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Original research

Estimating flow behavior of microwave-treated Wild sage seed gum dispersions using various flow behavior models

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ABSTRACT

This study aimed to analyze the influence of microwave treatment (MT) at various time intervals on the viscosity and flow behavior of Wild sage seed gum (WSSG) dispersion (0.2%, w/v). The flow behavior of WSSG dispersions were calculated from the resulting flow curves using four flow behavior models (Power law (PL), Bingham, Herschel-Bulkley (HB), and Casson). The fit quality of the selected models was evaluated using correlation coefficient (r), sum of squared error (SSE), and root mean square error (RMSE). It was observed that the apparent viscosity of WSSG dispersion reduced from 68 mPa.s to 19 mPa.s as the shear rate (SR) increased from 12.2 s^{-1} to 171.2 s^{-1}. Additionally, the apparent viscosity of the samples reduced from 34 mPa.s to 28 mPa.s as the MT time increased from 0 to 3 min (SR=49 s^{-1}). The HB model, which is a combination of Bingham and PL models, fitted the data very well with an overall r of more than 0.9990 and, SSE and RMSE values of lower than 0.0123, and, 0.0310, respectively, therefore, used to describe the shear stress (SS) and apparent viscosity of WSSG dispersions. The consistency coefficient of WSSG dispersion decreased significantly from 0.185 $Pa.s^n$ to 0.155 $Pa.s^n$ ($p<0.05$) with increasing MT time from 0 to 3 min. Also, the flow behavior index (PL and HB models) of dispersions increased as the MT time increased.

Keywords: Casson; Herschel-Bulkley; Microwave; Power law; Wild sage seed gum

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1. Introduction

Hydrocolloid, a term rooted in the Greek ‘hydro’ for water and ‘kolla’ for glue, encompasses a broad spectrum of high molecular weight, hydrophilic molecules (Zang et al., 2024). Hydrocolloids are one of the commonly used ingredients in the food industry to enhance final product quality, to improve food texture. They are well established as thickening additives, as gelling agents or to stabilize dispersions and solutions (Russ et al., 2014; Poçan and Çıkrıkcı Erünsal, 2024). Mucilage gums are natural adhesive polysaccharides, obtained from seeds or delicate stems of plants. All of mucilages are anionic polysaccharides with similar structures to some exudates gums. The increasing tendency to utilize them in specific food formulations is due to their great techno-functional characteristics (emulsifying, stabilizing, gelling, and thickening features) and their bioactive impacts in treatment of specific diseases (Sarabi-Aghdam et al., 2021). Wild sage seed gum (WSSG) is a hydrocolloid extracted from the seeds of *Salvia macrosiphon* L. Wild sage gum contains a mucilage layer that can be utilized in edible coatings for fruits and vegetables. The seeds of the sage plant serve as the source of this gum, which has been proven effective in creating a semi-permeable barrier to CO_2 and O_2. Also, this gum is good for making food thicker and keeping it stable (Salehi and Inanloodoghouz, 2023; Mohammadi et al., 2024).

Microwave technology has been widely used in food processing and consumption industries for various purposes. Unlike conventional heating methods, microwave heating has characteristics such as low cost, short start-up time, high heating rate, and efficiency (Wu and Xu, 2023). Microwave heating transfers energy via two mechanism: dipole rotation and ionic conduction

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which displace charged ions present in the solute via the solvent (Routray and Orsat, 2012). Microwave treatment (MT) is effective in changing the hydrocolloids' structure and improving their functional properties (Luo et al., 2006; Chandrasekaran et al., 2013; Yang et al., 2017; Zhong et al., 2021).

The viscosity and flow behavior of hydrocolloids is influenced by various intrinsic factors such as structural features, concentration, average molecular weight, molecular weight distribution, solubility, as well as extrinsic factors like pH, temperature, processing steps, food matrix characteristics (Akçay and Alkan, 2023). So, this manuscript gives information about WSSG dispersion physical properties changes after microwave treatment (MT) including viscosity and flow behavior.

2. Material and Methods

2.1. Gum extraction

The extraction of WSSG was performed according to method explained by Salehi and Inanloodoghouz (2023). The Wild sage seeds were put in water for 20 minutes at a temperature of 25°C, using 1 part of the seeds for every 20 parts of water. The WSSG was taken out from the seeds by using a machine called an extractor (FJ-479, Tulips, Iran). The extracted gum was dehydrated in an oven (Shimaz, Iran) with air blowing at 60°C and then the gum powder was ground, packaged, and stored in a cool and dry place. The WSSG powder was mixed with distilled water to make a dispersion (0.2%, w/v), using a stirrer.

2.2. Microwave treatment (MT)

To use the microwave to treat the WSSG, a microwave device (Gplus, Model; GMW-M425S.MIS00, Goldiran Industries Co., Iran) was employed. In this work, the impact of the MT time at four levels of 0, 1, 2, and 3 min, using a power of 440W, on the WSSG dispersion was examined.

2.3. Apparent viscosity

The flow behavior measurements were performed with a DV2T-RV viscometer (Brookfield, USA) using UL Adapter Kit. After each MT, the flow behavior of non-treated and microwave treated WSSG dispersion were measured. The apparent viscosity and shear stress (SS) of WSSG dispersions (0.2%, w/v) at various shear rates (12.2-171.2 s^{-1}) were measured (Salehi and Inanloodoghouz, 2024). The temperature of the WSSG dispersion was set at 20°C during viscosity measurement. The viscosity value was the average of three measurements.

2.4. Data analysis

A flow model may be considered to be a mathematical equation that can describe rheological data, such as shear rate versus shear stress, in a basic shear diagram, and that provides a convenient and concise manner of describing the data (Rao, 2007). The flow behavior data were fitted using several models including Power law (PL), Bingham, Herschel-Bulkley (HB), and Casson models. These models are common ways of representing the behavior of several gum dispersion. The PL and HB models were used to estimate consistency coefficient (k-value) and flow behavior index (n-value). The Bingham, HB and Casson models were used to estimate yield stress. In addition, plastic viscosity was estimated by the Bingham and Casson models (Salehi and Inanloodoghouz, 2023; Salehi et al., 2023b). In this research, these models were used to match the SS and shear rates (SR) results of the non-treated and microwave-treated WSSG dispersion. The experimental results were correlated for ease of use in flow behavior studies while maintaining appropriate accuracy using the function cftool (Curve Fitting Tool) in Matlab software (version R2012a). Correlation coefficient (r), sum of squared error (SSE), and root mean square error (RMSE) values were obtained to determine the best fitted model.

2.5. Statistical analysis

All measurements were carried out in triplicate in order to give statistically validated results and the data were expressed as mean ± SD. Statistical analysis was performed using one-way analysis of variance (ANOVA). SPSS 21 software was used to compare the mean value of different factors in Duncan's multiple range test ($p < 0.05$).

3. Results and Discussion

3.1. Apparent viscosity

Figure 1 displays how the viscosity of WSSG dispersion change when the shear is applied at different speeds. Viscosity curves representing the relationship between shear rate and apparent viscosity show a non-Newtonian behavior (shear thinning) at lower shear rate and subsequent Newtonian at higher shear rate for WSSG dispersion. The apparent viscosity of WSSG dispersion become less when it is stirred faster. The apparent viscosity reduced from 68 mPa.s to 19 mPa.s with the SR increased from 12.2 s^{-1} to 171.2 s^{-1} (non-treated dispersion). Salehi and Inanloodoghouz (2023) studied the flow behavior of ultrasonic-treated aqueous dispersion of WSSG. The finding of this study revealed that the apparent viscosity of aqueous dispersion of WSSG reduced with increasing SR, indicating the shear-thinning behavior of this aqueous dispersion.

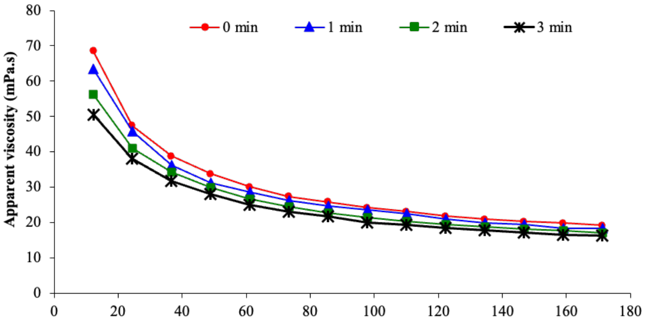

Fig. 1. Impact of microwave pretreatment on the apparent viscosity of Wild sage seed gum dispersions.

In addition, the influence of MT on the apparent viscosity of WSSG dispersion is shown in Figure 1. The MT of WSSG dispersion reduces its viscosity. This behavior was observed under all conditions and after 3 min of pretreatment, resulting in a significant decrease in gum viscosity. The results show that when the MT time is increased from 0 to 3 min, the apparent viscosity of the WSSG dispersion reduced from 34 mPa.s to 28 mPa.s (SR=49 s^{-1}). MT reduces the viscosity, which is likely due to molecular rearrangement limited to a portion of the hydrocolloid molecules (Luo et al., 2006). The effect of MT on acid hydrolysis of faba bean starch was examined by González-Mendoza et al. (2022). The finding of this study revealed that the lowest viscosity values for starch were achieved when combining more severe hydrochloric acid and microwave energy conditions.

3.2. Mathematical modeling

The flow behavior of WSSG dispersion was effectively modeled using the PL, Bingham, HB, and Casson models, and the HB model was found as the better model to describe the flow behavior of WSSG dispersion. Figure 2 shows the fit of flow behavior equations to the experimental SS data. This figure shows that the HB equation is suitable in predicting the relationships between SS and SR data of microwave-treated WSSG dispersion.

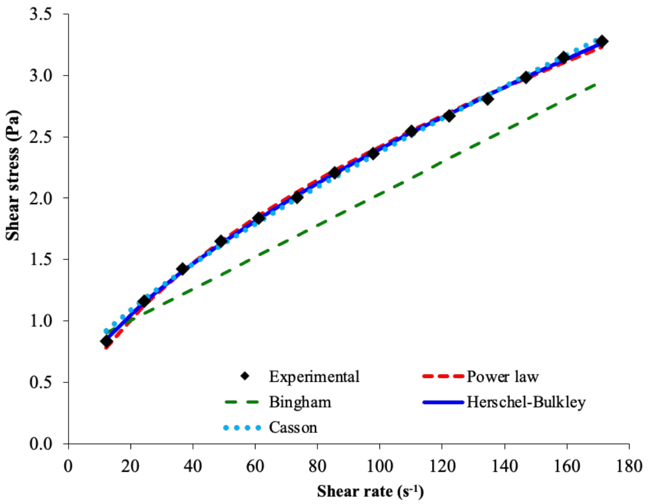

Fig. 2. Fitting ability of various rheological equations to experimental data.

3.3. Power law (PL) model

In the modeling process, the basic relationships have numbers that are found by matching them to real test results (Mullineux and Simmons, 2008). The PL model showed an excellent performance with the highest r-value (higher than 0.9987) and the lowest SSE values (lower than 0.0160) and RMSE values (lower than 0.0343) for all gum dispersion (Table 1). The PL was suggested to be the appropriate equation to depict the flow behavior of numerous gum dispersion (Xuewu et al., 1996; Song et al., 2006).

The impact of MT on the k-value of WSSG dispersion is reported in Figure 3. The k-value of WSSG dispersion significantly decreased from 0.185 $Pa.s^n$ to 0.155 $Pa.s^n$ ($p<0.05$) with increasing MT time from 0 to 3 min.

The shear-thinning behavior can be quantified by fitting the apparent viscosity vs shear rate curves using standard PL flow model (Liu et al., 2022). The PL equation shows that a fluid with shear-thinning behavior has a value of n less than 1 (Kumar et al., 2021). The impact of MT on the n-value of WSSG dispersion is reported in Figure 3. The flow behavior index (n-value) of WSSG dispersion increased from 0.556 to 0.564, but there was no significant difference between the values while the duration of MT increased. The alteration within the k-value and n-value of the WSSG dispersion may be due to the structural change of the gum during MT. Microwave energy is known to induce a series of physico-chemical reactions that lead to changes in the functional properties of gums in liquid food systems.

Table 1. Values of statistical parameters of Power law, Bingham, Herschel-Bulkley, and Casson models for estimating shear stress data.

Model name	Microwave treatment time (min)	Sum of squared error (SSE)	Correlation coefficient (r)	Root mean square error (RMSE)
Power law	0	0.0071	0.9995	0.0233
	1	0.0160	0.9987	0.0343
	2	0.0061	0.9995	0.0222
	3	0.0082	0.9993	0.0248
Bingham	0	0.1145	0.9917	0.0977
	1	0.1061	0.9915	0.0939
	2	0.0979	0.9922	0.0903
	3	0.0838	0.9928	0.0827
Herschel-Bulkley	0	0.0030	0.9998	0.0164
	1	0.0123	0.9990	0.0310
	2	0.0040	0.9997	0.0187
	3	0.0042	0.9996	0.0194
Casson	0	0.0213	0.9986	0.0417
	1	0.0284	0.9977	0.0483
	2	0.0209	0.9987	0.0417
	3	0.0187	0.9984	0.0384

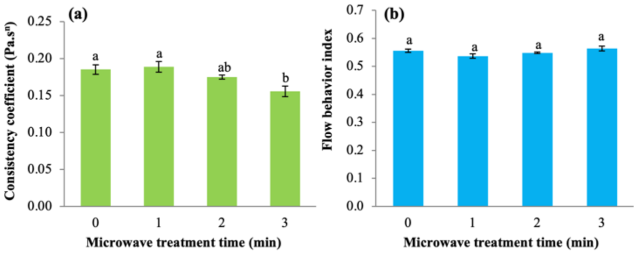

Fig. 3. Impact of microwave treatment on the consistency coefficient (a) and flow behavior index (b) of Wild sage seeds gum solution (Power law model). Data are shown as mean ± standard deviation (N = 3). Different letters above the columns indicate a significant difference ($p<0.05$).

3.4. Bingham model

The experimental values of SS versus SR for non-treated and treated WSSG dispersion were fitted to the Bingham model and the constant coefficients of this equation were calculated. The values of SSE, r, and RMSE for prediction of flow behavior of WSSG dispersion were between 0.0838 and 0.1145, 0.9915 and 0.9928, and 0.0827 and 0.0977, respectively Table 1.

The impact of MT on the Bingham yield stress parameter (τ_{0B}) of WSSG dispersion is reported in Figure 4. The Bingham yield stress parameter of WSSG dispersion in MT time of 0-2 min doesn't have significant differences and in MT time of 3 min it is significantly less than the 0 min and 1 min treatment. This parameter significantly decreased from 0.773 Pa to 0.692 Pa ($p<0.05$) with increasing MT time from 0 to 3 min. In addition, the impact of MT on the Bingham plastic viscosity (η_B) of WSSG dispersion is reported in Figure 4. The Bingham plastic viscosity of WSSG dispersion decreased from 0.014 Pa.s to 0.013 Pa.s while the duration of MT increased.

3.5. Herschel-Bulkley (HB) model

The experimental values of SS versus SR for non-treated and treated WSSG dispersion were fitted to the HB model and the constant coefficients of this equation were calculated. The values of SSE, r, and RMSE for prediction of flow behavior of WSSG dispersion ranged from 0.0030-0.0123, 0.9990-0.9998, and 0.0164-0.0310, respectively Table 1. Based on the HB model, all WSSG dispersion demonstrated shear-thinning behavior, described by the n-value (n_H) lower than 0.708 (Figure 5). The results of HB model showed that the values of the yield stress were between 0.150 Pa and 0.197 Pa.

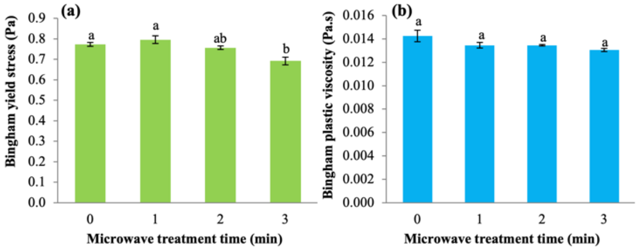

Fig. 4. Impact of microwave treatment on the Bingham yield stress (a) and Bingham plastic viscosity (b) parameters of Wild sage seeds gum solution (Bingham model). Data are shown as mean ± standard deviation (N = 3). Different letters above the columns indicate a significant difference ($p<0.05$).

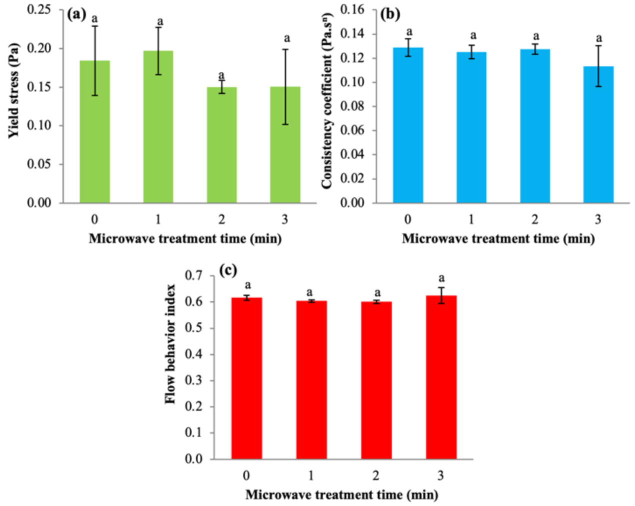

Fig. 5. Impact of microwave treatment on the yield stress (a), consistency coefficient (b), and flow behavior index (c) parameters of Wild sage seeds gum solution (Herschel-Bulkley model). Data are shown as mean ± standard deviation (N = 3). Different letters above the columns indicate a significant difference ($p<0.05$).

The impact of MT on the k-value of WSSG dispersion is reported in Figure 5. The k-value of WSSG dispersion reduced from 0.129 Pa.s^n to 0.113 Pa.s^n with increasing MT time from 0 to 3 min. In addition, the impact of MT on the n-value of WSSG dispersion is reported in Figure 5. The n-value of WSSG dispersion increased from 0.616 to 0.625 (decreases in shear-thinning behavior) while the duration of MT increased.

3.6. Casson model

The experimental values of SS versus SR for non-treated and treated WSSG dispersion were fitted to the Casson model and the constant coefficients of this equation were calculated. The values of SSE, r, and RMSE for prediction of flow behavior of WSSG dispersion were between 0.0187 and 0.0284, 0.9977 and 0.9987, and 0.0384 and 0.0483, respectively (Table 1).

Microwave technology for heating of foods is common in homes and are becoming more common in industrial applications (Salehi et al., 2023a). The impact of MT on the Casson yield stress (τ_{0C}) of WSSG dispersion is reported in Figure 6. The Casson yield stress of WSSG dispersion in MT time of 0-2 min doesn't have significant differences and in MT time of 3 min it is less than the other times. This parameter significantly reduced from 0.377 Pa to 0.317 Pa ($p<0.05$) with increasing MT time from 0 to 3 min. In addition, the impact of MT on the Casson plastic viscosity (η_C) of WSSG dispersion is reported in Figure 6.

The decrease in Casson plastic viscosities from time 0 to 3 min was not continuous. It decreased significantly in MT of 1 min and there was no significant difference in Casson plastic viscosities from 1 to 3 minutes. The Casson plastic viscosity of WSSG dispersion decreased significantly from 0.092 Pa.s to 0.086 Pa.s ($p<0.05$) while the duration of MT increased.

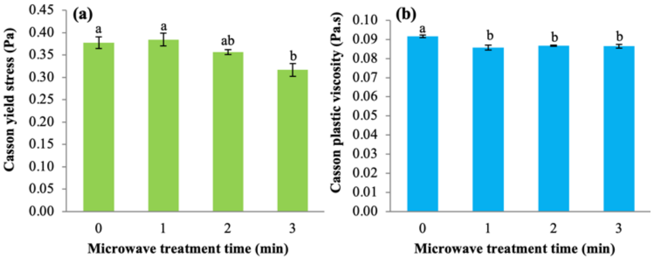

Fig. 6. Impact of microwave treatment on the Casson yield stress (a) and Casson plastic viscosity (b) parameters of Wild sage seeds gum solution (Casson model). Data are shown as mean ± standard deviation (N = 3). Different letters above the columns indicate a significant difference ($p<0.05$).

4. Conclusion

Dispersion of WSSG has high viscosity and exhibits shear-thinning behavior. In the current study, the impact of MT on the flow behavior of WSSG dispersion was investigated. WSSG dispersion showed the shear-thinning flow behavior. The MT of WSSG dispersion reduces its viscosity. The finding of this study revealed that the HB model became the most accurate model to show the flow behavior of WSSG dispersion compared to three other confirmed flow behavior models with RMSE values between 0.015 and 0.046. The k-value values (PL and HB models) of the samples decreased when the MT time was increased to 3 min. The highest n-value (PL and HB models) was for the dispersion treated in the microwave for 3 min.

Acknowledgments

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Conflict of interest

The authors declare that there is no conflict of interest.

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