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Research Article

A Research on Rheological Behavior of Aqueous Solutions of Pomegranate Peel Powder

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Abstract **–** Determining the viscosity of pomegranate peel powder (PPP) can aid in product development, process optimization, quality control, ingredient interactions, and scientific research related to pomegranate peel-based products or formulations. Therefore, in this study, the rheological behavior of dried and ground pomegranate peel has been investigated. The apparent viscosities of pomegranate peel solutions prepared with distilled water are measured by a rotational viscometer. The viscosity of the pomegranate peel solution at each concentration is measured at shear rates varying between 2.64 s^{-1} and 22 s^{-1} at constant temperature (25 °C). When the effect of concentration on apparent viscosity has been examined, it is observed that the viscosity rises with increasing concentration at a constant shear rate. Among the rheological models studied, Power model provides a good fit for the experimental viscosity data of aqueous solutions of pomegranate peel powder at different concentrations. The consistency coefficient and the flow behavior index are calculated using the power law model and the solutions have been found to exhibit pseudoplastic behavior.

Keywords – Pomegranate Peel, Power Law Model, Rotational Viscometer, Pseudoplastic, Rheological Behavior

I. INTRODUCTION

Pomegranate (*Punica granatum*) is a fruit-bearing deciduous shrub or small tree native to the region stretching from Iran to the Himalayas in Northern India. It is widely cultivated for its flavorful and nutrient-rich fruits. Pomegranates have been cultivated for thousands of years and are known for their cultural and symbolic significance in various societies [1]. Pomegranates have a significant presence in Türkiye, both in terms of cultivation and consumption. Türkiye is one of the major producers of pomegranates in the world. The favorable climate and fertile soil in various regions of Türkiye contribute to the successful cultivation of pomegranate orchards [2].

Pomegranate peel is a byproduct of the pomegranate fruit processing industry, and it is a rich source of bioactive compounds such as polyphenols and flavonoids. These compounds have been shown to have various health benefits, including antioxidant, anti-inflammatory, and anticancer properties [3-5]. Pomegranate peel has various potential uses in different industries, and its bioactive compounds make it a promising ingredient for the development of new products and applications. It is used in the food industry as a flavoring agent, food supplement, and coloring agent due to its high anthocyanin content, and as a functional ingredient in food products due to its bioactive compounds and other functional properties, in the pharmaceutical industry in the development of new drugs or supplements with the polyphenols it contains, and in the cosmetic industry as an ingredient in skin creams, lotions and masks due to its antioxidant and anti-inflammatory properties [6-10].

Rheological behavior refers to the flow and deformation characteristics of materials under the influence of applied forces or stresses. The rheological behavior of a material is determined by its rheological properties, which include viscosity, elasticity, yield stress, shear rate, and shear stress [11]. These properties describe how the material responds to different types and magnitudes of applied forces. The relationship between shear rate and shear stress in a material is described by its rheological behavior. In Figure 1, different materials exhibit different relationships, and this relationship is often depicted in a flow curve [12].

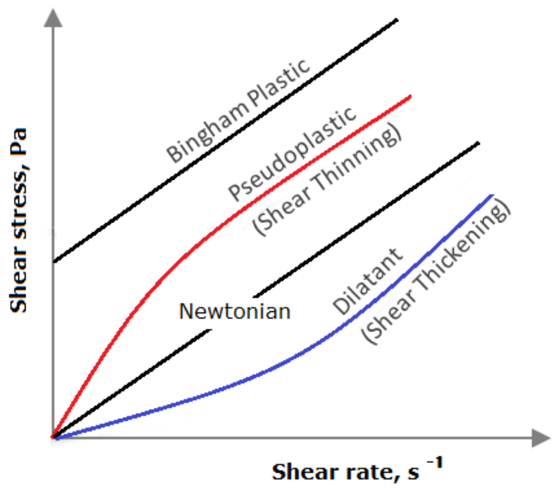

Figure 1. Newtonian and non-Newtonian flow behaviors

In a Newtonian fluid, shear stress is directly proportional to shear rate, whereas in non-Newtonian fluids, the relationship between shear stress and shear rate is more complex and exhibits different patterns such as shear thinning (pseudoplastic behavior), shear thickening (dilatant behavior) and Bingham plastic [13]. Many mathematical equations of varying complexity and form have been reported in the literature. Understanding the rheological behavior of materials using these models is crucial for designing and optimizing processes involving liquids such as manufacturing, food processing, pharmaceuticals, and many other industries [14-16].

This study, it was aimed to experimentally determine the relationship between shear rate and shear stress of aqueous solutions of PPP using a rotary viscometer and to find the mathematical model that best fits this relationship.

II. MATERIAL AND METHOD

Materials

Fresh pomegranate (*Punica granatum L.*) fruits were obtained from a local market in Elazığ, Türkiye. The peels were manually separated and sliced. After drying in an oven at 40 °C for 24 hours, it was ground. Powdered pomegranate peels were stored in polypropylene containers at 4 °C until use.

Rheological Analysis

PPP solutions were prepared by vigorous stirring with a magnetic stirrer for 24 hours to hydrate the powder in distilled water, and the supernatant was collected by filtration. Before the rheological measurements, it was kept in an ultrasonic water bath for 30 min to remove air bubbles from the solutions. The preparation steps of PPP solutions before rheological measurements are shown in Figure 2.

To determine the rheological properties, studies were carried out with a Brookfield viscometer, which is a rotational viscometer, in the shear rate range from 2.64 s^{-1} to 22 s^{-1}. LV-1 was used as the spindle. The rheological properties of aqueous solutions of PPP were evaluated at different concentrations ranging from 20 to 35 kg/m^3. Experiments were carried out at a constant temperature of 25 °C. To control the temperature, the water-jacketed stainless steel cylindrical vessel was connected to a constant temperature bath. After each sample was placed in the system, it was waited for 30 seconds for reading and all rheological tests were performed in triplicate.

Shear stress was found by the following relation Eq. 1. Where τ is shear stress (mPa), κ is apparent viscosity (mPa·s) and $\dot{\gamma}$ is shear rate (s^{-1}).

$$\tau = \kappa \, . \dot{\gamma} \qquad (1)$$

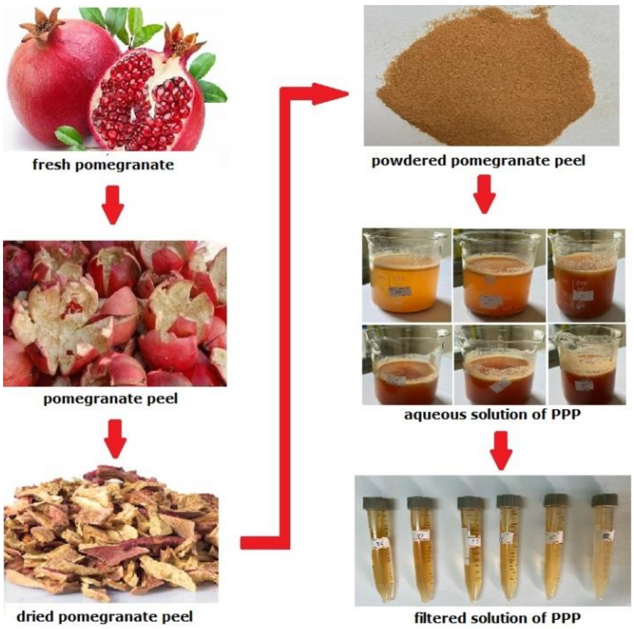

Figure 2. Preparation steps of PPP solutions before rheological measurements

Several mathematical models (Table 1) have been developed to explain the rheological behavior of PPP solutions. Model coefficients were calculated by nonlinear regression analysis to select the model that best fitted the experimental rheology data. The rheological parameters of the model, which had the minimum deviation as a result of the statistical tests applied between the apparent viscosity values calculated using the model coefficients and the experimental viscosity values, were used to explain the continuous shear flow behavior of the studied fluid systems [28-30].

Statistical Analysis

The statistical software package was used to perform the nonlinear regression analysis of experimental viscosity data [17]. Analysis of variance (*ANOVA*) was used to statistically evaluate the effect of concentration. Equations 2 and 3 were determined for comparison of model predictions.

$$R^2 = \left[\frac{\sum_i (\kappa_{i,pre}-\bar{\kappa})(\kappa_{i,exp}-\bar{\kappa})}{\sqrt{\sum_i(\kappa_{i,pre}-\bar{\kappa})^2} * \sqrt{\sum_i(\kappa_{i,exp}-\bar{\kappa})^2}}\right]^2 \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\kappa_{i,exp}-\kappa_{i,pre})^2}{N}} \quad (3)$$

Where $\kappa_{exp,i}$ is the experimental viscosity, $\kappa_{pre,i}$ is the predicted viscosity, *N* is the number of data points and *n* is the number of model parameters.

III. RESULTS AND DISCUSSION

Typical flow diagrams of the relations between shear stress and shear rate for PPP solutions prepared in varying concentrations at a constant temperature of 25 °C are given in Figure 3.

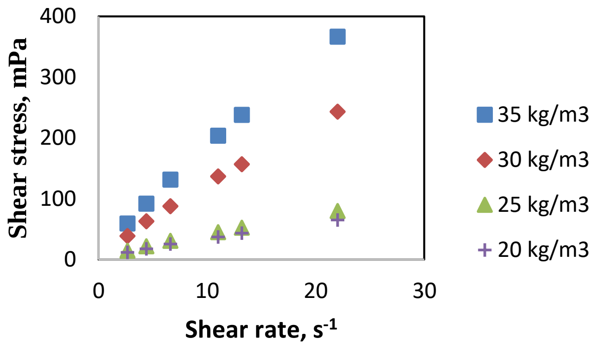

Figure 3. The plot of shear rate and shear stress for different concentrations of PPP

It is seen in Figure 4 that the apparent viscosity decreases with increasing shear rate and shear-thinning behavior. Shear thinning behavior has also been frequently reported in experiments with non-colloidal systems in high-volume fractions [18,19]. Since the particles in heterogeneous systems are weakly connected, when subjected to shear stress, the interparticle bonds are broken and less resistance to flow is applied during shear [20].

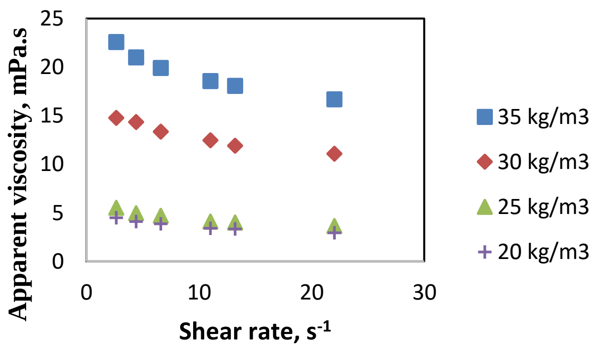

Figure 4. Variation of apparent viscosity with the shear rate for different PPP concentrations

Non-Newtonian fluids exhibit viscosity that is dependent on the applied shear rate or shear stress [24-27]. A few common rheological models used to describe non-Newtonian fluids are given in Table 1.

Table 1. Rheological model equations

No	Models	Equations
1	Power law	$\tau = \kappa.(\dot{\gamma})^n$
2	Bingham	$\tau = \tau_B + \kappa_B .\dot{\gamma}$
3	Casson	$\tau^{0.5} = \tau_C + \kappa_C.\dot{\gamma}^{0.5}$

In the equations in the table, κ is the consistency index (mPa·s^n) and n is the flow behavior index (dimensionless), τ_B and κ_B are Bingham model parameters, τ_B and κ_C are Casson model parameters.

Experimental data were analyzed according to Power Law, Bingham, and Casson model, and the model parameters are shown in Table 2. The statistical test results showed that Power law model was the most suitable model to explain the rheological behavior of all PPP solutions. In previous studies on pomegranates, it was found that Power law model was used to describe the rheological properties [21, 22].

Table 2. Model and statistical parameters of PPP solutions at different concentrations

C kg/m³	Model	*n*	*κ*	*τ₀*	*R²*	*RMSE*
20	1	0.801	5.514		0.9996	0.1420
	2	2.731		6.435	0.9949	1.603
	3	1.504		1.099	0.9978	0.6974
25	1	0.800	6.720		0.9997	0.1668
	2	3.355		7.446	0.9972	1.343
	3	1.665		1.190	0.9989	0.4192
30	1	0.857	17.34		0.9994	1.978
	2	10.47		16.94	0.9972	12.97
	3	3.031		1.513	0.9985	6.022
35	1	0.858	25.94		1.000	0.7145
	2	15.85		24.17	0.9978	23.58
	3	3.735		1.786	0.9992	9.495

The flow behavior index (n) showed that PPP solutions examined had values less than 1, meaning that they could be classified as pseudoplastic. The consistency index (κ) increases significantly with the percentage of PPP (p <0.05), as expected, due to its ability to increase viscosity at a higher PPP concentration. Also, the consistency index increases due to the higher polysaccharide content in its content, relative to the solids content and the concentration of the dispersed phase [23].

IV. CONCLUSIONS

The apparent viscosity of PPP solutions was examined using a rotary viscometer depending on the concentration and shear rate factors. As the shear rate increased, the shear stress decreased, resulting in a decrease in viscosity. As the shear rate increased, the shear stress decreased, causing the viscosity of PPP to decrease. In shear thinning (pseudoplastic behavior), easier yielding occurred at a higher shear rate. The power law equation was chosen as the most suitable model to explain the relationship between shear stress and shear rate. Rheological analysis of pomegranate peel can provide valuable insights into its potential uses in the food, pharmaceutical, and cosmetic industries.

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