INTRODUCTION

High pressure processing is also called high hydrostatic pressure (HHP), ultra-high pressure processing, pascalization, or cold pasteurization (Daher, Le Gourrierec, & Pérez-Lamela, 2017). It has been widely explored and has indicated a major potential for various type of food processing applications in recent years (Vatankhah, Taherian, & Ramaswamy, 2018). It is a food processing technology which employs high pressure to solid or liquid foods to improve their safety and, in some cases, organoleptic properties and quality (Daher et al., 2017). HHP has been successfully proven to be used as an alternative to conventional heat treatments (Franchi, Tribst, & Cristianini, 2013; Pinho, Oliveira, Leite Júnior, Tribst, & Cristianini, 2015) or in combination with mild temperatures (Ferragut et al., 2015) in some beverages. HHP is also an emerging process to modify food biopolymers.

Effects of high hydrostatic pressure on the rheological properties and foams/emulsions stability of Alyssum homolocarpum seed gum

Sajad Ghaderi1 | Mohammad Ali Hesarinejad2 | Elhamalsadat Shekarforoush3 | Seyyed Mahdi Mirzababaee4 | Farzad Karimpour5

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. Food Science & Nutrition published by Wiley Periodicals LLC.
the achievement and control of pressure-induced changes in the molecular structure (Olsen & Orlien, 2016). This includes starch gelatinization and protein denaturation or aggregation to improve the texture of foods (Knorr, Heinz, and Buckow (2006); Messens, Van Camp, & Huyghebaert, 1997; Molina, Papadopoulou, & Ledward, 2001; Li et al., 2011). High pressure is a rather useful tool by which the texture of foodstuff can be manipulated (Ledward, 1995). Several studies have reported the impacts of HHP on the rheological and functional properties of macromolecules associated with various food matrices (Ahmed, Ramaswamy, Ayad, Ali, & Alvarez, 2007; Laneuville, Turgeon, & Paquin, 2013; Panteloglou, Bell, & Ma, 2010; Vatankhah et al., 2018; Xue et al., 2018).

Seed gums are polysaccharides from the vegetal origin and are widely employed in the food and chemical industries as thickeners, stabilizers, gelling agents, and emulsifiers (Alizadeh Behbahani et al., 2017; Belmiro, Tribst, & Cristianini, 2018; Hesarinejad, Koocheki, & Razavi, 2014a). Regarding the structure and texture of food products, the rheological and functional properties of hydrocolloids are of utmost importance (Hesarinejad, Koocheki, & Razavi, 2015a). The choice of a specific gum depends on its application and purpose because each form of gum has particular values with respect to viscosity, intrinsic viscosity, stability, and emulsifying and gelling properties, with these parameters being determined by its structure (Belmio et al., 2018). HHP is able to alter those properties positively by inducing changes in the original polymer, allowing for new applications and improvements with respect to the technical properties of gums (Belmio et al., 2018). The effect of HHP on food hydrocolloids depends on the pressure amplitude, hydrocolloid type and concentration, pressurization time, temperature, and medium (Pei-Ling, Xiao-Song, & Qun, 2010; Porretta, Birzi, Ghizzoni, & Vicini, 1995).

Alyssum homolocarpum is natives of some Middle Eastern countries like Pakistan, Iran, Iraq, Saudi Arabia, and Egypt (Amin, 2005). Alyssum homolocarpum seed gum (AHSG) has been used as medicinal remedies. AHSG exhibited non-Newtonian, pseudoplastic behavior over a range of 1.5%–4% at 5°C–65°C (Koocheki, Mortazavi, Shahidi, Razavi, & Taherian, 2009). The elastic component of AHSG has always been higher than the viscous one at concentrations of 1.5%–3%, which means that AHSG has had weak gel-like properties (Hesarinejad, Koocheki, & Razavi, 2014b). AHSG is highly purified and contains 85.33% carbohydrate with a small amount of uronic acid (5.63%) (Hesarinejad, Razavi, & Koocheki, 2015b). AHSG has a low molecular weight ($3.66 \times 10^5$ Da) with relatively flexible chain and medium intrinsic viscosity (18.34 dl/g) at ambient temperature (Hesarinejad et al., 2015b). The electrostatic interaction and particle size of AHSG solution were −25.81 mV (at neutral pH) and 225.36 nm, respectively (Hesarinejad et al., 2015b). The major monosaccharide compositions of AHSG are galactose (82.97%), glucose (5.7%), rhamnose (5.04%), xylose (2.72%), mannose (3.04%), and arabinose (0.53%), and it is likely a galactan-type polysaccharide (Hesarinejad et al., 2015b). AHSG behaves like a typical poly-electrolyte because of the presence of carboxyl and hydroxyl groups (Hesarinejad et al., 2015b). AHSG can be applied for thickening, suspending, stabilizing, and as a gelling agent (Koocheki & Hesarinejad, 2019).

The rheological properties of food hydrocolloids are forcefully influenced by temperature, pressure, concentration, and physical state of dispersion (Van Vliet & Walstra, 1980). Owing to the difference in extrinsic conditions within the fluid food systems, the benefits of AHSG solutions will be changed from one situation to another. Therefore, the aim of this work was to study the simultaneous effect of high hydrostatic pressure level (200–600 MPa) on the rheological and functional properties of this gum.
2 | MATERIALS AND METHODS

2.1 | Materials

The AHSG was extracted and purified according to Koocheki et al. (2010). AHSG dispersion at 1% (w/w) was prepared by adding an appropriate amount of freeze-dried AHSG powder to a portion of deionized water that contained 0.02% sodium azide as an anti-microbial preservative. Then, these dispersions stirred for 2 hr on a magnetic stirrer at ambient temperature and put on roller shaker overnight to ensure complete hydration. This sample was kept at refrigerator before carrying out the experiments. All chemicals used in this study were of analytical grade and purchased from Merck (Darmstadt, Germany) company.

2.2 | High hydrostatic pressure treatment

A hydrostatic pressurization unit (RIFST, Mashhad, Iran) with a chamber volume of 120 ml was applied to generate high pressure levels (Figure 1). The device has the ability to adjust the pressure level through a manual valve control. The pressure level is visible both in analogue and in digital, and the permissible pressure is controlled through a pressure transducer and a pressure relief valve. The pressure applied to the samples was 200, 400, and 600 MPa, and a pressure rise of 10 MPa.s\(^{-1}\) was implemented, and also, the decompression time was less than 5 s. The time is taken to apply the samples 30 min. The samples were stored at a temperature of 4°C before loading in the refrigerator and did not have a significant change in pressure applied to the samples (the maximum measured temperature was 23°C for a sample of 600 MPa). Triplicate samples were applied for each treatment. Untreated AHSG was used as control.

2.3 | Measurement of rheological properties

Steady and dynamic shear measurements were conducted with a Physica MCR301 controlled stress/strain rheometer (AnTon paar GmbH, Germany) using a parallel plate geometry (50 mm diameter). After transferring the sample onto the rheometer plate, the minimum gap was adjusted to 1.0 mm. The excess material was wiped off with a spatula, and the edges were coated with a thin layer of silicone oil to reduce evaporation during measurements. After loading, the sample was allowed to relax for 1 min before the measurements. The linear viscoelastic region (LVR) of pressurized-AHSG dispersions was determined by performing an amplitude sweep tests. Frequency sweep measurements at a very low strain of 0.1% (LVR) were carried out where it approaches linear behavior. The mechanical spectra were characterized by values of G’ and G” as a function of frequency in the range of 0.1-10 Hz at 25°C. Steady flow behavior of pressurized-AHSG dispersions was measured over a range of shear rates from 0.1 to 300 s\(^{-1}\) with a linearly increasing scale. The apparent viscosity at a given shear rate was determined as the ratio of shear stress to shear rate (Steffe, 1996). The Rheoplus/32 software V3.40 was employed for data evaluation. At least, triplicate of each measurement was made.

In order to perform a quantitative comparison of pressurized-AHSG dispersions, six rheological flow models based on shear stress–shear rate were measured (Ostwald–Waele, Bingham, Herschel–Bulkley, Casson, National Confectioners Association/CMA Casson and Vocadlo). The best fit model was selected according to the determination coefficient (R\(^2\)) and root mean square error (RMSE).

Ostwald–Waele’s (or Power law) model:

\[
\tau = k\dot{\gamma}^n
\]  
(1)

where k is the consistency coefficient (Pa.s\(^n\)), and n is the flow behavior index for Ostwald–Waele model.

Bingham’s model:

\[
\tau = \tau_0 + \eta\dot{\gamma}
\]  
(2)

where \(\tau_0\) is the yield stress (Pa) and \(\eta\) is called the Bingham plastic viscosity (Pa.s) and \(\dot{\gamma}\) is the yield stress (Pa).

Herschel–Bulkley’s model:

\[
\tau = \tau_0 + k(\dot{\gamma})^n
\]  
(3)

where \(\tau_0\) is the yield stress (Pa), k is the consistency coefficient (Pa.s\(^n\)), and n is flow behavior index for Herschel–Bulkley model.

Casson’s model:

\[
\tau^{0.5} = \tau_0^{0.5} + k(\dot{\gamma})^{0.5}
\]  
(4)

where \(\tau_0^{0.5}\) (Pa\(^{0.5}\)) and k (Pa.s\(^{0.5}\)) are the intercept and slope of plot of \(\tau^{0.5}\) versus \(\dot{\gamma}^{0.5}\), respectively. Then, the magnitudes of \(\tau_0\) and k have been used as the Casson yield stress (Pa) and Casson plastic viscosity (Pa.s), respectively.

NCA/CMA Casson’s model:

\[
\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta}\sqrt{\dot{\gamma}}
\]  
(5)

where \(\tau_0\) is the Casson yield value (Pa), and \(\eta\) is the Casson plastic viscosity (Pa.s).

Vocadlo’s model:

\[
\tau = \left(\tau_0^{0.5} + k\dot{\gamma}\right)^n
\]  
(6)

where \(\tau_0\) is the yield stress (Pa), k is the consistency coefficient (Pa.s\(^{0.5}\)), and n is the flow behavior index.

2.4 | Emulsion preparation and characterization

The oil in water emulsions (30:70 v/v) were prepared by adding 18 ml of sunflower oil into 60 ml of pressurized-AHSG dispersions (1%w/v)
while mixing by a mechanical high speed stirrer (2000 rpm). After mixing (3 min), the suspension was homogenized by Ultra-Turrax T-25 homogenizer (IKA Instruments, Germany) at 20,000 rpm for 6 min in alternate cycles of homogenization for 1 min and rest for 2 min at ambient temperature. Prepared emulsions were then centrifuged at 2000×g for 10 min. Emulsion stability was calculated based on the following equation (Sciarini, Maldonado, Ribotta, Pérez, & León, 2009):

\[\text{Emulsion Stability} = \frac{f_{ev}}{t_{sv}} \times 100\]  

(7)

where \(f_{ev}\) is the final emulsion volume and \(t_{sv}\) is initial emulsion volume.

The size distribution of the pressurized-AHSG emulsions at various pressure level (200–600 MPa) was determined by a laser diffraction particle sizer (Fritsch Particle sizer Analysette 22, Fritsch Co., Germany) at 25°C. The refractive index of the solvent was equal to 1.33. The average sizes of particles were measured by light beam scattering at a wavelength of 633 nm. Three measurements of the particle size were made, and the average value is reported.

### 2.5 Foaming and foam characterization

0.3% (w/v) ovalbumin (Applichem, USA) was added to the 20 ml of diluted pressurized-AHSG dispersions (0.1% w/v) while whipping strenuously at 15,000 rpm for 2 min with a homogenizer (Ultra-Turrax T-25, Heidolph, Germany) (Koocheki, Razavi, & Hesarinejad, 2012). The foam stability was calculated using the following equation:

\[\text{Foam Stability (\%) } = \frac{f_{fo}}{t_{sv}} \times 100\]  

(8)

where \(f_{fo}\) is the foam volume after 30 min and \(t_{sv}\) is total suspension volume.

### 2.6 Statistical analyses

Statistical analysis was performed using SPSS software (SPSS 24.0 for Windows, SPSS Inc., Chicago, IL, USA). Significant difference at 95% confidence level was evaluated using Duncan’s multiple range test to compare the treatment means.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Effects of HHP on rheological properties of AHSG

Applied pressure plays the main role in the rheological and textural characteristics in foods. HHP has been modified the rheological and textural properties of food proteins and hydrocolloids (Ahmed & Ramaswamy, 2004; Ahmed, Ramaswamy, Ali, & Ngadi, 2003; Ahmed et al., 2007; Alvarez, Ramaswamy, & Ismail, 2008; Belmiro et al., 2018). The rheological parameters of pressurized-AHSG dispersions at the different hydrostatic pressure levels obtained by fitting the shear stress–shear rate data to the various time-independent rheological models are shown in Table 2. Based on the Herschel–Bulkley and Vogado models, pressurized-AHSG dispersions demonstrated a non-Newtonian shear-thinning fluid with the presence of yield stress at all hydrostatic pressure tested. Among rheological models, the Herschel–Bulkley model founded best, with higher \(R^2\) and lower RMSE. This was in agreement with results of Koocheki & Razavi (2009), who reported that Herschel–Bulkley equation well described the flow behavior of AHSG dispersion (Koocheki & Razavi, 2009). Similar this was also reported for pressurized-Xanthan gum by Ahmed & Ramaswamy (Ahmed & Ramaswamy, 2004). On the contrary, Koocheki et al. (2009) and Anvari et al. (2016) showed that the flow behavior was described with Ostwald power law and Carreau models, respectively (Anvari et al., 2016; Koocheki et al., 2009). This difference could be due to pressure application, range of shear rate, source of seed, etc.

The \(k\) value has been considered as an important quality factor in food processing among the rheological parameters. Table 2 represented that pressure level had a significant effect on the consistency coefficient (\(k\)). The pressure affected the \(k\) value of AHSG (Table 2). The result demonstrated that the magnitude of \(k\) increased with an increase in pressure level. As pressure level elevated, the AHSG chains probably come closer and resulting in their mutual entanglement. This increment of consistency coefficient was also possibly due to the decreasing particle size of gum. The highest consistency coefficient for pressurized-AHSG dispersion was shown when the pressure treated was the highest level (600 MPa).

The values of flow behavior indices (\(n\)) ranged between 0.20 and 0.43 and displayed shear-thinning nature of pressurized-AHSG dispersions at all measurement conditions. The lower \(n\) values represented a greater departure from Newtonian behavior (Koocheki et al., 2010). To prepare high viscosity and good mouthfeel, hydrocolloids which have a low \(n\) value are desirable (Marcotte, Hoshahili, & Ramaswamy, 2001).

Increase in pressure level from 200 to 600 MPa slightly decreased the \(n\) value resulted in an augmentation of pseudoplasticity (Table 2). As lower values of \(n\) represent a pseudoplastic behavior of gum, it can be concluded that HHP treatment tends to induce higher pseudoplasticity. It has been also reported that the value of \(n\) and its changes is strongly dependent on molecular size (Hamza-Chaffai, 1990). Among all samples, HHP-treated AHSG dispersions at the maximum pressure level (600 MPa) had the highest consistency coefficient and shear-thinning behavior (Table 1).

Yield stress, which results from the formation of a weak network in the gum solution, is one of the momentous qualitative factors for determining the properties of hydrocolloids (Hesarinejad et al., 2015a). The value of yield stress represented the finite stress required of hydrocolloids to initiate flow (Ahmed & Ramaswamy, 2004). It has an enormous range of practical applications in foods such as...
coating, spread ability, firmness of gels, and mouthfeel (Ahmed & Ramaswamy, 2004; Sun & Gunasekaran, 2009). The yield stress for native AHSG is 1.29 Pa, while this varied from 2.09 to 3 Pa as a result of the HHP treatment. The yield stress slightly increased with pressure for AHSG and followed polynomial models of order 2 (Figure 2). A similar trend was reported by Ahmed, Ramaswamy, & Hiremath (2005) for Alphanso pulp (Ahmed, Ramaswamy, & Hiremath, 2005). This observation could be due to the structural arrangement and intramolecular interactions of AHSG. Further investigations of intramolecular AHSG interactions at other HHP conditions may be beneficial to fully explore the impact of these factors on the rheological behavior (Ahmed et al., 2005).

**TABLE 1** Shear rate dependency of AHSG dispersions at different pressures using various rheological flow functions

| Models          | Pressure levels (MPa) | 0.101 | 200 | 400 | 600 |
|-----------------|-----------------------|-------|-----|-----|-----|
| **Ostwald–Waele** | k                     | 3.03  | 2.99| 3.21| 4.28|
|                 | n                     | 0.26  | 0.23| 0.25| 0.20|
|                 | R²                    | 0.98  | 0.98| 0.99| 0.91|
|                 | RMSE                  | 0.233 | 0.174| 0.186| 0.403|
| **Bingham**     | η                      | 0.060 | 0.049| 0.061| 0.078|
|                 | τ₀                    | 5.00  | 4.75| 5.26| 5.90|
|                 | R²                    | 0.94  | 0.88| 0.92| 0.66|
|                 | RMSE                  | 0.362 | 0.449| 0.438| 0.789|
| **Herschel–Bulkley** | k                  | 1.00  | 2.17| 2.99| 4.28|
|                 | n                     | 0.43  | 0.30| 0.23| 0.20|
|                 | τ₀                    | 1.29  | 2.09| 2.72| 3.00|
|                 | R²                    | 0.99  | 0.99| 0.99| 0.98|
|                 | RMSE                  | 0.119 | 0.175| 0.174| 0.211|
| **Vocadlo**     | k                      | 16.24 | 19.10| 25.37| 28.13|
|                 | n                     | 0.30  | 0.29| 0.29| 0.28|
|                 | τ₀                    | 3.39  | 4.01| 4.31| 4.35|
|                 | R²                    | 0.98  | 0.98| 0.99| 0.97|
|                 | RMSE                  | 0.196 | 0.181| 0.175| 0.231|
| **Casson**      | η                      | 0.130 | 0.113| 0.130| 0.133|
|                 | τ₀                    | 3.72  | 3.63| 3.93| 4.68|
|                 | R²                    | 0.98  | 0.94| 0.97| 0.79|
|                 | RMSE                  | 0.221 | 0.305| 0.268| 0.620|
| **NCA/CMA Casson** | η                  | 0.017 | 0.016| 0.017| 0.017|
|                 | τ₀                    | 3.72  | 3.85| 3.93| 3.98|
|                 | R²                    | 0.98  | 0.96| 0.97| 0.95|
|                 | RMSE                  | 0.221 | 0.213| 0.268| 0.210|

The frequency sweep test is used to characterize and classify the dispersions (Hesarinejad et al., 2018). Figure 3 indicates the changes in storage modulus (G’) and loss modulus (G”) as a function of frequency (Hz) and high hydrostatic pressure (MPa). They were measured over the frequency range of 0.1–10 Hz at a strain level of 0.1%. This strain was found to be within the linear viscoelastic region of the pressurized and unpressurized-AHSG samples tested. In dilute solutions, the storage modulus is less than the loss modulus and approaches each other at higher frequencies, while in the gel-like systems, the elastic modulus is higher than the loss modulus at all of the studied frequency domain. In addition, in concentrated polymer solutions, at low frequencies, the elastic modulus is less than the viscous modulus and intersects the middle of the frequency (Hesarinejad, Shekarforoush, Attar, & Ghaderi, 2019). As previously reported, AHSG solution at high concentration (>0.7%) has a typical weak gel-like behavior where the magnitudes of G’ and G” slightly elevated with increasing frequency, having small frequency dependence (Alaeddini, Koocheki, Mohammadzadeh Milani, Razavi, & Ghanbarzadeh, 2017; Hesarinejad et al., 2015a). At low frequencies, G’ values were much greater than G”. With increasing frequency, the magnitude of loss modulus increased rapidly and became closer to storage modulus. This phenomenon also displayed weak gel behavior for the AHSG samples. Similar this has been reported by Karazhiyan et al. (2011) and Hesarinejad et al. (2014) for Lepidium sativum and Lepidium perfoliatum seed gums, respectively (Hesarinejad et al., 2014a; Karazhiyan et al., 2011).

The effect of high hydrostatic pressure treatment on the viscoelastic behavior of AHSG is shown in Figure 3. At the range of pressure studied (200–600 MPa), the viscoelastic moduli of pressurized-AHSG were higher than those of nonpressurized-AHSG, depicting that AHSG had pressure sensitivity, and thus, it is attended that this gum can be used as a new source of a thickening agent in the food and pharmaceutical formulation, which requires the enhancement of viscoelastic properties after application high pressure.
This observation can also be related to the ever-increasing complex structure at higher pressures.

A more detailed examination of the structures obtained after the pressurization of AHSG is given in Figure 4. This indicates the complex modulus ($G^*$) as a function of frequency for both pressurized and native AHSG. High pressure treatment could also enhance the overall dynamic moduli ($G^*$) of AHSG. This would suggest that pressure treatment may enhance overall consistency (similar values of $G^*$) of the AHSG. These changes should be caused by an underlying structure/interaction after pressure treatment (Panteloglou et al., 2010). A similar was reported by Panteloglou et al., (2010) for pressurized hydrated gum Arabic samples (Panteloglou et al., 2010).

### 3.2 Effect of HHP on emulsion characterization

Evaluation of the particle size distribution of emulsion is very momentous as it influences the viscosity of this system (Venugopal & Abhilash, 2010). The particle size distribution of the pressurized-AHSG emulsions was set using a Laser Particle Size Analyzer (Fritsch Analysette 22—Nanotec, Idar-Oberstein, Germany). These data are tabulated in Table 2. In this study, $d_{4,3}$ represents the volume mean diameter and $d_{3,2}$ represents the area mean diameter. Table 2 exhibits a decrease in $d_{4,3}$ and $d_{3,2}$ with high hydrostatic pressure treatment ($p < .05$). For the pressurized-AHSG emulsion, volume mean diameter decreased progressively with increasing pressure so that the size was reduced to about 158.4 nm (~62% of the initial size) after treatment at 600 MPa. The area mean diameter of native AHSG was approximately 223.3 nm. Following HHP

![Figure 3](image-url)  
**Figure 3** Effect of high hydrostatic pressure levels on storage modulus (closed symbols) and loss modulus (open symbols) of AHSG dispersions as functions of frequency.

![Figure 4](image-url)  
**Figure 4** Complex modulus ($G^*$) as a function of frequency for native and pressurized-AHSG over the range 0.1–10 Hz at a strain of 0.1%. Error bars extend one SE above and below the mean.

| Pressure (MPa) | $d_{3,2}$ (nm) | $d_{4,3}$ (nm) | Emulsion stability (%) |
|---------------|---------------|---------------|------------------------|
| 0.101         | 223.3 ± 0.2a  | 420.8 ± 0.8a  | 93.1 ± 1.0c            |
| 200           | 217.8 ± 0.5a  | 254.0 ± 0.6b  | 95.9 ± 0.9b            |
| 400           | 188.4 ± 0.3b  | 172.3 ± 0.6c  | 97.1 ± 1.1b            |
| 600           | 125.1 ± 0.3c  | 158.4 ± 0.4d  | 100 ± 0.7a             |

Note: Different letters within columns present significant differences ($p < .05$).
treatment at 600 MPa, the area mean diameter was 125.1 nm, indicating the increased number of small particles. These results were in agreement with the results reported by Anema (2008), who reported the particle size of casein was decreased after 600 MPa of pressure treatment (Anema, 2008). Smaller particle size can lead to a more stable emulsion (Samavati, Razavi, & Mousavi, 2008), showing the pressurized-AHSG emulsions might be more stable than the native AHSG.

The centrifugation assay is a rapid procedure for the evaluation of emulsion stability. Based on Stokes’ law, the stability of the emulsion to gravitational separation can be increased by increasing the viscosity of the aqueous continuous phase (McClements, 2015). Hydrocolloids could improve the viscosity of aqueous continuous phase and precipitate or absorb onto oil droplets. The food gums could form a solid-like structure and thicker stabilizing layer and protects oil droplets against flocculation and coalescence by modifying the rheological behavior of the aqueous phase between dispersed particles or droplets (Dickinson, 2003; Huang, Kakuda, & Cui, 2001; Imeson, 2000). Emulsion stability of pressurized-AHSG as a function of high pressure level was shown in Table 1. The result was shown that the emulsion contains pressurized-AHSG can be stable at all tested conditions during centrifugation. As the pressure level increased, the particle size and viscosity of the AHSG dispersions decreased and increased, respectively. Therefore, enhancing the pressure level increases the emulsion stability of AHSG. According to our observations, the size of gum particle had a direct effect on viscosity and lower particle size of AHSG improved viscosity of continuous phase and imparted more emulsion stability. The highest increase in emulsion stability was observed for emulsions containing 1% AHSG treated at 600 MPa, which increased emulsion stability by 27% compared to the control sample (Table 2). This result demonstrated that rheological characteristics are not the reason for the stability of AHSG emulsion merely. Therefore, the stability of an emulsion can also be affected by the size of the gum particle.

3.3 | Effect of HHP on foam stabilization of AHSG

Foam colloidal systems contain gas bubbles that are randomly dispersed in an aqueous phase. Instability of foams arises when the bubbles tend to join and create large bubbles. This coalescence phenomenon is accelerated by drainage of water between the bubbles (Kalsbeek & Prins, 1999). Hydrocolloids could improve foam stability by thickening or gelling roles (Dickinson, 2010). These impart positive effects on foaming properties in foods because of their high viscosity (Mott, Hettiarachchy, & Qi, 1999; Xie & Hettiarachchy, 1998). As shown in Figure 5, the effect of the hydrostatic pressure level was significant ($p < .05$) on the foam stability of pressurized-AHSG. As hydrostatic pressure increased up to 600 MPa, foam stability of pressurized-AHSG increased gradually. The highest foam stability of pressurized-AHSG was obtained at the maximum pressure level of 600 MPa which had the highest consistency coefficient. The viscosity of pressurized-AHSG dispersions was highly correlated with foam stability ($r = 0.96, p < .001$) (data not shown). The foam stability of pressurized-AHSG at the hydrostatic pressure of 600 MPa was 40% better than that of 0.101 MPa. Hence, pressurized-AHSG has the potential to be applied in foods to modify foaming properties due to its appropriate foaming stability and relatively high viscosity.

4 | CONCLUSION

The high pressure processing, as an economical and environmentally friendly technology, has many applications in the food industry (preservation, color and nutritional maintenance, functional properties modifications) (Tan, 1990). In this study, it was experimentally proved that it is possible to apply HHP to change the rheological and functional properties of AHSG. The particle size of AHSG emulsion decreased steadily with increasing pressure. The maximum particle size reduction was observed at a pressure of 600 MPa. The results showed also that the emulsion stability was challenged after HHP treatment since particle size plays a predominant role in deciding the emulsion stability. The results represented that the pressurized-AHSG showed more emulsion and foam stability. The storage and loss moduli of pressurized-AHSG were higher than those of non-pressurized-AHSG. The pressurized-AHSG showed shear-thinning behavior with yield stress which described by Herschel–Bulkley model. It was indicated that pressure level and concentration have a profound effect on $n$, $k$, and yield stress of AHSG. The HHP intensified the pseudoplasticity of AHSG which causes to make a supreme mouthfeel in the foods contain it. Regarding the change of the rheological and functional characteristics of AHSG, HHP treatment at 600 MPa for 30 min would be recommended to improve these properties. The promising findings of this work should encourage further research on using HHP or combining with other emerging technologies to improve the rheological and functional properties of hydrocolloids.
ACKNOWLEDGMENT
This research was supported by the Research Grant from Yasuj University of Medical Sciences of Iran.

ORCID
Sajad Ghaderi https://orcid.org/0000-0002-9522-938X
Mohammad Ali Hesarinejad https://orcid.org/0000-0002-2799-6982

REFERENCES
Ahmed, J., & Ramaswamy, H. S. (2004). Effect of high-hydrostatic pressure and concentration on rheological characteristics of xanthan gum. Food Hydrocolloids, 18, 367–373. https://doi.org/10.1016/S0268-005X(03)00123-1
Ahmed, J., Ramaswamy, H. S., Alli, I., & Ngadi, M. (2003). Effect of high pressure on rheological characteristics of liquid egg. LWT - Food Science and Technology, 36, 517–524. https://doi.org/10.1016/S0022-6438(03)00050-1
Ahmed, J., Ramaswamy, H. S., Ayad, A., Alli, I., & Alvarez, P. (2007). Effect of high-pressure treatment on rheological, thermal and structural changes in Basmati rice flour slurry. Journal of Cereal Science, 46, 148–156. https://doi.org/10.1016/j.jcereal.2007.01.006
Ahmed, J., Ramaswamy, H. S., & Hiremath, N. (2005). The effect of high pressure treatment on rheological characteristics and colour of mango pulp. International Journal of Food Science & Technology, 40, 885–895. https://doi.org/10.1111/j.1365-2621.2005.01026.x
Alaeddini, B., Koocheki, A., Mohammadzadeh Milani, J., Razavi, S. M. A., & Ghanbarzadeh, B. (2017). Steady and dynamic shear rheological behavior of semi dilute Alyssum homolocarpum seed gum solutions: Influence of concentration, temperature and heating/cooling rate. Journal of the Science of Food and Agriculture, 97, 1807–1817. https://doi.org/10.1002/jsfa.7501
Alizadeh Behbahani, B., Tabatabaee Yazdi, F., Shahidi, F., Hesarinejad, M. A. M. A., Mortazavi, S. A. S. A., Mohebbi, M., ... Mohebbi, M. (2017). Plantago major seed mucilage: Optimization of extraction and some physicochemical and rheological aspects. Carbohydrate Polymers, 155, 68–77. https://doi.org/10.1016/j.carbpol.2016.08.051
Alvarez, P. A., Ramaswamy, H. S., & Ismail, A. A. (2008). High pressure gelation of soy proteins: Effect of concentration, pH and additives. Journal of Food Engineering, 88, 331–340.
Amin, G. H. (2005). Medicinal plants of Iran (p. 106), Tehran, Iran Tehran Univ. Publ.
Anema, S. G. (2008). Effect of milk solids concentration on whey protein denaturation, particle size changes and coagulation of casein in high-pressure-treated skim milk. International Dairy Journal, 18, 228–235. https://doi.org/10.1016/j.idairyj.2007.08.009
Anvari, M., Tabarsa, M., Cao, R., You, S., Joyner, H. S., Behnam, S., & Rezaei, M. (2016). Compositional characterization and rheological properties of an anionic gum from Alyssum homolocarpum seeds. Food Hydrocolloids, 52, 766–773. https://doi.org/10.1016/j.foodhyd.2015.07.030
Belmilo, R. H., Tribst, A. A. L., & Cristianini, M. (2018). Application of high-pressure homogenization on gums. Journal of the Science of Food and Agriculture, 98, 2060–2069. https://doi.org/10.1002/jsfa.8695
Daher, D., Le Gourrierec, S., & Pérez-Lamela, C. (2017). Effect of high pressure processing on the microbial inactivation in fruit preparations and other vegetable based beverages. Agriculture, 7, 72.
Dickinson, E. (2003). Hydrocolloids at interfaces and the influence on the properties of dispersed systems. Food Hydrocolloids, 17, 25–39. https://doi.org/10.1016/S0268-005X(01)00120-5
Dickinson, E. (2010). Food emulsions and foams: Stabilization by particles. Current Opinion in Colloid & Interface Science, 15, 40–49. https://doi.org/10.1016/j.cocis.2009.11.001
Ferragut, V., Hernández-Herrero, M., Veciana-Nogués, M. T., Borras-Suarez, M., González-Linares, J., Vidal-Carou, M. C., & Guamin, B. (2015). Ultra-high-pressure homogenization (UHPH) system for producing high-quality vegetable-based beverages: Physicochemical, microbiological, nutritional and toxicological characteristics. Journal of the Science of Food and Agriculture, 95, 953–961.
Franchi, M. A., Tribst, A. A. L., & Cristianini, M. (2013). High-pressure homogenization: A non-thermal process applied for inactivation of spoilage microorganisms in beer. Journal of the Institute of Brewing, 119, 237–241.
Hamza-Chaffai, A. (1990). Effect of manufacturing conditions on rheology of banana gelified milk: Optimization of the technology. Journal of Food Science, 55, 1630–1633.
Hesarinejad, M. A. M. A., Koocheki, A., & Razavi, S. M. A. S. M. A. (2014). Dynamic rheological properties of Lepidium perfoliatum seed gum: Effect of concentration, temperature and heating/cooling rate. Food Hydrocolloids, 35, 583–589.
Hesarinejad, M. A., Razavi, S. M. A., & Koocheki, A. (2015). Alyssum homolocarpum seed gum: Dilute solution and some physicochemical properties. International Journal of Biological Macromolecules, 81, 418–426. https://doi.org/10.1016/j.ijbiomac.2015.08.019
Hesarinejad, M. A., Razavi, S. M. A., & Koocheki, A. (2015). The viscoelastic and thermal properties of Qodume shirazi seed gum (Alyssum homolocarpum), Iran. Food Science and Technology Research Journal, 1394, 116–128.
Hesarinejad, M. A., Sami Jokandian, M., Mohammadifar, M. A., Koocheki, A., Razavi, S. M. A., Ale, M. T., & Attar, F. R. (2018). The effects of concentration and heating-cooling rate on rheological properties of Plantago lanceolata seed mucilage. International Journal of Biological Macromolecules, 115, 1260–1266. https://doi.org/10.1016/j.ijbiomac.2017.10.102
Hesarinejad, M. A., Shekarforoush, E., Attar, F. R., & Ghaderi, S. (2019). The dependency of rheological properties of Plantago lanceolata seed mucilage as a novel source of hydrocolloid on mono- and di-valent salts. International Journal of Biological Macromolecules, 147, 1278–1284. https://doi.org/10.1016/j.ijbiomac.2019.10.093
Huang, X., Kakuda, Y., & Cui, W. (2001). Hydrocolloids in emulsions: Particle size distribution and interfacial activity. Food Hydrocolloids, 15, 533–542.
Imeson, A. P. (2000). Carrageenan, Handbook Hydrocolloids. 87–102.
Karazhiyan, H., Razavi, S. M. A., Phillips, G. O., Fang, Y., Al-Assaf, S., & Nishinari, K. (2011). Physicochemical aspects of hydrocolloid from the seeds of Lepidium sativum. International Journal of Food Science & Technology, 46, 1066–1072. https://doi.org/10.1111/j.1365-2621.2011.02583.x
Knorr, D., Heinz, V., & Buckow, R. (2006). High pressure application for food biopolymers. Biochimica et Biophysica Acta (BBA) - Proteins and Proteomics, 1764, 619–631. https://doi.org/10.1016/j.bbapap.2006.01.017
Koocheki, A., & Hesarinejad, M. A. (2019). Qodume Shirazi (Alyssum homolocarpum) Seed Gum. Emerging Natural Hydrocolloids Rheology and Functions, 205–223.
Koocheki, A., Mortazavi, S. A., Shahidi, F., Razavi, S., Kadkhodaee, R., & Milan, J. M. (2010). Optimization of mucilage extraction from Qodume shirazi seed (Alyssum homolocarpum) using response surface methodology. Journal of Food Process Engineering, 33, 861–882.
Koocheki, A., Mortazavi, S. A., Shahidi, F., Razavi, S. M. A., & Taherian, A. R. (2009). Rheological properties of mucilage extracted from Alyssum homolocarpum seed as a new source of thickening agent. Journal of Food Engineering, 91, 490–496. https://doi.org/10.1016/j.jfoodeng.2008.09.028
Koocheki, A., & Razavi, S. M. A. (2009). Effect of concentration and temperature on flow properties of Alyssum homolocarpum seed gum solutions: Assessment of time dependency and thixotropy. Food Biophysics, 4, 353–364.
Koocheki, A., Razavi, S. M. A., & Hesarinejad, M. A. (2012). Effect of extraction procedures on functional properties of enuca sativa seed mucilage. Food Biophysics, 7(1), 84–92. https://doi.org/10.1007/s11483-011-9245-9

Laneuville, S. I., Turgeon, S. L., & Paquin, P. (2013). Changes in the physical properties of xanthan gum induced by a dynamic high-pressure treatment. Carbohydrate Polymers, 92, 2327–2336. https://doi.org/10.1016/j.carbpol.2012.11.077

Ledward, D. A. (1995). High pressure processing of foods. Nottingham University Press.

Li, W., Zhang, F., Liu, P., Bai, Y., Gao, L., & Shen, Q. (2011). Effect of high pressure to modify the functionality of food proteins. Food Hydrocolloids, 25, 2244(97)01015-7

Marcotte, M., Hoshahili, A. R. T., & Ramaswamy, H. S. (2001). Rheological properties of selected hydrocolloids as a function of concentration and temperature. Food Research International, 34, 695–703. https://doi.org/10.1016/S0963-9969(01)00091-6

McClements, D. J. (2015). Food emulsions: Principles, practices, and techniques. CRC Press.

Messens, W., Van Camp, J., & Huygebaert, A. (1997). The use of high pressure to modify the functionality of food proteins. Trends in Food Science & Technology, 8, 107–112. https://doi.org/10.1016/S0924-2244(97)01015-7

Molina, E., Papadopoulou, A., & Ledward, D. A. (2001). Emulsifying properties of high pressure treated soy protein isolate and 7S and 11S globulins. Food Hydrocolloids, 15, 263–269. https://doi.org/10.1016/S0268-005X(01)00023-6

Mott, C. L., Hettiarachchy, N. S., & Qi, M. (1999). Effect of xanthan gum on enhancing the foaming properties of whey protein isolate. Journal of the American Oil Chemists Society, 76, 1383–1386. https://doi.org/10.1007/s11746-999-0154-8

Olsen, K., & Orlien, V. (2016). High-Pressure Processing for Modification of Food Biopolymers. In K. Knoerzer, P. Juliano, & G. Smithers (Eds.), Innov. Food Process. Technol. (pp. 291–313). Cambridge, UK: Woodhead Publishing Limited.

Paneteloglou, A. G., Bell, A. E., & Ma, F. (2010). Effect of high-hydrostatic pressure and pH on the rheological properties of gum arabic. Food Chemistry, 122, 972–979. https://doi.org/10.1016/j.foodchem.2010.02.037

Pei-Ling, L., Xiao-Song, H., & Qun, S. (2010). Effect of high hydrostatic pressure on starches: A review. Starch-Stärke, 62, 615–628. https://doi.org/10.1002/star.201000001

Pinho, C. R. G., Oliveira, M. M., Leite Júnior, B. R. C., Tribst, A. A. L., & Cristianini, M. (2015). Inactivation of Pseudomonasfluorescens, Listeria innocua and Lactobacillus helveticus in skimmed milk processed by high pressure homogenization. International Food Research Journal, 22.

Porretta, S., Birzi, A., Ghizzoni, C., & Vicini, E. (1995). Effects of ultra-high hydrostatic pressure treatments on the quality of tomato juice. Food Chemistry, 52, 35–41. https://doi.org/10.1016/0308-8146(94)P4178-1

Samavati, V., Razavi, S. H., & Mousavi, S. M. (2008). Effect of sweeteners on viscosity and particle size of dilute guar gum solutions. Iranian Journal of Chemistry & Chemical Engineering, 27, 23–31.

Sciarini, L. S., Maldonado, F., Ribotta, P. D., Pérez, G. T., & León, A. E. (2009). Chemical composition and functional properties of Gleditsia triacanthos gum. Food Hydrocolloids, 23, 306–313. https://doi.org/10.1016/j.foodhyd.2008.02.011

Steffe, J. F. (1996). Rheological methods in food process engineering. Freeman Press.

Sun, A., & Gunasekaran, S. (2009). Yield stress in foods: Measurements and applications. International Journal of Food Properties, 12, 70–101. https://doi.org/10.1080/1094210802308502

Tan, C. T. (1990). Beverage emulsions. In K. Larsson, & S. E. Friberg (Eds.) Beverage Emuls (2nd ed., pp. 445–478), New York: Dekker.

Van Kalsbeek, H., & Prins, A. (1999). Department of Food Technology and Nutritional Sciences, Food Physics Group, Wageningen Agricultural University, Po Box 8129, 6700 EV Wageningen, The Netherlands, Food Emuls. Foam. Interfaces, Interact. Stab, 91.

Van Vliet, T., & Walstra, P. (1980). Relationship between viscosity and fat content of milk and cream. Journal of Texture Studies, 11, 65–68. https://doi.org/10.1111/j.1745-4603.1980.tb00308.x

Vatankhah, H., Taherian, A. R., & Ramaswamy, H. S. (2018). High-pressure induced thermo-viscoelasticity and dynamic rheology of gum Arabic and chitosan aqueous dispersions. LWT-Food Science Technology, 89, 291–298. https://doi.org/10.1016/j.lwt.2017.10.059

Venugopal, K. N., & Abhilash, M. (2010). Study of hydration kinetics and rheological behaviour of guar gum. International Journal of Pharmaceutical Sciences Research, 1, 28–39.

Xie, Y. R., & Hettiarachchy, N. S. (1998). Effect of xanthan gum on enhancing the foaming properties of soy protein isolate. Journal of the American Oil Chemists Society, 75, 729–732. https://doi.org/10.1007/s11746-998-0214-5

Xue, S., Xu, X., Shan, H., Wang, H., Yang, J., & Zhou, G. (2018). Effects of high-intensity ultrasound, high-pressure processing, and high-pressure homogenization on the physicochemical and functional properties of myofibrillar proteins. Innovative Food Science & Emerging Technologies, 45, 354–360. https://doi.org/10.1016/j.ifset.2017.12.007

How to cite this article: Ghaderi S, Hesarinejad MA, Shekarforoush E, Mirzababae SM, Karimpour F. Effects of high hydrostatic pressure on the rheological properties and foams/emulsions stability of Alyssum homolocarpum seed gum. Food Sci Nutr. 2020;8:5571–5579. https://doi.org/10.1002/fsn3.1834