

Rheological properties of *Lepidium sativum* seed extract as a function of concentration, temperature and time

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ABSTRACT

The seeds of *Lepidium sativum* (Garden Cress) were selected as a new source of hydrocolloid and its chemical composition and molecular parameters were determined. The macromolecular component of the extract had a molecular weight of 540 kDa, and was nearly as rigid as xanthan with regard to chain conformation. The main rheological features were investigated as a function of shear rate, concentration and temperature. The extract exhibited strong shear-thinning behaviour, which was even more pronounced than for xanthan. An increase in concentration or temperature led to an increase in pseudoplasticity. The Arrhenius model was applied to the temperature dependence of viscosity, and the activation energy (E_a) was found to decrease with increasing concentration. The extract solutions showed thixotropic behaviour at all the concentrations and temperatures studied, and the first-order stress decay model with a non-zero equilibrium stress fairly described the time-dependent behaviour. The rheological characteristics found indicated a potential application of the extract as a novel thickener.

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1. Introduction

Hydrocolloids are broadly used in food systems for various purposes, for example as thickeners, gelling agents, texture modifiers, and stabilizers (Williams & Phillips, 2000). There has been an increase in the demand for hydrocolloids in the last decade. The volume share of hydrocolloids depends on the security of their supply, quality and price. Hydrocolloids from plants have the advantage over those from animals because of their friendly image to consumers. Starch and derivatives, pectin, galactomannans, carrageenans, alginates, agars, gum arabic and cellulose and its derivatives are the main plant hydrocolloids used in food systems. Studies on these hydrocolloids are currently concentrated on the structure–functionality relationships in order to maximize effectiveness and produce novel textures. Consequentially there are opportunities in the hydrocolloid market for new sources of plant hydrocolloids to meet the demand for ingredients with more specific functionalities.

A number of studies have been carried out to quantify the rheological characteristics of food hydrocolloids individually or in food formulations (Abdelrahim, Ramaswamy, & van de Voort, 1995;

Clasen & Kulicke, 2001; Da Silva, Pedro, Oliveira, & Rao, 1997; Da Silva & Rao, 1995; Dickie & Kokini, 1983; Krumel & Sarkar, 1975; Lapasin & Pricl, 1999; Ma & Barbosa-Canovas, 1996; Sanderson, 1981; Stanley, 1990; White, Davidson, & Otten, 1993; Williams & Phillips, 2000). The viscosity of solutions of hydrocolloids can be significantly affected by variables such as shear rate, concentration, temperature, ionic strength, pH etc.

Several models have been used to characterize the shear rate dependence of flow behaviour of gum solutions and among these the power-law model is the most used (Barnes, Hutton, & Walters, 1989). The effect of concentration on the apparent viscosity of hydrocolloids is generally described by either an exponential or a power relationship (Rao & Kenny, 1975; Speers & Tung, 1986). Temperature also has an important influence on the flow behaviour of hydrocolloid solutions. The effect of temperature on viscosity at a specified shear rate is generally expressed by an Arrhenius-type model (Rao & Anantheswaran, 1982; Rao & Kenny, 1975; Speers & Tung, 1986).

Hydrocolloid solutions may also exhibit time-dependent properties, mainly thixotropy. When a material is sheared at a constant shear rate, the viscosity of a thixotropic material will decrease over a period of time, implying a progressive breakdown of the structure (Abu-Jdayil & Mohameed, 2004). Modeling of the thixotropic behaviour of food products has been based on equations, such as the Weltmann model (Weltmann, 1943), first-order stress decay

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models (Steffe, 1996) and structural kinetic model (Nguyen, Jensen, & Kristensen, 1998). A modified Weltmann logarithmic model (Weltmann, 1943) was utilized to describe the thixotropic behaviour of carboxymethyl cellulose (Abdelrahim, Ramaswamy, Doyon, & Toupin, 1994) and pectin solutions in flavoured yogurt (Ramaswamy & Basak, 1991, 1992) and a first-order stress decay model with a non-zero equilibrium stress value was applied to the thixotropic behaviour of salep and balangu solutions (Razavi & Karazhiyan, 2009).

Lepidium sativum commonly called “Garden Cress” is a polymorphic species. Despite its great medicinal value, *L. sativum* has not received the attention it deserves. Pharmacological studies revealed its cardiovascular and diuretic functions (Saba, Haseeb, Ali, Iqbal, & Srivastava, 1999). The garden cress is an annual herb belonging to the family Cruciferae growing in Middle East Countries, Europe and US. It is an underutilized crop. Garden cress is usually cultivated for its leaves, which are used in salad, sandwiches etc. The leaves and seedpods have a peppery taste. The seedlings are consumed in Europe as salad and spice. The major secondary compounds of this plant are glucosinolates (Gill & MacLeod, 1980) which occur to Ca 1.2% and are isolated from the steam distillate of leaves and seeds. Farnsworth and the associates (Smolenski, Silinis, & Farnsworth, 1974) discovered that the seeds of *L. sativum* are a rich source of alkaloids. The edible whole seed is known to have health promoting properties, and hence is assumed to be a functional food. There have also been preliminary studies into the possibility of using this hydrocolloid as nutraceutical food ingredient in dietary fiber formulations (Gokavi, Malleshi, & Guo, 2004).

The seeds of *L. sativum* have been shown to contain gum of high molecular weight (Karazhiyan, 2008; Razavi et al., 2007). A basic physicochemical understanding of *L. sativum* seed extract is still lacking. This study aims to i) provide a chemical composition and structural analysis of the extract; ii) characterize rheological properties of the extract as a function of shear rate, concentration and temperature; iii) investigate its thixotropic behaviour.

2. Materials and methods

2.1. Sample preparation

The crude extract powder of *L. sativum* seeds was prepared as described by Karazhiyan (2008). Sample solutions (w/w) were prepared by dispersing the hydrocolloid powder in de-ionized water, and stirring at room temperature overnight for complete hydration.

2.2. Chemical analysis

The moisture content of the extract in a dry powder form was quantified from weight loss upon heating at 105 °C for 3 h in an oven. Ash content was determined by weighing the sample (1 g) in a pre-weighed ashing dish after heating at 550 °C for 3 h. The dish was cooled to room temperature in a desiccator and was weighed again. The weight loss was calculated as a percentage of the initial weight taken. Fat content was measured by the Soxhlet method. Protein content was determined by the Kjeldahl method. Major constituent sugars were analyzed after hydrolysis using a combination of acid and pectinase treatments by a high-performance anion-exchange chromatography coupled with pulsed amperometric detection (HPAEC–PAD) system as reported by Funami et al. (2007). The metal ion content (Ca, Mg, K and Na) was determined by using Atomic Absorption Spectroscopy (AANALYST 100, Perkin Elmer, USA) at wavelength of 422.7, 285.5, 766.5 and 589 nm for Ca, Mg, K and Na, respectively. Metal ion contents were read from calibration curves established for each ion.

2.3. Molecular weight measurement

2.3.1. Sample preparations

A 200 ml 0.4% sample solution containing 0.005% NaN_3 was prepared and stirred overnight. The solution was centrifuged at 2500 rpm for 5 min (Megafuga 1.0 R, Heraeus; Kendro lab products, Germany) and filtered through 100 micron, 1.2 micron (glass microfibers paper, 90 mm, Fisher Scientific), 0.8 micron (25 mm, Whatman GmbH) and 0.45 micron filters (Syringe filter, 17 mm, nylon), successively. The final solution was dried in an oven (Heraeus, Kendro lab products, Germany) at 70 °C for 7 h, and the dried material was collected and used for preparing solutions for refractive index increment (dn/dc) and molecular weight measurements.

2.3.2. Measurement of dn/dc

The system used to determine dn/dc consisted of an HPLC Knauer pump K-501 model and an EC-3215 α (ERC Inc.) vacuum degasser connected to the solvent reservoir (0.2M NaCl containing 0.005% NaN_3 filtered through 0.2 micron cellulose nitrate filter). The samples solutions were prepared in 0.2–1 mg/ml and were injected (filtered through 0.2 micron nylon Whatman filter) into a refractive index detector RI 2000A (Schambeck SFD, Germany) operated at 690 nm with a 1 ml loop syringe. Specific refractive index increment (dn/dc) of the *L. sativum* seed extract was determined to be 0.110 ml/g, and this value was used for molecular weight determination.

2.3.3. Gel permeation chromatography–multi angle laser light scattering (GPC–MALLS)

The GPC–MALLS had the same solvent pump and degasser as in the dn/dc measurement. A sample of 1 mg/ml was filtered through 0.2 micron nylon Whatman filter prior injection into GPC columns (Shodex SB-G guard column + Shodex SB-806M HQ + Shodex SB-803 HQ) by a manual Rheodyne Model 7125 syringe loading sample injector equipped with a 100 μl loop. The columns were coupled to a Shimadzu SPD-6 model ultraviolet detector operated at 280 nm, a DAWN DSP multiangle light scattering detector equipped with a He-Ne laser at 632.8 nm (Wyatt Technology Corporation, USA) and the RI 2000A operated at 690 nm. Data was collected by using an Astra Software (version 4.90.08, Wyatt Technology Corporation, USA), and molecular weight and distribution were analyzed by Berry method.

2.4. Rheological measurements

Rheological evaluations were performed using a rotational viscometer (Bohlin Model Visco 88, Bohlin Instruments, UK). Appropriate measuring spindles (C14, C25, and C30) were selected according to the viscosity of dispersion.

2.4.1. Shear rate dependence

Flow behaviour was described by fitting experimental data (shear stress–shear rate) with a power-law model $\eta = k\dot{\gamma}^{n-1}$, where η is the viscosity (Pa.s), $\dot{\gamma}$ is the shear rate (s^{-1}), k is the consistency coefficient ($\text{Pa}\cdot\text{s}^n$) and n is the flow behaviour index (dimensionless).

2.4.2. Concentration dependence

The viscosity at 50 s^{-1} was used to determine the viscosity-concentration and viscosity–temperature relationships since an effective oral shear rate has been reported as 50 s^{-1} (Bourne, 2002, Morris, 1983). The concentration dependence of the viscosity at each temperature was examined using a power-law model $\eta = aC^b$ and an exponential model $\eta = a \exp(bc)$.

Table 1
Chemical composition, constituent sugars, and molecular parameters of *L. sativum* seed extract.

Composition	Constituent sugars		Molecular parameters		
Moisture	7.17%	Man	38.9%	M_w (kDa)	540 (4800, 480) ^c
Ash	11.5%	Ara	19.4%		
Protein	2.45%	GalA	8.0%	M_w/M_n	1.44
Fat	1.85%	Fru	6.8%		
Sugar	77.03% ^a	GluA	6.7%	R_g (nm)	75
Ca	0.17%	Gal	4.7%		
K	0.062%	Rha	1.9%	% Mass	91.4 (1.2, 90.2) ^c
Na	0.039%	Glu	1.0%		
Mg	0.0076%	Total	87.4% ^b		

^a Sugar was determined from 100%-(Moisture + Ash + Fat + Protein).

^b Total sugar content recovered in HPAEC-PAD measurement.

^c The values in the bracket are the parameters when the elution of macromolecular component of the extract is processed as two peaks as shown in Fig. 1.

2.4.3. Temperature dependence

The temperature dependency of the viscosity at 50 s^{-1} for each concentration was evaluated by applying the Arrhenius model: $\eta = A \exp(E_a/RT)$, where A is the frequency factor or viscosity coefficient at a reference temperature (Pa.s), E_a is the activation energy (kJ/mol), R is the gas constant (kJ/mol K) and T is the absolute temperature (K). Activation energy can be determined from the slope of $\ln \eta$ vs. $1/T$ plot.

2.4.4. Thixotropy and time dependence

The thixotropic behaviour of extract solutions was evaluated by measuring the hysteresis loop area enclosed by shear rate upstream data and the subsequent downstream data.

Extract solutions were sheared at constant shear rates of 100, 200, 300, 400, 500, 600, 700 and 800 s^{-1} and the shear stress and the apparent viscosity were recorded as a function of shearing time until a steady state was reached. Our experiments demonstrated that 11 min was enough for hydrocolloid solutions to reach steady state.

The measured time-dependent stress was modeled by a first-order stress decay model with a non-zero equilibrium stress: $\tau = (\tau_0 - \tau_{eq})e^{-kt} + \tau_{eq}$, where τ_0 is the initial shear stress value, τ_{eq} is the equilibrium stress value and k is the breakdown rate constant.

3. Results and discussion

3.1. Chemical composition and molecular weight determination

The composition of main chemical components in the *L. sativum* seed extract is listed in Table 1. The majority of the extract was carbohydrate with a sugar content of nearly 77%. In addition, it contained only a small amount of protein and fat (2.45% and 1.85% respectively). Metal ion content analysis showed that Ca was the major ion present in the extract with a content of 0.17%. There was also trace amounts of K, Na, and Mg.

The total sugar content determined by HPAEC-PAD was 87.4%, which was higher than that of 77% estimated from 100% - (Moisture + Ash + Fat + Protein). The difference can be attributed to incomplete ashing at $550 \text{ }^\circ\text{C}$ for 3 h. The major sugars in a descending content order were mannose (38.9%), arabinose (19.4%), galacturonic acid (8.0%), fructose (6.8%), glucuronic acid (6.7%), galactose (4.7%), rhamnose (1.9%), and glucose (1.0%). The presence of the two uronic acids (~15%) suggested a polyelectrolyte nature of the *L. sativum* seed extract. The content of the uronic acids is comparable to that found in gum arabic (~16%) (Williams & Phillips, 2000). The high mannose content might explain its relatively poor water solubility where long hydration time was needed and a considerable amount of hydrogel was present. A full structural analysis including linkage and arrangement of the sugars is our future objective.

GPC elution profiles of *L. sativum* seed extract are shown in Fig. 1. Light scattering, RI and UV responses all exhibited a peak at an elution volume of ~13.5 mL. Additionally, light scattering showed a small shoulder around 11.5 mL, which however was not pronounced in RI and the UV response, suggesting that this high molecular weight population accounted for only a very small fraction of the macromolecular part of the extract. The molecular parameters obtained by analysis using Astra Software are included in Table 1. The whole extract had a weight-average molecular weight of 540 kDa, and a radius of gyration of 75 nm. When processed as two peaks, the fraction corresponding to the shoulder had an extreme high molecular weight of 4800 kDa, and the fraction corresponding to the major peak had a molecular weight of 480 kDa. The higher molecular weight fraction accounted for only

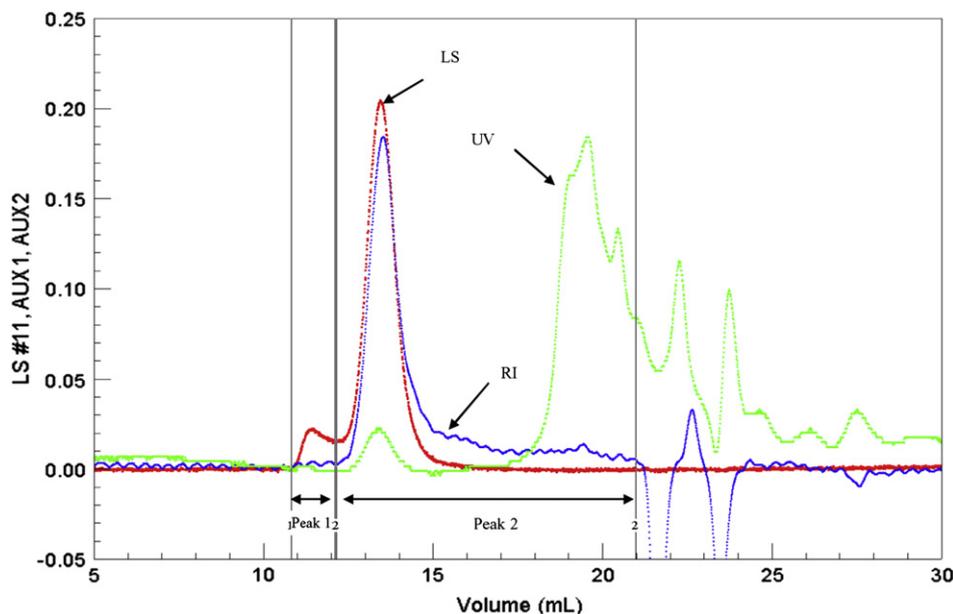


Fig. 1. GPC chromatogram of *Lepidium sativum* seed extract.

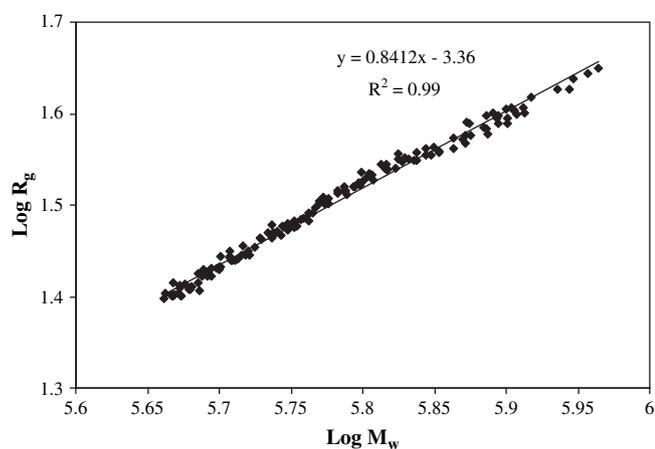


Fig. 2. Log R_g vs. Log M_w for *Lepidium sativum* seed extract.

1.2% of the whole extract, and may be attributed to the aggregated form of hydrocolloid molecules of the extract. As the elution peaks in light scattering and RI profiles were concurrent with the UV peak, it indicated that the macromolecular component of the extract was somehow associated with protein. The macromolecular component might exist in the forms of glycoprotein or protein–polysaccharide complex as has been found in gum arabic (Randall, Phillips, & Williams, 1989).

The plot of log R_g vs. log M_w for macromolecular component of the extract is shown in Fig. 2. The relationship between molecular weight and radius of gyration for macromolecules was given by Mark-Houwink–Sakurada equation: $R_g = K M_w^\alpha$. The coefficient α and K determined for the *L. sativum* seed extract was 0.84 and 0.000437, respectively. It has been reported that for macromolecules with spherical conformation, α is ~ 0.33 and for random coil conformation it is in the range of 0.5–0.6, while for rigid rod conformation its value is ~ 1.0 (Tombs & Harding, 1998). The value of 0.84 determined in the present study suggested that the macromolecular component in *L. sativum* extract had a semi-rigid chain conformation with intermediate flexibility between random coil and rigid rod. For xanthan in a similar molecular weight range, the coefficient α can be estimated to be 0.87 from the data by Sato, Norisuye, and Fujita (1984). The radius of gyration R_g of the macromolecular component of the extract was 75 nm (Table 1), which is quite close to the value of 70–90 nm reported for xanthan

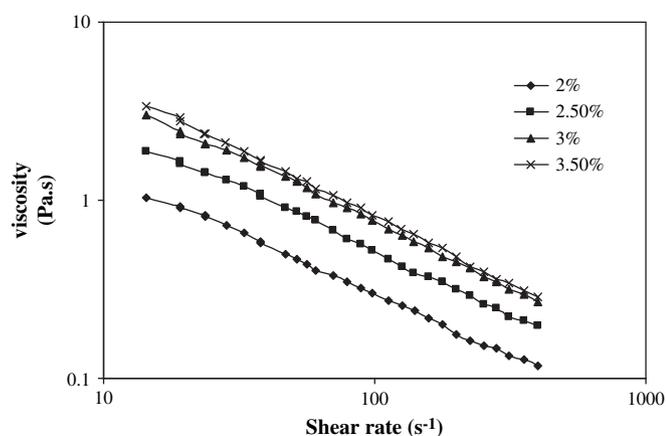


Fig. 3. Typical flow curves for different concentrations of *Lepidium sativum* seed extract at 25 °C.

Table 2

Power-law parameters for *L. sativum* seed extract at different concentrations and temperatures.

Concentration/Temperature	k (Pa.s ^{n})	n (–)	R^2
2%			
10 °C	11.2	0.327	0.99
25 °C	9.9	0.316	0.99
40 °C	8.3	0.309	0.99
55 °C	4.6	0.298	0.99
70 °C	4.4	0.261	0.98
2.5%			
10 °C	19.7	0.261	0.98
25 °C	16.7	0.259	0.99
40 °C	16.4	0.257	0.99
55 °C	13.0	0.252	0.99
70 °C	9.6	0.243	0.99
3%			
10 °C	25.2	0.259	0.99
25 °C	22.2	0.252	0.99
40 °C	18.7	0.250	0.99
55 °C	17.4	0.248	0.99
70 °C	15.2	0.245	0.99
3.5%			
10 °C	38.3	0.242	0.99
25 °C	32.5	0.210	0.99
40 °C	31.8	0.208	0.98
55 °C	28.3	0.206	0.99
70 °C	20.0	0.200	0.99

with a similar molecular weight (Sato et al., 1984; Lee & Brant, 2002a). This indicated that the macromolecular component in *L. sativum* seed extract possessed comparable chain stiffness with xanthan. The semi-rigid chain conformation is favorable for the formation of macromolecular entanglement, which can explain the relatively high viscosity and pseudoplasticity of the extract as shown in the following rheological studies.

3.2. Effect of shear rate

Typical flow curves for *L. sativum* seed extract at 25 °C are shown in Fig. 3. A clearly shear-thinning behaviour was observed for all concentrations. Similar behaviour was obtained at other concentrations and temperatures. The parameters obtained for the power-law model are summarized in Table 2. The results showed that n values were less than unity conforming that these products are pseudoplastic materials at all temperatures and concentrations studied. The coefficients of determination (R^2) obtained were very close to 1, indicating that the power-law model was adequately suitable for describing the flow behaviour of samples. The value of consistency coefficient, k , ranged from 4.43 to 38.26 Pa.s ^{n} and the flow behaviour index, n , ranged between 0.2 and 0.327. The flow behaviour index, for example, of 3% extract at 25 °C was 0.252. This value is even smaller than that of 0.410 reported for xanthan with similar molecular weight and concentration (Lee & Brant, 2002b), suggesting a stronger shear-thinning behaviour than xanthan.

Table 3

Concentration dependence coefficients for viscosities of *L. sativum* seed extract measured at shear rate 50 s^{–1}.

Temperature (°C)	Power law $\eta = aC^b$			Exponential $\eta = a \exp(bc)$		
	a	b	R^2	a	b	R^2
10	0.26	1.64	0.99	0.28	0.057	0.97
25	0.19	1.75	0.96	0.21	0.611	0.98
40	0.16	1.83	0.97	0.16	0.662	0.98
55	0.064	2.47	0.99	0.073	0.846	0.99
70	0.036	2.75	0.99	0.056	0.853	0.97

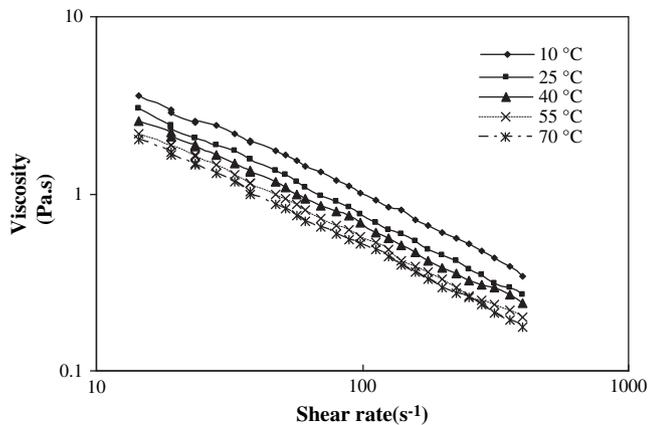


Fig. 4. Viscosity of *Lepidium sativum* seed extract at 3% concentration and selected temperatures.

For all samples, an increase in concentration was accompanied by an increase in pseudoplasticity, shown by a decrease in values of the flow behaviour index (Table 2). This suggested that the deviation from the Newtonian behaviour ($n = 1$) increased with increasing the solids concentration of hydrocolloid extracts. As expected, the consistency coefficient increased with the concentration of hydrocolloid extracts (Table 2) (Clasen & Kulicke, 2001; Lapasin & Pricl, 1999). A higher solid content generally causes an increase in the viscosity resulting from increased restriction of molecular motion due to entanglements between polymer chains (Bhattacharya, Bhat, & Raghuvver, 1992; Maskan & Gogus, 2000).

The viscosity of solutions decreased with increasing shear rate. Such behaviour has been observed for many hydrocolloid solutions (Clasen & Kulicke, 2001; Lapasin & Pricl, 1999; Marcotte, Taherian Hoshahili, & Ramaswamy, 2001; Togrul & Arslan, 2003). The decrease in viscosity with increasing shear rate is mainly related to the disentanglement of macromolecular chains under shear field and breaking of possible structure in solution. The conspicuously strong shear-thinning behaviour observed for *L. sativum* seed extract is attributable to its rather rigid chain conformation that gives rise to a highly entangled macromolecular solution.

The flow behaviour index showed a decreasing trend with increasing temperature, which indicates that hydrocolloid solutions tend to be more shear thinning at higher temperatures.

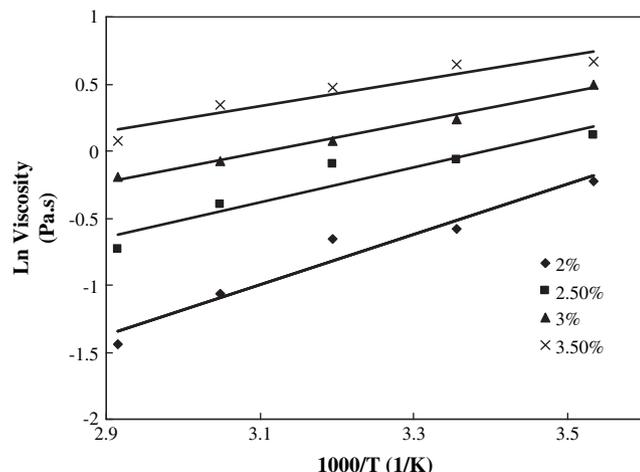


Fig. 5. Arrhenius plot for the viscosities at shear rate of 50 s^{-1} . Experimental data: (◆) 2%; (■) 2.5%; (▲) 3%; (×) 3.5%; (—) Arrhenius model prediction.

Table 4

Arrhenius model ($\eta = A \exp(E_a/RT)$) for temperature dependency of viscosity at 50 s^{-1} for *L. sativum* seed extract at different concentrations.

Concentration (%)	A (Pa.s)	E_a (kJ/mol)	R^2
2%	0.001	15.59	0.96
2.5%	0.012	10.83	0.98
3%	0.031	9.23	0.99
3.5%	0.075	7.82	0.99

A decrease in consistency coefficient was observed with increasing the temperature, indicating a decrease in viscosity at higher temperatures.

Szczesniak and Farkas (1962) showed that gum solutions with a high value of n tend to feel slimy in the mouth. When a less slimy mouth feel characteristics are desired, the choice should be a gum system having a low n value. Therefore the *L. sativum* seed extract is suitable for the applications that require less slimy texture or mouth feel, e.g. a possible thickener in the treatment of dysphagia.

3.3. Effect of concentration

The regression model parameters a and b obtained from the concentration dependence of viscosity at 50 s^{-1} are summarized in Table 3. The coefficients of determination (R^2) were close to unity indicating that both models adequately describe the associated variability. The parameter “ a ” decreased and parameter “ b ” increased with increasing temperature. The increase in parameter b with increasing temperature means that the concentration dependence becomes stronger at higher temperatures. This can be due to increasing intermolecular interaction in the extract solutions at elevated temperatures. Decreasing of parameter a and increasing of parameter b have been reported by Dak, Verma, and Jaaffrey (2007) for mango juice. Marcotte, Taherian Hoshahili, and Ramaswamy (2001) also reported a decrease in parameter a with increasing temperature for some food hydrocolloids (carrageenan, pectin, gelatin, starch, and xanthan) for power-law and exponential models.

3.4. Effect of temperature

The effect of temperature on viscosity is shown in Fig. 4. There was a reduction in viscosity as the temperature increased. This

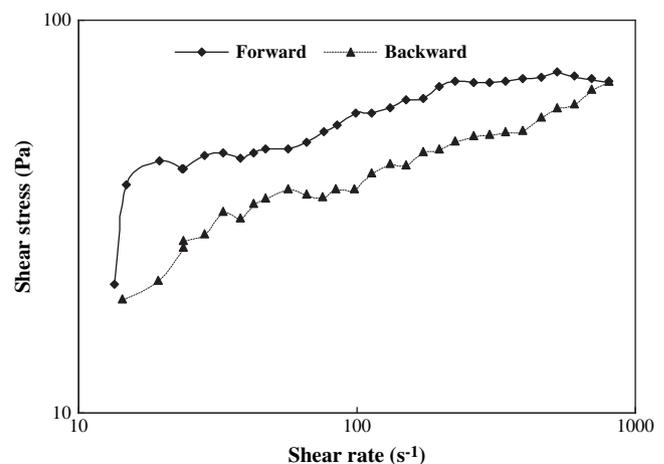


Fig. 6. A sample hysteresis loop of the flow curves of *Lepidium sativum* seed extract at 6.75% (w/w) concentration and temperature of 45 °C .

behaviour may be due to an increase in the mobility of the macromolecules in the extract, showing less resistance to flow.

The temperature dependency of the viscosity at 50 s^{-1} was investigated using the Arrhenius model. Fig. 5 illustrates that the change of apparent viscosity with temperature generally obeyed the Arrhenius model. Frequency factors, activation energies and coefficients of determination are listed in Table 4. Good agreement (R^2) with linearity was found. The activation energy indicates the energy barrier that must be overcome before the elementary flow process can occur (Rao, 1999). The magnitude of the temperature effect varied with concentration as shown by the E_a values in Table 4. In general, the higher the activation energy, the greater the effect of temperature on the viscosity (Mohd, Nurul, Mohd, Azemi, & Manan, 1999). As can be seen in Table 4, the activation energy for the extract decreased from 15.59 kJ/mol at 2% concentration to 7.82 kJ/mol at 3.5%. This indicates that the effect of temperature on viscosity is more pronounced at low extract concentrations. The frequency factors increased from 0.001 to 0.075 (Pa.s) as the concentration increased.

Decrease in activation energy and increase in frequency factor with increasing concentration are comparable to the results of Farhoosh and Riazi (2006) and Kim and Yoo (2006) for salep solutions and rice starch-xanthan gum mixtures, respectively. Marcotte, Taherian Hoshahili, and Ramaswamy (2001) also reported an increase in frequency factor for some hydrocolloids (carrageenan, pectin, gelatin, starch, and xanthan) and a decrease in activation energies for gelatin with increasing concentration.

3.5. Thixotropy and time-dependent behaviour

The cycle of increasing-decreasing shear rate showed that a hysteresis loop appeared from a 6% (w/w) concentration of the extract. Existence of a hysteresis loop indicated time-dependent flow behaviour (Fig. 6) and its area is a measure of the extent of thixotropy (Steffe, 1996). Some authors have determined thixotropic behaviour by evaluation of the area of the hysteresis loop between the upward and downward curves (Köksoy & Kılıc, 2003; Razavi & Karazhiyan, 2009; Tárrega, Durán, & Costell, 2004).

Table 5 shows the data of hysteresis loop area at the different temperatures and concentrations studied. It was found that the hysteresis area increased as the concentration of the extract increased. The increasing hysteresis area with concentration is in agreement with the results of Altan, Kus, and Kaya (2005) reported for Gilaboru juice, and it means an increased extent of structuring of the extract solutions with concentration. Furthermore, the

Table 5

Hysteresis area of different concentrations of *L. sativum* seed extract at different temperatures.

Concentration	Temperature (°C)	Hysteresis area ($\times 10^3 \text{ Pa s}^{-1}$)
6%	5	50
	25	106
	45	129
	65	150
6.25%	5	95
	25	117
	45	131
	65	161
6.5%	5	125
	25	137
	45	159
	65	172
6.75%	5	132
	25	152
	45	161
	65	175

Table 6

The parameters of the first-order stress decay model with a non-zero equilibrium stress for a 6% w/w *L. sativum* seed extract at different temperatures.

Temperature (°C)	Shear rate (s^{-1})	τ_0 (Pa)	τ_{eq} (Pa)	$k \times 10^3$ (s^{-1})	R^2
5	100	243.8	90.4	2.7	0.91
	200	227.7	85.2	12	0.96
	300	194.9	77.3	9.1	0.99
	400	211.5	65.2	4.6	0.98
	500	205.2	36.7	4.1	0.95
	600	226.6	36.7	8.4	0.98
	700	217.7	41.0	7.2	0.99
	800	216.3	71.7	7.1	0.98
25	100	213.7	80.7	4.8	0.99
	200	221.5	81.5	6.3	0.98
	300	186.0	70.9	7.2	0.99
	400	184.5	60.6	8.1	0.99
	500	185.4	30.3	5.6	0.99
	600	217.4	30.2	5.9	0.99
	700	210.0	35.9	4.3	0.99
	800	214.1	42.2	4.1	0.99
45	100	211.9	50.3	1.1	0.98
	200	210.4	65.5	5.7	0.96
	300	181.0	60.0	1.8	0.97
	400	182.0	40.4	5.7	0.99
	500	180.4	25.7	3.6	0.97
	600	198.9	19.2	9.3	0.98
	700	199.9	29.8	4.6	0.98
	800	206.9	29.7	5.6	0.98
65	100	127.7	18.3	3.3	0.97
	200	192.2	14.4	6.4	0.98
	300	176.6	29.7	4.1	0.99
	400	171.9	18.5	6.2	0.99
	500	178.6	21.8	8.3	0.99
	600	178.2	12.2	9.1	0.99
	700	177.3	22.0	4.7	0.98
	800	174.2	25.0	5.3	0.99

hysteresis area is greater at higher temperatures for all the concentrations studied (Table 5). Abu-Jdayil and Mohameed (2004) reported a similar phenomenon for sweetened sesame paste (halawa tehneh). The increasing hysteresis area with increasing temperature can also be explained as a result of increased intermolecular interaction as suggested previously for the greater concentration dependence of viscosity at higher temperatures.

Different kinetic models including structural kinetic model (Razavi & Karazhiyan, 2009), Weltmann model (Weltmann, 1943), and first-order stress decay model have been tested to describe the thixotropy behaviour when the extract solution is subjected to a constant shearing. It was found that only the first-order stress decay model with a non-zero equilibrium stress could be reasonably applied to the dependence of stress on shearing time ($R^2 > 0.9$). The relevant parameters for this model obtained by curve fitting are shown for a 6% w/w solution in Table 6. It was found that initial shear stress (τ_0) and equilibrium stress (τ_{eq}) decreased with increasing temperature. Abu-Jdayil, Al-Malah, and Asoud (2002) reported a similar decrease in τ_{eq} value with increasing temperature for milled sesame (tehneh). It was also found that τ_0 and τ_{eq} decreased with decreasing concentration (data not shown). However, breakdown rate constant k did not have a clear dependence on temperature, concentration or shear rate, which is in agreement with the findings of Altan et al. (2005) for Gilaboru juice.

4. Conclusions

Chemical and structural analysis showed that *L. sativum* seed extract was mainly composed of a carbohydrate polymer with a molecular weight of about 540 kDa. The macromolecular component was either a glycoprotein or polysaccharide-protein

complex with a chain conformation nearly as rigid as xanthan. Rheological studies showed that the extract behaved as a shear-thinning fluid and could be described by the power-law model. For all samples, an increase in concentration or temperature led to an increase in pseudoplasticity. The extent of shear thinning is even more pronounced than that observed for xanthan. The viscosity of the extract had a greater concentration dependence at higher temperatures, and its dependence on temperature obeyed the Arrhenius model. The activation energy decreased with increasing concentration. Thixotropic behaviour occurred when the extract concentration is above 6%, the extent of which increased with increasing concentration and temperature.

Based on its conformational and rheological similarities with xanthan, *L. sativum* seed extract could be used as a thickening agent in food and related industries.

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