (−)	MRD (%)	a_2 (Pa.s)	b_2 (%$^{-1}$)	MRD (%)	a_3 (%$^{-1}$)	b_3 (%$^{-1}$)	MRD (%)
5	0.2973	1.5845	0.20	0.0573	1.4452	8.47	−1.5945	0.7946	25.08
20	0.2352	1.6932	1.82	0.0404	1.546	9.28	−1.6708	0.8027	31.77
40	0.2034	1.7132	0.53	0.0341	1.5667	8.64	−1.6809	0.7835	36.13
60	0.1771	1.7157	2.77	0.029	1.5855	6.32	−1.7232	0.7898	47.15
85	0.2114	1.5149	5.52	0.0456	1.3504	13.40	−1.5682	0.6996	36.08

vessels which may sometimes be undesirable (Rao and Kenny, 1975).

The parameters of fitted models for apparent viscosity of different concentration of BSG at each temperature using upward data are summarized in Table 3. The Power model with the lowest MRD values was the best model to predict concentration dependency of apparent viscosity. A strong effect of gum concentration on the apparent viscosity of BSG solutions showed 240%, 513% and 980% increase in viscosity as the concentration increased from 0.5% to 1%, 1.5% and 2% wt/wt, respectively. Comparatively, increasing rate of apparent viscosity of BSG solutions was equal to xanthan gum based on Marcotte et al. (2001) study (79% increase in apparent viscosity as the concentration changed from

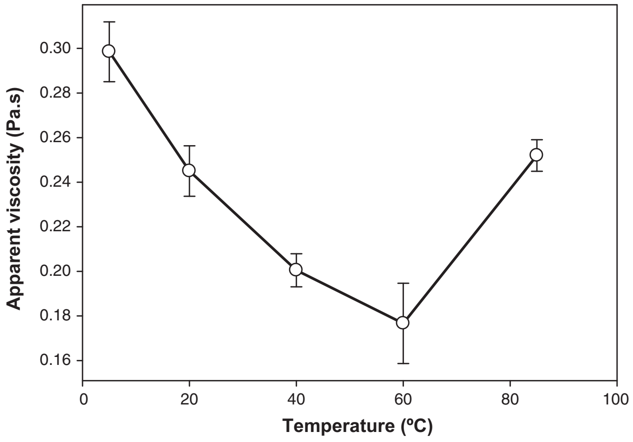

Fig. 4. Changing the apparent viscosity (at 100 s^{-1}) of 1% BSG solution at different temperatures.

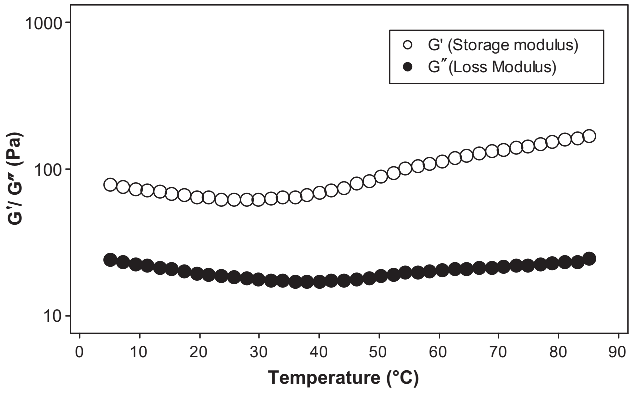

Fig. 5. Temperature sweep of 1% BSG solution at 0.5% strain and frequency of 1 Hz.

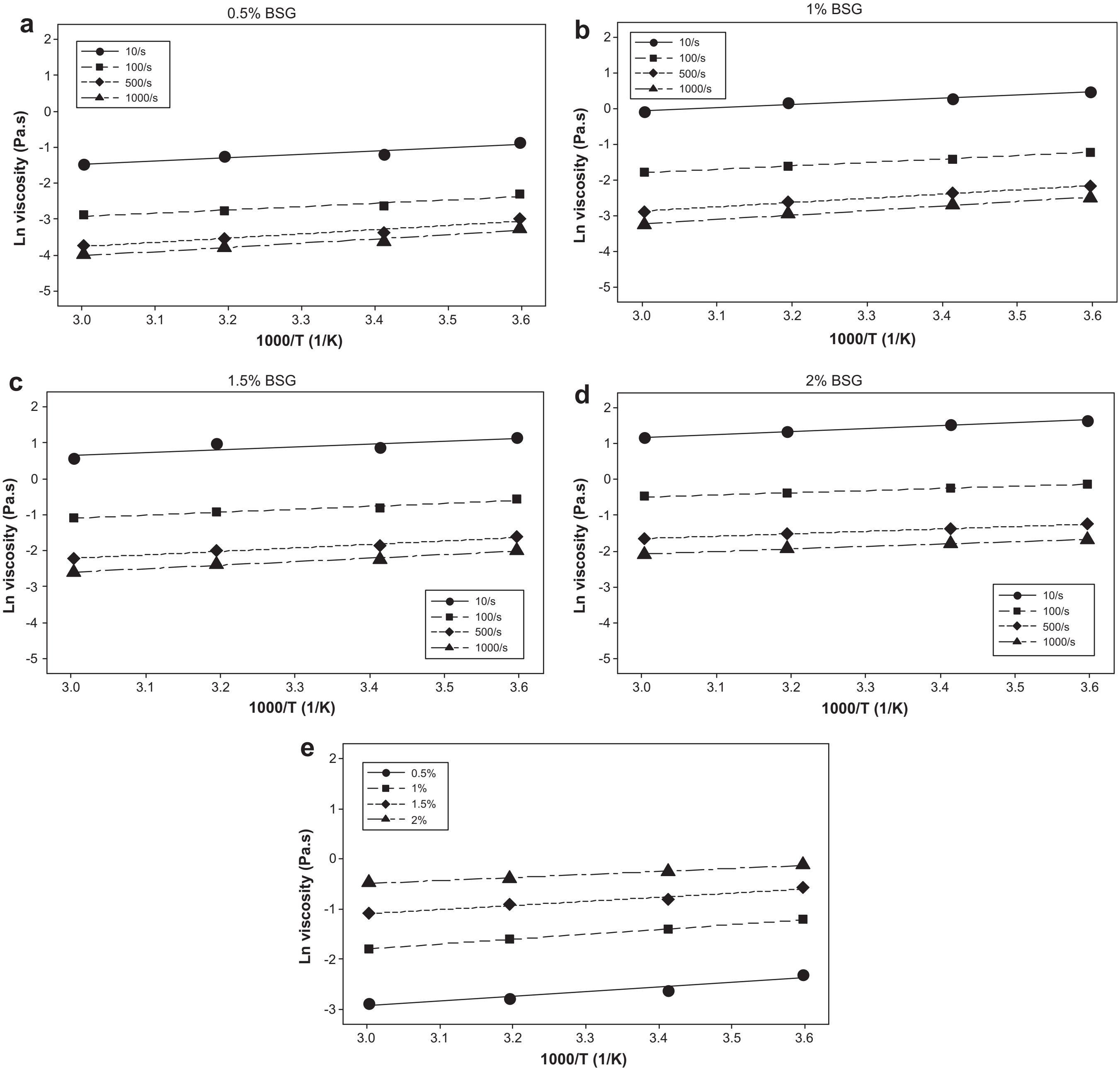

Fig. 6. Temperature dependency of BSG solutions viscosity at different concentrations and shear rates using Arrhenius equation (a–d). Temperature dependency of viscosity at different concentrations (e).

1.6% to 2% wt/wt); and lower than carrageenan (112% increase from 1.5% to 1.9% wt/wt concentration). However, apparent viscosity of 2% BSG solution was equal to carrageenan and higher than xanthan gum.

3.3. Effect of temperature on the rheological properties of BSG

In general, differences between flow behavior index (n) and consistency coefficient (K) values in both upward and downward curves (Table 2) showed a weak thixotropic behavior for BSG solutions especially at low shear rates ($p < 0.05$). The order of magnitudes ranged between 0.276 and 0.547 (n) and between 0.378 and 24.196 Pa.s^n (K) for the upward curve and between 0.349 and 0.595 (n) and between 0.22 and 16.333 Pa.s^n (K) for the downward curve, across different concentrations (0.5–2.0%) and temperatures (5–85 °C). For both curves, n decreased and K increased, with increasing BSG concentration at a fixed temperature. K values clearly decreased from 5 to 85 °C for both curves for each BSG concentration. However, n did not follow a clear trend in the upward

Table 4
Temperature dependency of apparent viscosity (at 100 s^{-1}, 20 °C) for different concentration of BSG solutions based on Arrhenius-type equation.

BSG concentration (%)	η_0 (Pa.s)	E_a (J mol^{-1})	R^2
0.5	3.40×10^{-3}	7636.05	0.925
1	9.14×10^{-3}	8036.80	0.999
1.5	2.84×10^{-2}	6835.36	0.960
2	1.01×10^{-1}	4995.36	0.990

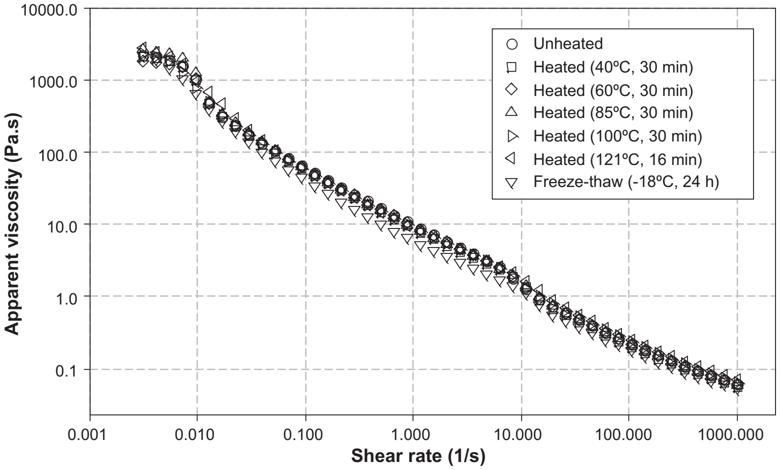

Fig. 7. Effect of heat treatment and freeze–thaw on apparent viscosity of BSG solution (1%, w/w, 20 °C).

curve but consistently increased with temperature in the downward curve.

An increase in the flow behavior index with temperature indicates that the gum becomes less pseudoplastic especially at low shear rates (Vardhanabhuti and Ikeda, 2006). Comparatively, BSG showed a smaller change in *n* values with increasing temperature than Monoi gum, guar gum (Vardhanabhuti and Ikeda, 2006) or carrageenan (Marcotte et al., 2001).

A dynamic yield stress was measured at all concentrations and temperatures (Table 2). Whereas an increase in yield stress with BSG concentration is clear, no trend was observed with temperature.

Fig. 4 shows the apparent viscosity of 1% BSG at different temperatures. The apparent viscosity of BSG was dramatically affected by temperature, so that a decrease was observed with increasing temperature from 0.3 Pa.s at 5 °C to 0.18 Pa.s at 60 °C. However, the viscosity increased to 0.25 Pa.s at 85 °C.

The temperature sweep of 1% BSG solution at 0.5% strain and frequency of 1 Hz is presented in Fig. 5. It is obvious that both storage (G′) and loss (G″) modulus gradually increased from 40 to 85 °C. Considering the effect of temperature on the apparent viscosity data and the frequency sweep data (Fig. 5), the results seemed to suggest the presence of hydrophobic interactions which get stronger with temperature. This could result in stronger interaction among BSG polysaccharides molecules (increase in viscosity at 85 °C).

The apparent viscosities of BSG solutions at temperatures of 5, 20, 40 and 60 °C followed an Arrhenius type model (Fig. 6). Parameters of Arrhenius model including frequency factors (η_0), activation energies (E_a) and coefficients of determination (R^2) at 100 s^{-1} shear rate are presented in Table 4. The magnitude of η_0 increased from 3.40×10^{-3} to 0.114 as BSG concentration increased from 0.5% to 2%. An increase in activation energy was also observed with increasing BSG concentration from 0.5% to 1%. However, increasing the concentration from 1% to 2% decreased the activation energy.

As shown in Fig. 6a–d, slope values of fitted lines were relatively low at all BSG concentrations at each shear rate which is related to low activation energy of BSG. Low values of activation energy imply that the BSG can maintain its viscosity at higher temperatures. Gums such as xanthan (activation energy of 1% xanthan reported 5740 J/mol by Marcotte et al., 2001) have been reported to be temperature stable by Marcotte et al. (2001), Sworn (2000) and Rocks (1971). However, a decrease in viscosity by 50% from 20 to 80 °C has been detected in galactomannans (Wielinga, 2000). Our BSG was very similar to xanthan gum.

Heat and freeze/thaw stability of BSG solutions were evaluated by measuring apparent viscosity of 1% BSG at 20 °C, after various treatments as described in Section 2.4. The apparent viscosities of 1% BSG before and after heat treatments as well as after a freeze/thaw cycle were nearly identical (Fig. 7). These results make BSG a very promising ingredient in food formulations that require good heat and freeze/thaw stability similar to xanthan and guar gum (Downey, 2002). However, further work is required to study the effect of subjecting BSG solution to several freeze–thaw cycles.

4. Conclusions

Basil seed (*O. basilicum* L.) provided reasonable yield of gum which exhibited interesting rheological properties. The presence of high yield stress in BSG solution was comparable to xanthan gum. The Herschel-Bulkely model was found the most suitable time independent rheological model to characterize flow behavior of BSG. The pseudoplacticity increased with increasing concentration of BSG. Comparison of flow behaviors of 1% BSG, xanthan, konjac and guar gum suggested that BSG had very high zero-shear rate viscosity. The values of activation energy for BSG and xanthan gum were in the same range. Low activation energy of BSG implies that BSG solution could maintain its viscosity at higher temperatures. Apparent viscosity measurements of BSG before and after heat treatment, and one freeze–thaw cycle indicated that BSG was tolerant to temperatures commonly applied in food manufacture. The presence of a high yield stress and high pseudoplastic behavior of BSG could qualify BSG as a good stabilizer in some food formulations such as mayonnaise and salad dressing.

At temperature above 60 °C, BSG gel network appeared to be strengthened. Further work is underway to understand the mechanisms behind the unique properties of BSG at high temperatures.

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