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Research article

Use of Microwave for Change in Rheological Properties of Balangu Seed Mucilage

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Abstract

Aqueous solutions of Balangu seeds mucilage (BSM) have high viscosity and exhibit pseudoplastic behavior. The purpose of this study was to analyze the impact of microwave treatment at different time intervals on the rheological behavior of BSM solutions. The study's findings revealed that the apparent viscosity of BSM solution (non-treated solution) reduced from 0.044 Pa.s to 0.015 Pa.s as the shear-rate (SR) raised continuously from 12.2 s^{-1} to 171.2 s^{-1}. Additionally, the apparent viscosity of the BSM solutions reduced from 0.029 Pa.s to 0.026 Pa.s as the microwave exposure time increased from 0 to 3 min (SR=37 s^{-1}). The power law rheological model showed a good performance with the maximum correlation coefficient (>0.9984), and the minimum sum of squared error (SSE) values (<0.0107) and root mean square error (RMSE) values (<0.0298) for all mucilage solutions. The consistency coefficient of BSM solution increased significantly from 0.130 $Pa.s^n$ to 0.153 $Pa.s^n$ ($p<0.05$) with increasing microwave exposure time from 0 to 3 min. The flow behavior index of BSM solutions reduced significantly from 0.577 to 0.512 ($p<0.05$) as the microwave treatment time increased. The results of Casson model showed that the values of the Casson yield stress were between 0.2475 Pa and 0.3294 Pa, and the Casson plastic viscosity were between 0.0666 Pa.s and 0.0845 Pa.s. In total, microwave treatment changed the rheological parameters and reduced the viscosity of BSM.

Keywords: Balangu seed mucilage; Casson model; Microwave; Plastic viscosity; Power law.

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1. Introduction

Plant seed mucilages are complex polysaccharide polymers commonly used as plasticizers, emulsifiers, stabilizers, thickeners, gelling agents, binders and coatings, fat substitutes, flavor encapsulating agents, and carriers [1]. Balangu seed mucilage (BSM) is a hydrocolloid extracted from the seeds of *Lallemantia royleana* L. This mucilage is good for making food thicker and keeping it stable. Besides, this mucilage is a good choice for use in food products. This mucilage performs very well compared to some commercially available food grade gums. When this mucilage is mixed with water, it becomes thick (viscous fluid) and this gel-like substance becomes thin when stirred or shaken (pseudoplastic behavior) [2]. The BSM features many advantages over most of its polymer counterparts, including a lower production cost, higher efficiency, and better medicinal properties [3]. Impact of the Balangu and Basil seeds mucilages on physicochemical properties of part baked frozen Barbari bread was studied by Hejrani et al. [4]. Their results showed that the addition of Basil and Balangu to bread recipe could improve the crumb texture, specific volume, sensory properties, as well as the overall quality of the product during frozen storage, which removed the negative effects of the process conditions. Sadeghi-Varkani et al. [3] examined the feasibility of producing polysaccharide edible films from BSM as a new carbohydrate source. Their findings showed that the optimal BSM edible film exhibits mechanical, water vapour permeability, and oxygen permeability properties that were comparable to those of other popular polysaccharide edible films, making it a potential candidate for packaging applications.

The microwave field is an alternating electromagnetic field in which polar molecules and ions rearrange continuously, rub together and collide with surrounding molecules, producing a volumetric heating effect. Microwave technology has been widely applied in food processing because of its energy saving, high efficiency, and green processing [5-7]. Microwaves are absorbed in food materials, causing ionic polar molecules (primarily water) to rotate and collide, which result in rapid temperature increases. Microwave treatment can affect the structural and rheological properties of macromolecules [8]. The effect of microwave irradiation on the conformation and hydration properties of low-acetyl gellan gum was investigated by Yan et al. [9] to reveal the mechanism using experimental methods and molecular dynamics simulations. The experimental data showed that cross-sectional radius of gyration of the gellan chain treated by microwave or water bath were identical and microwave treatment could improve the water holding capability and restrict water mobility. Chen et al. [10] investigated the effect of microwave heating on gel properties of low-acetyl gellan and explored the potential mechanism of gelation behavior under microwave irradiation. Their study found that the microwave heating dramatically enhanced the gel strength, hardness of low-acetyl gellan. Further, the rheological analysis demonstrated that microwave heating increased the storage modulus and loss modulus values of gels compared to water bath-induced gels. The effect of microwave treatment (900 W and 1 min) on technological, physicochemical, rheological and microstructural properties of mango kernel starch was examined by Ramírez-Brewer et al. [11]. The findings revealed that after microwave treatment, the water absorption capacity and amylose content increased significantly.

This study looked at how using microwaves for a certain amount of time (ranging from 0 to 3 min) affected the flow behavior of BSM solution.

2. Materials and methods

2.1. Preparation of mucilage solution

Balangu seeds (also known as *Lallemantia royleana* L.) were checked and any dirt or other unwanted items were removed during the cleaning process. Then, the seeds were put in water for 20 minutes at a temperature of 25°C, using 1 part of seeds for every 20 parts of water [2]. The BSM was taken out from the seeds by using a machine called an extractor (FJ-479, Tulips, Iran). This machine has a rotating disc that scrapes the mucilage off the surface of the seeds. The solution was dehydrated in an oven (Shimaz, Iran) with air blowing at 60°C and then the mucilage powder was ground, packaged and stored in a cool, dry place. The BSM powder was dissolved in distilled water to make a solution (0.20%, w/v), using a stirrer.

2.2. Microwave treatment process

In recent years, microwave as an important processing method has attracted attention in the food field due to its high efficiency, high heating speed, and environmental friendliness [8]. In this study, to use the microwave to treat the BSM, a microwave device (Gplus, Model; GMW-

M425S.MIS00, Goldiran Industries Co., Iran) was employed [12]. In this study, the impact of the microwave exposure time at four intervals of 0, 1, 2, and 3 min, using a power of 440W, on the BSM solution was examined (Figure 1).

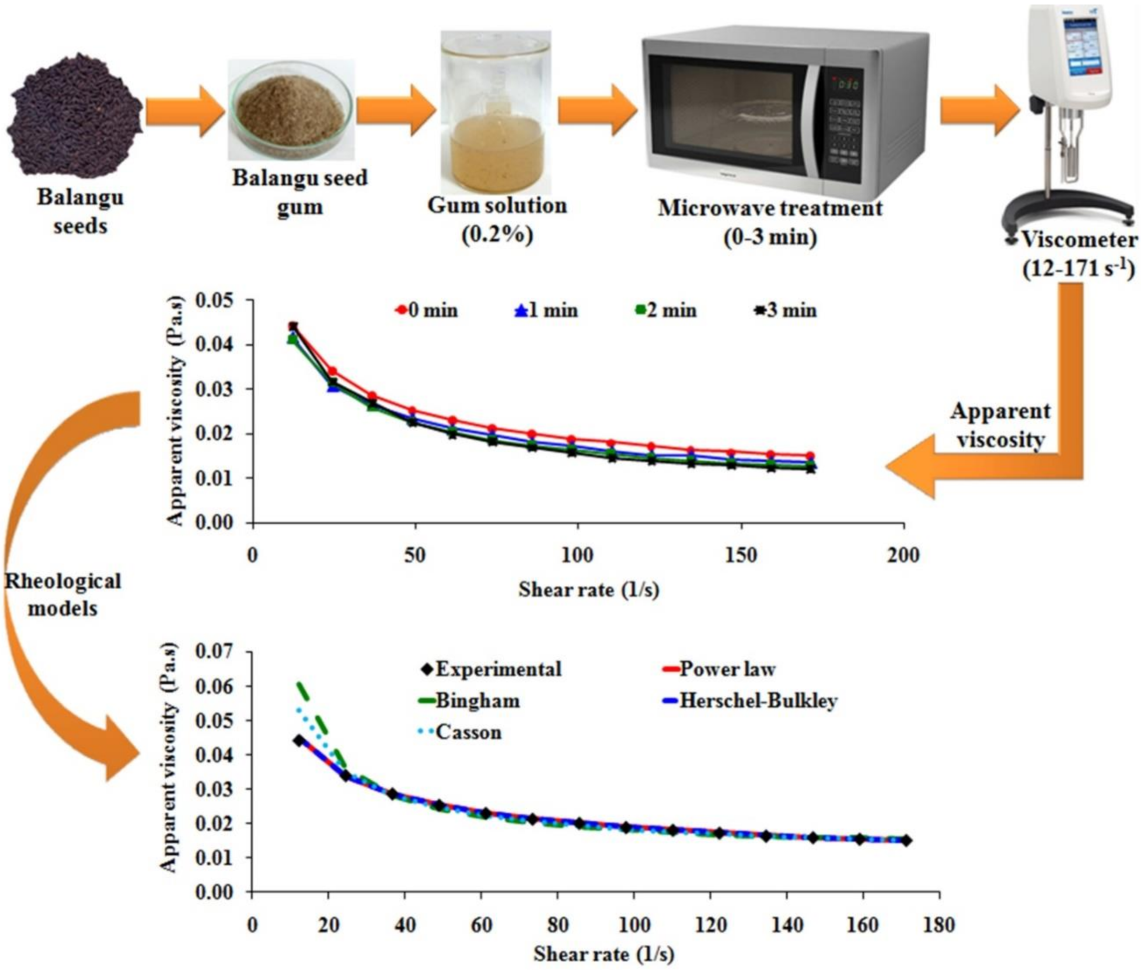

Fig. 1. Microwave treatment of Balangu seed mucilage solution.

2.3. Apparent viscosity

After each microwave treatment, the rheological properties and apparent viscosity of non-treated and microwave-treated BSM solutions were measured by a viscometer at 20°C (Brookfield, DV2T, RV, USA). A UL Adapter Kit was used to measure the apparent viscosity and shear-stress (SS) of BSM solutions at various shear-rate (SR) (12.2-171.2 s^{-1}) [13].

2.4. Mathematical modeling

Power law (PL), Bingham, Herschel-Bulkley, and Casson models are common equations of representing the behavior of a number of mucilage solutions [2, 14]. In this research, these models were utilized for fitting the experimental SS and SR results of the non-treated and microwave-treated BSM solutions. The test results were correlated for ease of use in rheological studies while maintaining appropriate accuracy using the function cftool (Curve Fitting Tool) in Matlab software (v. R2012a).

2.5. Statistical analysis

The results were evaluated in triplicate for each sample and presented as mean values and standard deviation. One-way analysis of variance (ANOVA) was performed on the results by SPSS statistics V. 21 software. Duncan’s procedure was used to evaluate the significant differences between these data ($p < 0.05$).

3. Results and discussion

3.1. Apparent viscosity

Figure 2 displays how the viscosity of BSM solution changes when the shear is applied at different speeds. It can be seen that the apparent viscosity of BSM solution becomes less when it is stirred faster. The apparent viscosity reduced obviously from 0.044 Pa.s to 0.015 Pa.s with the SR raised in a range of 12.2 s^{-1} to 171.2 s^{-1} (non-treated solution). Salehi and Inanloodoghouz [2] studied the rheological properties of ultrasonic treated aqueous solutions of BSM. The finding of this study revealed that the apparent viscosity of aqueous solutions of BSM reduced with enhancing SR, indicating shear-thinning behavior of this aqueous solution.

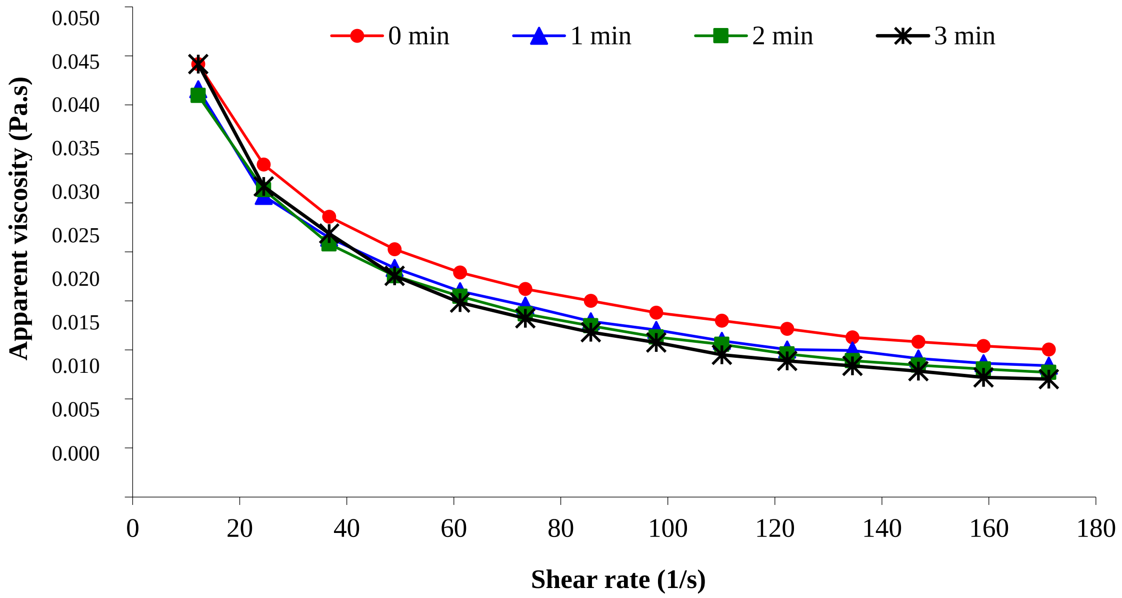

Fig. 2. Impact of microwave treatment on the apparent viscosity of Balangu seed mucilage solution.

Microwave is widely used in food for processes such as heating, sterilization, drying, and extraction, and can heat the whole material at the same time rather than using heat conduction from the outside to the inside [6]. The effect of microwave pretreatment on the apparent viscosity of BSM solutions was illustrated in Figure 2. The use of microwave to the BSM solution reduces its viscosity. This behavior was observed for all solutions and after 3 min of pretreatment, resulting in a significant decrease in solutions viscosity. The findings show that when the microwave exposure time increases from 0 to 3 min, the average apparent viscosity of the BSM solution reduced from 0.029 Pa.s to 0.026 Pa.s (SR=37 s^{-1}). Microwave treatment reduces the viscosity, which is likely due to molecular rearrangement limited to a portion of the hydrocolloids molecules [15]. The impact of microwave treatment on acid hydrolysis of faba bean starch was examined by González-Mendoza et al. [16]. The findings 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 behavior of food thickening agents can be influenced by temperature, quantity, and physical state. The flow behavior of BSM solution was effectively modeled using the

PL, Bingham, Herschel-Bulkley, and Casson models, and the PL model proved to be a suitable equation to describe the flow behavior of the BSM solutions. Figure 3 shows the fit of rheological equations to the actual data. This figure shows that both the PL and Herschel-Bulkley equations can equally predict the relationship among SS and SR data for microwave-treated BSM solutions.

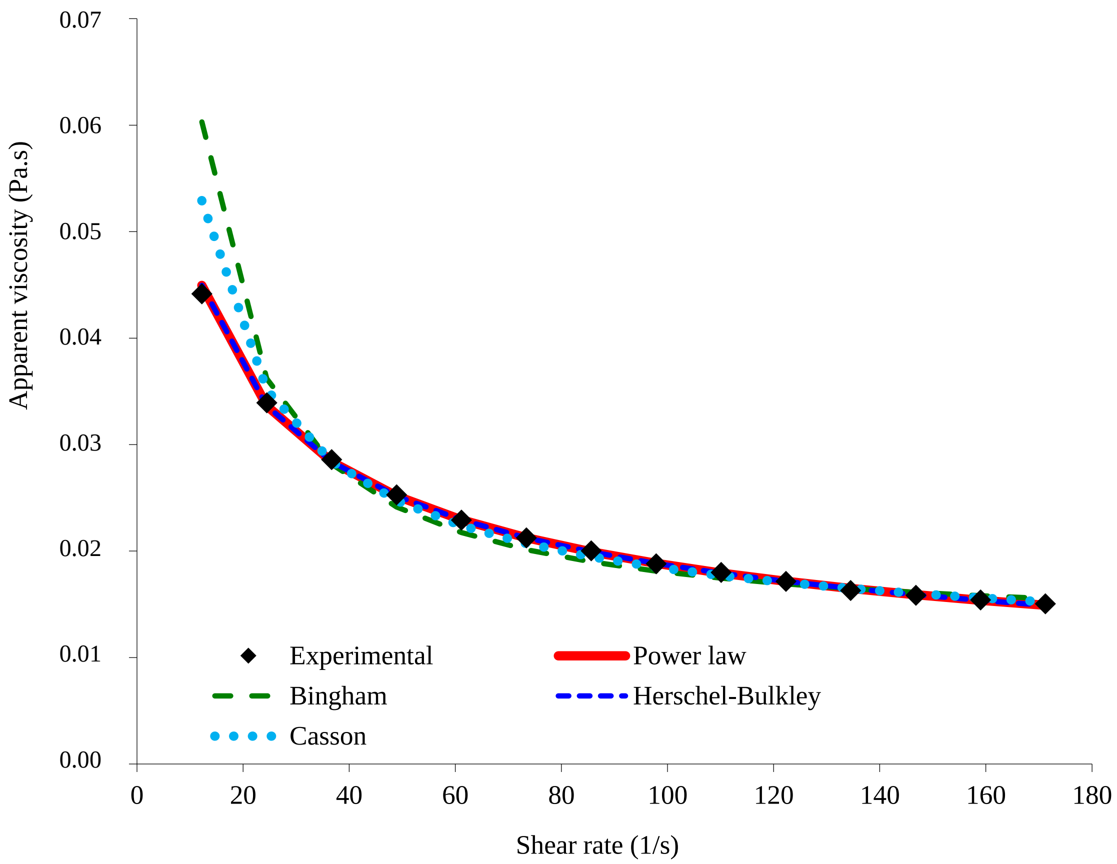

Fig. 3. Fitting ability of various rheological equations to experimental data.

3.3. Power law model

The PL model showed an excellent performance with the highest r-value (higher than 0.9984) and the lowest SSE values (lower than 0.0107) and RMSE values (lower than 0.0298) for all mucilage solutions (Table 1). It has been suggested that PL is a suitable equation to describe the rheological behavior of a large number of mucilage solutions [17, 18]. Moreover, treatment with microwave had a significant effect on the change of consistency coefficient and flow behavior index of BSM solutions ($p<0.05$).

Table 1. The coefficients of Power law model for calculating shear-stress values of microwave-treated Balangu seed mucilage solution

Microwave treatment time	k[1]	n[1]	Sum of squared error (SSE)	Correlation coefficient (r)	Root mean square error (RMSE)
0 min	0.1295±0.006[b]	0.5768±0.009[a]	0.0016	0.9998	0.0111
1 min	0.1268±0.003[b]	0.5595±0.004[ab]	0.0025	0.9997	0.0138
2 min	0.1272±0.007[b]	0.5496±0.009[b]	0.0049	0.9993	0.0186
3 min	0.1530±0.013[a]	0.5120±0.018[c]	0.0039	0.9994	0.0176

1- The coefficients of Power law model ($\tau = k\dot{\gamma}^{n}$); where τ is shear-stress (Pa), k is consistency coefficient (Pa.s^n), $\dot{\gamma}$ is shear-rate (1/s), and n is flow behavior index.

Different letters within each column represent significance difference ($p < 0.05$)

Microwave treatment is now important for changing hydrocolloids because it can heat them evenly, is safe and easy to use, needs little maintenance, and is effective in changing the hydrocolloids' structure and improving their functional characteristics [15, 19-21]. The impact of microwave treatment on the consistency coefficient of BSM solutions is reported in Table 1. The consistency coefficient of BSM solution considerably increased from 0.130 Pa.s^n to 0.153 Pa.s^n ($p<0.05$) with increasing microwave exposure time from 0 to 3 min.

The PL equation shows that a fluid with pseudoplastic behavior has a value of n less than 1 [22]. The influence of microwave treatment on the flow behavior index of BSM solutions is reported in Table 1. The flow behavior index of BSM solutions decreased significantly from 0.577 to 0.512 ($p<0.05$) (increases in pseudoplastic behavior) while the duration of microwave treatment increased. The alteration within the consistency coefficient and flow behavior index of the BSM solutions may be due to the structural modification of the mucilage during microwave treatment. Microwave energy is known to induce a series of physico-chemical reactions that lead to modify in the consistency and functional properties of food dispersion containing various types of hydrocolloids.

3.4. Bingham model

The experimental values of SS versus SR for non-treated and treated BSM solutions were fitted to the Bingham model and the determined parameters of the Bingham equation consisting of the Bingham yield stress (τ_{0B}) and the Bingham plastic viscosity (η_B) are presented in Table 2. The results of Bingham model with two parameters using the SSE, r, and RMSE statistics are reported in this table. The mean values of SSE, r, and RMSE for BSM solutions ranged from 0.0673-0.8017, 0.9866-0.9914, and 0.0749-0.0872, respectively. The results of Bingham model showed that the values of the Bingham yield stress ranged from 0.5352 Pa to 0.6482 Pa, and the Bingham plastic viscosity ranged from 0.0088 Pa.s to 0.0121 Pa.s.

Table 2. The coefficients of Bingham model for calculating shear-stress values of microwave-treated Balangu seed mucilage solution

Microwave treatment time	τ_{0B}[1]	η_B[1]	Sum of squared error (SSE)	Correlation coefficient (r)	Root mean square error (RMSE)
0 min	0.5899±0.016[a]	0.0116±0.0004[a]	0.0883	0.9909	0.0858
1 min	0.5587±0.008[a]	0.0105±0.0001[b]	0.0778	0.9897	0.0805
2 min	0.5486±0.018[a]	0.0099±0.0001[bc]	0.3201	0.9882	0.0813
3 min	0.6003±0.048[a]	0.0095±0.0005[c]	0.0715	0.9885	0.0772

1- The coefficients of Bingham model ($\tau = \tau_{0B} + \eta_B \dot{\gamma}$); where τ is shear-stress (Pa), τ_{0B} is Bingham yield stress (Pa), η_B is Bingham plastic viscosity (Pa.s), and $\dot{\gamma}$ is shear-rate (1/s).
Different letters within each column represent significance difference ($p < 0.05$)

3.5. Herschel-Bulkley model

The experimental values of SS versus SR for non-treated and treated BSM solutions were fitted to the Herschel-Bulkley model and the determined constant coefficients of the Herschel-Bulkley equation are presented in Table 3. The results of Herschel-Bulkley model with three parameters (τ_{0H}, k_H, and n_H) using the SSE, r, and RMSE statistics are reported in this table. The SSE, r, and RMSE values for the BSM solutions were between 0.0004 and 0.0107, 0.9984 and 0.9999, and 0.0061 and 0.0311, respectively. Based on the Herschel-Bulkley model, all BSM solutions exhibited pseudoplastic behavior, expressed by the flow behavior index (n_H) values less than 0.585. The findings of the Herschel-Bulkley model were yield stress values between 1.22×10^{-10} Pa and 5.98×10^{-1} Pa, consistency coefficients between 0.122 Pa.s^n and 0.160 Pa.s^n, and the flow behavior indexes between 0.493 and 0.585. The effect of microwave treatment on the rheological properties of mango kernel starch was examined by Ramírez-Brewer et al. [11]. Their results revealed that the microwave-modified starch had higher consistency index and yield stress values than natural starch.

Table 3. The coefficients of Herschel-Bulkley model for calculating shear-stress values of microwave-treated Balangu seed mucilage solution

Microwave treatment time	τ_{0H}[1]	k_H[1]	n_H[1]	Sum of squared error (SSE)	Correlation coefficient (r)	Root mean square error (RMSE)
0 min	$2.1\times10^{-4}\pm3.0\times10^{-4a}$	0.1294 ± 0.006^{ab}	0.5769 ± 0.009^{a}	0.0016	0.9998	0.0112
1 min	$2.2\times10^{-6}\pm2.9\times10^{-6a}$	0.1268 ± 0.003^{b}	0.5595 ± 0.004^{a}	0.0025	0.9997	0.0144
2 min	$6.1\times10^{-6}\pm8.2\times10^{-6a}$	0.1272 ± 0.007^{b}	0.5496 ± 0.009^{a}	0.0049	0.9993	0.0194
3 min	$2.0\times10^{-1}\pm2.8\times10^{-1a}$	0.1450 ± 0.011^{a}	0.5204 ± 0.019^{b}	0.0038	0.9994	0.0182

1- The coefficients of Herschel-Bulkley model ($\tau = \tau_{0H} + k_H\dot{\gamma}^{n_H}$); where τ is shear-stress (Pa), τ_{0H} is yield stress (Pa), k_H is consistency coefficient (Pa.s^n), $\dot{\gamma}$ is shear-rate (1/s), and n_H is flow behavior index.

Different letters within each column represent significance difference ($p < 0.05$)

3.6. Casson model

The experimental values of SS versus SR for non-treated and treated BSM solutions were fitted to the Casson model and the determined parameters of the Casson equation consisting of Casson yield stress (τ_{0C}) and Casson plastic viscosity (η_C) are presented in Table 4. The results of Casson model with two parameters (τ_{0C} and η_C) using the SSE, r, and RMSE statistics are reported in this table. Mean values of SSE, r, and RMSE for BSM solutions were between 0.0185 and 0.0352, 0.9948 and 0.9977, and 0.0393 and 0.0541, respectively. The results of Casson model showed that the values of the Casson yield stress were between 0.2475 Pa and 0.3294 Pa, and the Casson plastic viscosity were between 0.0666 Pa.s and 0.0845 Pa.s.

Table 4. The coefficients of Casson model for calculating shear-stress values of microwave-treated Balangu seed mucilage solution

Microwave treatment time	τ_{0C}[1]	η_C[1]	Sum of squared error (SSE)	Correlation coefficient (r)	Root mean square error (RMSE)
0 min	0.2620±0.012[b]	0.0834±0.0013[a]	0.0242	0.9975	0.0449
1 min	0.2573±0.006[b]	0.0772±0.0004[b]	0.0226	0.9970	0.0434
2 min	0.2580±0.013[b]	0.0744±0.0008[b]	0.0260	0.9962	0.0461
3 min	0.3086±0.026[a]	0.0702±0.026[c]	0.0206	0.9966	0.0414

1- The coefficients of Casson model ($\tau^{0.5} = \tau_{0C}^{0.5} + \eta_C \dot{\gamma}^{0.5}$); where τ is shear-stress (Pa), τ_{0C} is Casson yield stress (Pa), η_C is Casson plastic viscosity (Pa.s), and $\dot{\gamma}$ is shear-rate (1/s).

Different letters within each column represent significance difference ($p < 0.05$)

4. Conclusion

In the present study, the influence of microwave treatment on the rheological behavior of BSM solution was investigated. BSM solution showed the shear-thinning flow behavior. The use of microwave to the BSM solution reduces its viscosity. The findings of this study revealed that the PL equation became the most accurate equation to explain the rheological characteristics of BSM solutions compared to three other verified rheological models with SSE values ranging from 0.0004-0.0107. The consistency coefficient values of the samples rose significantly when the microwave treatment duration was raised to 3 min ($p<0.05$). The maximum flow behavior index was for the non-treated mucilage, and the minimum flow behavior index was for the mucilage treated in the microwave for 3 min.

Conflict of interest: No conflict of interest has been declared by the authors.

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مقاله پژوهشی

استفاده از مایکروویو برای تغییر در خصوصیات رئولوژیکی موسیلاژ دانه بالنگو

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چکیده

محلول‌های آبی موسیلاژ دانه‌های بالنگو ویسکوزیته بالایی دارند و رفتار شبه پلاستیکی از خود نشان می‌دهند. هدف از این مطالعه تجزیه‌وتحلیل تأثیر تیمار مایکروویو در فواصل زمانی مختلف بر رفتار رئولوژیکی محلول‌های تهیه شده از موسیلاژ دانه بالنگو بود. یافته‌های این مطالعه نشان داد که با افزایش پیوسته سرعت برشی از ۱۲/۲ بر ثانیه به ۱۷۱/۲ بر ثانیه، ویسکوزیته ظاهری محلول موسیلاژ دانه بالنگو (محلول تیمار نشده) از ۰/۰۴۴ پاسکال ثانیه به ۰/۰۱۵ پاسکال ثانیه کاهش می‌یابد. همچنین، ویسکوزیته ظاهری محلول‌های موسیلاژ دانه بالنگو با افزایش زمان قرار گرفتن در معرض مایکروویو از ۰ تا ۳ دقیقه، از ۰/۰۲۹ پاسکال ثانیه به ۰/۰۲۶ پاسکال ثانیه کاهش یافت (سرعت برشی برابر ۳۷ بر ثانیه). برای همه محلول‌های موسیلاژ، مدل رئولوژیکی قانون توان عملکرد خوبی با حداکثر مقدار ضریب تبیین (۰/۹۹۸۴<)، و حداقل مجموع مربعات خطا (۰/۰۱۰۷>) و جذر میانگین مربعات خطا (۰/۰۲۹۸>) را نشان داد. ضریب قوام محلول موسیلاژ دانه بالنگو با افزایش زمان قرار گرفتن در معرض مایکروویو از ۰ تا ۳ دقیقه، به‌طور معنی‌داری از ۰/۱۳۰ $Pa.s^n$ به ۰/۱۵۳ $Pa.s^n$ افزایش یافت ($p<0.05$). شاخص رفتار جریان محلول‌های موسیلاژ دانه بالنگو با افزایش زمان تیماردهی با مایکروویو به‌طور معنی‌داری از ۰/۵۷۷به ۰/۵۱۲ کاهش یافت ($p<0.05$). نتایج مدل کاسون نشان داد که مقادیر تنش تسلیم کاسون بین ۰/۲۴۷۵ پاسکال و ۰/۳۲۹۴ پاسکال و ویسکوزیته پلاستیک کاسون بین ۰/۰۶۶۶ پاسکال ثانیه تا ۰/۰۸۴۵ پاسکال ثانیه است. درمجموع، تیماردهی با مایکروویو پارامترهای رئولوژیکی را تغییر داد و باعث کاهش ویسکوزیته موسیلاژ دانه بالنگو شد.

واژه‌های کلیدی: **قانون توان، مایکروویو، مدل کاسون، موسیلاژ دانه بالنگو، ویسکوزیته پلاستیک**

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