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AUTHOR CONTRIBUTIONS

Dewi Fortuna: Conceptualization, Methodology, Formal Analysis, Validation, Investigation, Resources, Visualization, Writing – Original Draft; Emmy Darmawati: Methodology, Formal Analysis; Titi Chandra Sunarti: Methodology, Resources; Sutrisno Suro Mardjan: Writing – Review & Editing, Supervision, Nanik Purwanti: Conceptualization, Methodology, Supervision, Project administration, Writing – Review & Editing.

CONFLICT OF INTEREST

The authors declare that they hold no competing interests.

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DECLARATIONS

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Abstract

This study determined the rheological properties of *Dioscorea alata* mucilage (DAM) solution at different concentrations and temperatures (steady shear flow and dynamic oscillatory rheology). The steady shear flow experiment results showed that the shear apparent viscosity-shear rate data was well fitted with the Carreau model and showed the highest R^2. The Carreau model that the DAM solutions at 1-8% presented non-Newtonian shear-thinning behavior. The strain and frequency sweep data of 8% (w/w) DAM solution showed dominant elastic behavior (gel-like structure). A G_f between G'' and G'' of 8% (w/w) DAM solution at 30 °C occurs at very high frequencies (» 83.70 Hz). The Arrhenius equation and activation energy (Ea) described the temperature effect. The rheological properties study of DAM aqueous solutions can provide information about its flow behavior, which helps apply DAM as a source of hydrocolloids in the food and non-food industries.

Keywords: *Dioscorea alata* · yam · mucilage · Carreau model · shear-thinning · activation energy

List of symbols

η_a	apparent viscosity (Pa s)
η_0	zero-shear viscosity (Pa s)
η_∞	infinite-shear viscosity (Pa s)
η^*	complex viscosity (Pa s)
τ	Shear stress (Pa)
γ	Shear strain (%)
$\dot{\gamma}$	shear rate (s^{-1})
λ_c	time constants related to the relaxation times of the polymer in solution (s)
N	dimensionless exponent.
G'	storage modulus (Pa)
G''	loss modulus (Pa)
G_f	Crossover point (Pa)
f	frequency (Hz)
$\tan\delta$	Loss tangent
k'	intercepts (Pa s^n)
b	slopes of frequency dependence of G'
d	slopes of frequency dependence of G''
ω	angular frequency (rad/s)
A	pre-exponential constant (Pa s)
E_a	activation energy (kJ mol^{-1})
R	gas constant (8.314 J mol^{-1} K^{-1})
T	absolute temperature (K)

1 Introduction

Mucilage is considered a minor component of *Dioscorea alata* (DA) tubers, which is a waste from the starch extraction process that is thrown away. Mucilage found in wastewater resulting from soaking the tubers before starch extraction or further processing increases the viscosity and sliminess of the wastewater. *Dioscorea* sp mucilage has the potential to be used as a hydrocolloid in the food and non-food industry because it is a water-soluble polysaccharide composed of mannan-protein macromolecules [1–4]. The main component of polysaccharides from DA mucilage (DAM) is mannose; other minor components are rhamnose, glucose, galactose, xylose, and arabinose [5, 6]. *Dioscorea* sp mucilage has pseudoplastic characteristics, shows potential as a thickener and emulsifier properties, and is easy to incorporate into food matrices [7, 8]. Emulsification properties *Dioscorea* sp mucilage is better than konjac glucomannan [8], so it has possibilities for applications such as in the pharmaceutical, food stabilizers, lubricants in the chemical industry, and additives in cosmetics.

Research on DAM's extraction, structure, and biological activity has been carried out, but no reported paper described the DAM rheology properties. Rheological data are crucial for design, product development, predicting shelf life, sensory assessment, and evaluating the stability of food products on processing, transporting, and storage. The rheology of DAM was evaluated as steady shear and dynamic oscillatory rheology of the DAM for investigation of time-independent and viscoelastic behavior of the emulsion of the DAM. Rheological parameters, such as viscosity-shear rate, are required to consider a compound for its potential as a thickener [9]. Flow models are mathematical equations that describe rheological data that are essential to measure how state variables influence the magnitudes of model parameters (e.g., concentration, temperature), thereby establishing relationships that may be widely applied [10].

Dynamic rheological properties can be used in conjunction with steady shear rheological properties to provide insight into the structure of mucilage solutions. Dynamic shear rheological tests have characterized or classified the viscoelastic properties of macromolecular dispersions. A sinusoidal strain cycle was used in the dynamic test to calculate the G', G'', and η^*. Dynamic testing is a nondestructive technique that allows measurements to be made without structural damage to the sample and allows researchers to relate dynamic rheological parameters to the sample's molecular structure. Thus, dynamic rheology is one of the most widely used methods to assess the viscoelastic behavior of mucilage gels. Therefore, this study investigated the rheological properties of DAM in solution form to contribute to applying natural thickeners in the food industry.

2 Materials and Methods

2.1 Materials

Fresh yellow DA tuber harvested after the stem withered approximately 12 months of planting and collected from Leuwicopo Farm, IPB University. absolute ethanol (Cat. No. 1009835000, Merck, Germany), calcium chloride (Cat. No.1023780500, Merck, Germany), and distilled water were used as analytical grade reagents in this study.

2.2 Extraction of *Dioscorea alata* mucilage

DAM was extracted using the previously described modifications [11]. Fresh DA tubers were washed, sliced, and steam blanched for 10 min, then 250 g tuber was peeled. The peeled tubers and 1 L of 1% w/v $CaCl_2$ solution were homogenized in an ice crusher blender (±25.000 rpm) for 10 min. The slurry samples were stored at 36.2 °C for 13.3 h, then centrifuged (SorvallTM LegendTM XTR centrifuge, Fisher Scientific Ltd, UK) at 12322 ×g for 30 min at 4 °C to separate the fiber materials from the supernatant. The supernatant was precipitated with 1 L of absolute ethanol and kept overnight at 4 °C to separate starch and mucilage. Starch forms as a precipitate, whereas mucilage forms as two layers of supernatant in the middle and cream on top. The mucilage was poured out, centrifuged again (12000 ×g, 30 min, 4 °C), then dried with freeze-drying for two days and ground to obtain mucilage powder. The powder was sealed in a foil pouch and kept at room temperature.

2.3 Rheological analysis of *Dioscorea alata* mucilage

2.3.1 Solution preparation

The necessary quantity of DAM powder was dissolved into distilled water to create DAM solutions (1, 2, 3, 4, 5, 6, 7, and 8% w/w), stirring gently and continuously for 2 h at room temperature (25 °C), then refrigated at 4 °C to completely hydration. The solutions were equilibrated at 25 °C for 1 h, then slowly stirring for 30 min at 25 °C.

2.3.2 Rheological measurements

The rheological properties of the samples were investigated using a Rheometer MCR 301 (Anton Paar, Austria) with cone plate geometry (60 mm diameter, cone angle 2°). The device was controlled using RheoPlus software, and data was processed with RheoCompass software and Microsoft Excel 2010 software.

2.3.2.1 Shear stress-shear rate relationships

The steady flow behavior of DAM was examined in the range of $\dot{\gamma}$ from 0.01 to 1.000 s^{-1} at a constant temperature of 30 °C at different concentrations (1, 2, 3, 4, 5, 6, 7, and 8 % w/w). The DAM solution was held for 5 minutes at 30 °C before testing to allow stress relaxation and temperature balance, and data was not taken during this interval. An increasing $\dot{\gamma}$ ramp ranging from 0.01 – 1.000 s^{-1} was set to measure the upward curve. Then, the $\dot{\gamma}$ was set between 1.000 to 0.01 s^{-1} to calculate the downward curve. After loading, the exposed edge of the sample was covered with a thin layer of palm oil to prevent evaporation during measurements. As a function of $\dot{\gamma}$, the $\eta_a - \dot{\gamma}$ data were obtained. The Carreau model effectively predicted the flow dynamics [10, 12].

$$\eta_a = \eta_\infty + \frac{(\eta_0 - \eta_\infty)}{[1+(\lambda_c \dot{\gamma})^2]^N} \quad (1)$$

2.3.2.2 Hysteresis Loop

The hysteresis loop test was performed in three-steps operation: the $\dot{\gamma}$ increased linearly from 0.01 to 100 s^{-1} and decreased linearly from 100 to 0.01 s^{-1}. RheoCompass software version 1.30.1064 was used to calculate the area of the hysteresis loop.

2.3.2.3 Strain amplitude sweep test

Two stages were used to measure the strain sweep. Prior to testing, the DAM solution was kept for 5 minutes at 30 °C to allow stress relaxation and temperature balance; no data was taken during this stage. The linear viscoelastic region (LVER) was identified in the second stage by measuring at a temperature of 30 °C with a constant ω of 1 rad s^{-1} from 0.01% to 100% with up to 10 measurement points per decade interval. Trends of G' and G'' reflect the DAM solution's ability to withstand deformation with applied strain.

2.3.2.4 Frequency sweep test

The dynamic rheological properties of the DAM solution (8% w/w) [G', G'', $\tan\delta = G''/G'$, and $\eta^* = [(G'/\omega)^2 + (G''/\omega)^2]^{1/2}$] as a function of ω were investigated using frequency sweep measurements. There were two stages to the frequency sweep measurements. Prior to testing, the DAM solution was kept for 5 minutes at 30 °C to allow stress relaxation and temperature balance; no data was collected during this stage. The second stage was set with a frequency sweep (ω) ranging from 0.1 to 100 Hz at 30 °C was implemented within LVR (γ = 1%) with 20 measurement points per decade to obtain relationships with G', G'', η^*, and $\tan\delta$, respectively. The Power Law equation will be used to calculate the correlation between G', G'' and ω as follows:

$$G' = k' \times \omega^b \quad (2)$$

$$G" = k" \times \omega^d \quad (3)$$

2.3.2.5 Temperature ramp

The temperature ramp measurements were performed at constant shear stress values of 10 or 100 s^{-1} to investigate the effect of temperature on the rheological properties of DAM solutions (8 % w/w). The DAM solution was transferred to the rheometer plate at 30 °C. The exposed edges of the samples were covered with a thin layer of palm oil to prevent evaporation during measurement. The DAM solution was held for 5 minutes at 30 °C before testing to allow stress relaxation and temperature balance, and data was not taken during this interval. A heating step with a linear temperature increased from 30 to 90 °C, using a heating rate of 2 °C/min. The rheological behavior of DAM solutions was subjected to the Arrhenius equation for kinetic analysis:

$$\eta_a = A\exp\left(\frac{E_a}{RT}\right) \quad (4)$$

2.4 Statistical analysis

RheoCompass software version 1.30.1064 was utilized to choose the acceptable steady shear flow behavior due to their R^2 and RMSE values, measure the area of the hysteresis loop, and analyze the dynamic rheology data.

3 Results and Discussion

3.1 Steady shear flow rheological properties

The η_a at a concentration of 1–8% (w/w) at 30 °C was presented in Figure 1. The η_a decreased with increasing $\dot{\gamma}$ at all concentrations. Figure 1 showed the same trend at 5–8% (w/w) of DAM solutions, and the η_a at 5% was close to 6%. However, the viscosity decreased rapidly at a concentration of 6–8% ($\dot{\gamma}$= 10–100 s^{-1}). A Newtonian plateau occurs at the high $\dot{\gamma}$ range (100–1.000 s^{-1}) at low concentrations (≤ 2%, w/w). On the other hand, the η_a of the dispersions increased with an increase in DAM concentration from 1% to 8% (w/w). These phenomena could be attributed to the higher total solids content in the solution, causing an increase in viscosity due to increased restriction of intermolecular motion caused by hydrodynamic forces and the formation of interfacial layers [13]. Our findings are in agreement with the previous results reported by [8], who mentioned that *D. opposita* mucilage flow behavior.

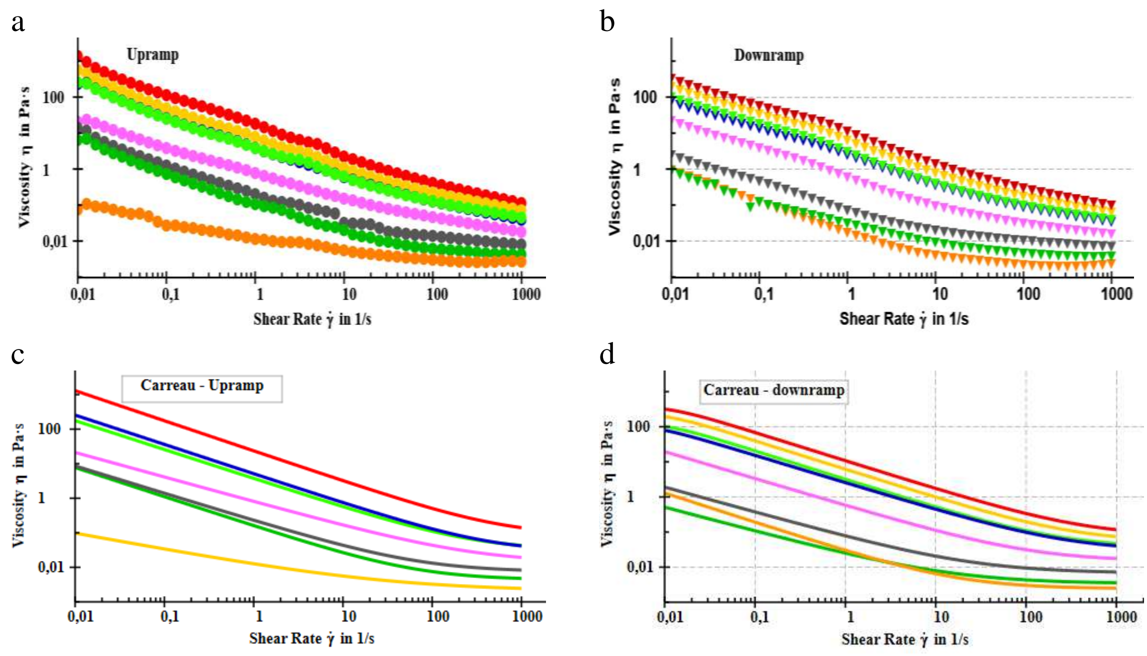


Fig. 1 Apparent viscosity as a function of shear rate (a – : 0,01–1000 s^{-1}, (●) 1%, (●) 2%, (●) 3%, (●) 4%, (●) 5%, (●) 6%, (●) 7%, (●) 8%); b – : 1000–0,01 s^{-1}, (▼) 1%, (▼) 2%, (▼) 3%,

(▼) 4%, (▼) 5%, (▼) 6%, (▼) 7%, (▼) 8%) dan Carreau model fittings (▬) (c – ; d –) at several *Dioscorea alata* mucilage concentrations (1–8% b/b), 30°C.

Generally, polysaccharide molecules in DAM with stiff conformations contribute to high zero–shear rate viscosity and possess strong shear-thinning properties [14]. The chains of polymer molecules were randomly aligned with the flow with increasing shear rate, and the bonds between the hydrocolloid components were broken and thus produced a less viscous solution by increasing shear rate [15]. This indicates that at low concentrations, the molecules are well separated from each other and move freely. An increase in the concentration of DAM solution causes an increase in η_a, which increases the formation of molecular interfacial films and cross-links [16].

The flow behavior of the DAM solution was fitted with the Carreau model (Fig. 1c-d), which was used to determine the boundary between Newtonian and shear-thinning behavior, showing the end point of Newtonian behavior and starting point of shear-thinning behavior [17]. The logarithmic plot between viscosity and shear rate using the Carreau model provides an intuition about the shear-thinning fluid viscosity decreasing with increasing shear rate. A number of authors have also used the Carreau model to represent the flow properties of *Plantago major* seed gums [17], chia seed mucilage [18], *Ocimum basilicum* seed mucilage [14], and *Opuntia* sp. mucilage [19, 20]. The Carreau model was chosen because of its ability to model steady shear, complex viscosity, and stress relaxation functions [21].

The parameters of the Carreau model with a high R^2 (0.917-0.999) can be seen in Table 1. The η_0 of the model ranges from 1.22×10^7 to 1.58×10^{17} Pa s (upramp) and 4.12×10^5 to 2.09×10^{12} Pa s (downramp). The higher η_0 showed, the greater the number of bonds between macromolecules. In Figure 2, it can be seen that the value of η_0 in the concentration of 8% was higher than 1%, indicating that the microstructure of the DAM changed during the test due to the higher viscosity at low shear rates, indicating strong interparticle forces attracting each other to produce aggregates during shear. While η_∞ indicates the consistency of mucilage during processing. The greater the value of η_∞, the greater the energy required for processing. The higher the concentration of mucilage, the higher η_∞ can be seen in Table 1.

Table 1: Parameters of Carreau model at several *Dioscorea alata* mucilage (Upramp dan Downramp).

C (%)	**η_0 (mPa s)**	**η_∞ (mPa s)**	**λ (s)**	**N**	**R^2**
		Upramp			
1	1.22×10^{7}	2.07	4.95×10^{12}	0.24	0.949
2	1.55×10^{13}	4.34	9.82×10^{12}	0.42	0.923
3	4.46×10^{11}	7.42	5.47×10^{11}	0.40	0.952
4	3.11×10^{10}	13.50	4.69×10^{10}	0.36	0.965
5	7.83×10^{14}	27.23	1.48×10^{13}	0.42	0.932
6	1.57×10^{14}	31.65	4.93×10^{12}	0.42	0.924
7	8.54×10^{12}	53.95	4.86×10^{10}	0.42	0.922
8	1.58×10^{17}	83.77	5.17×10^{14}	0.44	0.917
		Downramp			
1	2.09×10^{12}	2.44	1.14×10^{13}	0.42	0.964
2	5.48×10^{8}	3.41	6.67×10^{10}	0.34	0.923
3	1.38×10^{10}	6.79	4.23×10^{11}	0.36	0.967
4	8.72×10^{10}	14.74	4.64×10^{10}	0.38	0.999
5	1.25×10^{5}	29.13	1.46×10^{2}	0.39	0.994
6	1.38×10^{5}	35.71	1.04×10^{2}	0.41	0.992
7	2.57×10^{5}	51.89	9.89×10^{1}	0.41	0.989
8	4.12×10^{5}	75.95	9.17×10^{1}	0.40	0.986

C : concentration (%), η_∞ : infinite-shear viscosity (mPa s), η_o : zero-shear viscosity (mPa s), λ : characteristic time (s), N : dimensionless exponent, R^2 : coefficient of determination

The time constant related to the relaxation times of the polymer in solution (λ) at 8% concentration was higher than 1%, caused by the formation of strong intermolecular networks in the higher mucilage concentrations. The decreased values of the λ indicate the lower the rate of formation of new attachments. *N* at all concentrations was less than one (0.24 – 0.42), which indicates that the DAM solution was shear-thinning behavior. Similar behavior was observed for different solutions of DAM [22], Chinese yam mucilage [23], *D. opposita* mucilage [24, 25], *Salvia hispanica* mucilage [13], dan Chinese quince seed mucilage [16], *Lepidium perfoliatum* seed gum [26], Barhang seed [27], *Ocimum basilicum* seed (0,1–2%) [14], Tragacanth gum [28], Basil seed gum, Cress and Quince seed gum [29]. However, the different behavior of D. rotundata mucilage showed shear thickening behavior [7].

3.2 Fitting on apparent viscosity-concentrations-based models

Figure 2 shows η_a as a function of DAM concentration at different $\dot{\gamma}$ (10 and 100 s^{-1}, 30 °C). The η_a showed a decrease in viscosity with decreasing concentration and increasing shear rate, and η_a at a shear rate of 10 s^{-1} was higher than that of 100 s^{-1}. The critical concentration or overlapping concentration (c*) was the transition point from the polymer in the aqueous to the semi-aqueous form in which the polymer coils begin to interact and form overlapping coils [30]. When the concentration of polymer in solution is above c*, the viscosity can increase sharply if the polymer is added. The power law equation was plotted from the two logarithmic relationship lines between η_{app}–concentration to produce a confluence of points c* [31], carried out at the same shear rate. DAM began to experience bonds between the DAM molecules in solution so that it experienced a transition from dilute to semi-aqueous at c* estimates of 1.74% (τ = 10 s^{-1}) and 1.81% (τ = 100 s^{-1}).

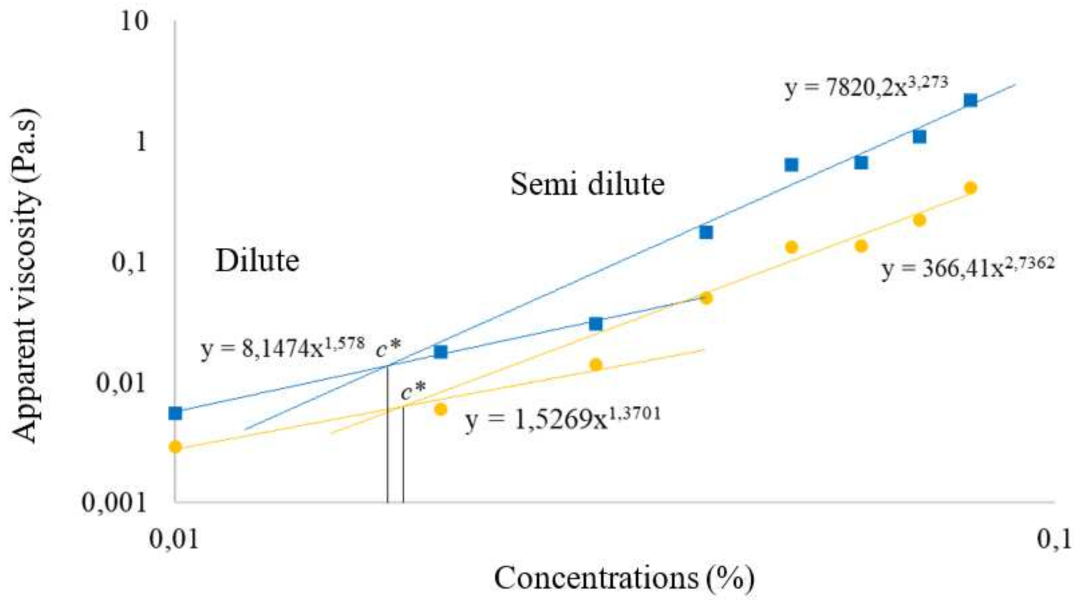


Fig. 2 Critical concentration (*c**) of *Dioscorea alata* mucilage solution (8% w/w) at shear rates of 10 (■) and 100 (●) s^{-1} (30 °C).

The DAM solution shows a shear-thinning behavior, as shown in Figure 2. At concentrations below 1.81%, η_a decreased slightly with increasing shear rate; the Newtonian plateau occurred at shear rates above 100 s^{-1}. Similar qualitative flow behavior has been reported for highly branched compact structure polysaccharides exhibiting low viscosities at high concentrations.

3.2.1 Hysteresis Loop

The "hysteresis area method" determines the behavior of the moving flow and the structural decomposition phase, which was calculated based on the area between the upward and downward curves of a flow curve test [12]. The hysteresis area represents the energy loss for the sol-gel transition or the energy index per unit of time and volume required to remove the effect of time on flow behavior [32]. As shown in Table 2, the hysteresis area of the DAM solutions increased with increasing concentration. The pointed positive value of the hysteresis area indicates DAM structure's recovery in decreasing the shear rate [33].

Table 1: Hysteresis area (mPa) as function of concentrations.

Concentrations	Hysteresis Area (mPa)
1%	0.337±0.250
2%	1.012±0.593
3%	1.709±1.070
4%	5.192±1.155
5%	22.054±5.728
6%	13.739±1.191
7%	23.464±6.719
8%	76.229±8.479

Results are indicated as means ± standard deviations for triplicate trials

3.3 Dynamic rheological properties

Therefore, the following measurements (strain sweep, frequency sweep, and temperature ramp) were used for the 8% (w/w) concentration of each sample because the 8% (w/w) of DAM was quite close, possibly caused by oversaturation. Complex fluids are viscoelastic materials that simultaneously exhibit viscous (liquid-like) and elastic (solid-like) characteristics under mechanical strain.

3.3.1 Strain sweep test

The strain sweep test was used to determine the linear-viscoelastic range (LVER) of 8% w/w DAM solution, carried out at a low angle frequency (ω = 1 rad/s), which can be seen in Figure 3. LVER shows gel strength and has two different regional characteristics: G' and G''. LVER shows the range of values for viscoelastic materials (fluid-like and solid-like materials). The LVER of the DAM solution of 8% w/w was found at the limit γ between 1–3.57% with a shear stress of 2.20–7.71 Pa and a $G'$of 215.68–210.51 Pa. γ at LVER equal to or greater than one identified an 8% (w/w) DAM solution as a natural biopolymer gel [27]. A 1% strain was used for the frequency sweep test because it was in the LVER, where the weak gel network was not damaged by the strain applied during the measurement.

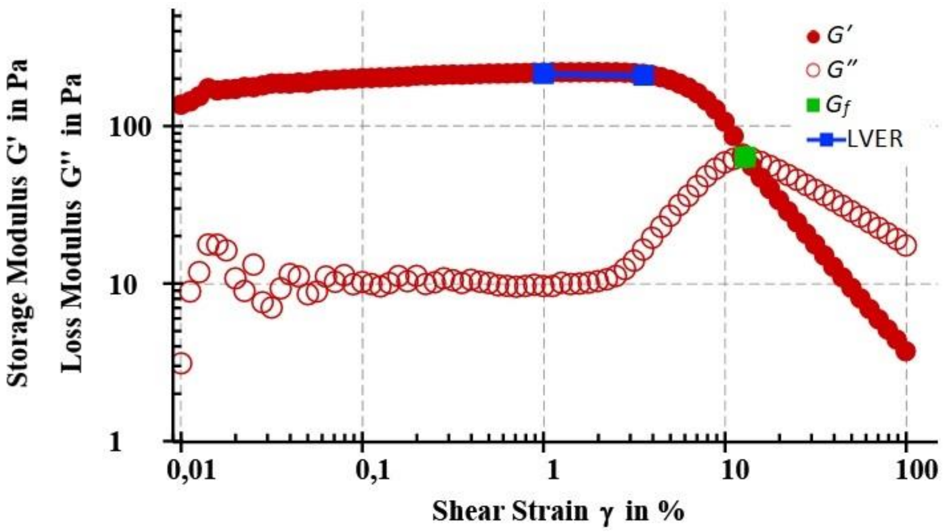


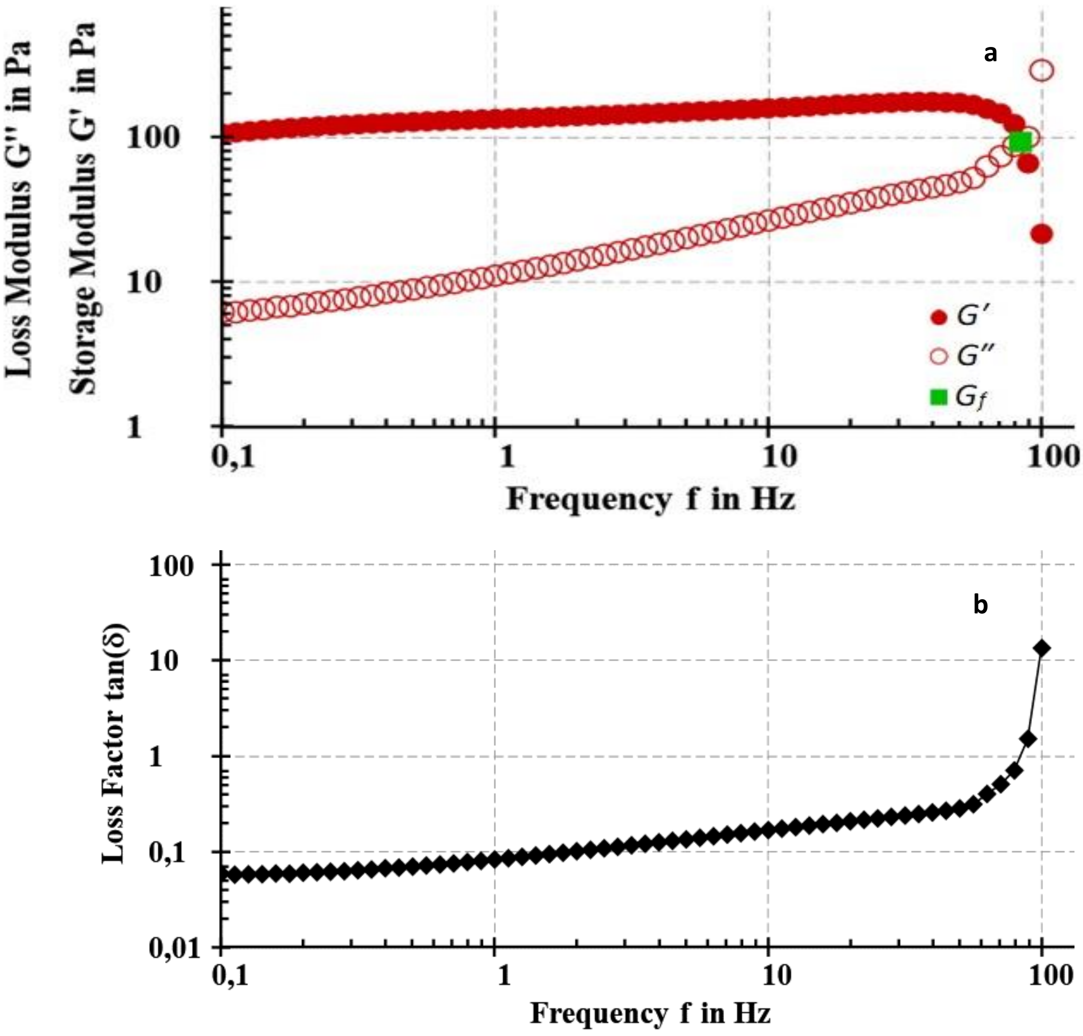
Fig. 3 Strain sweep at 8% w/w concentration of *Dioscorea alata* mucilage solution (ω= 1 rad/s, γ = 0.01–100%, 30 °C).

G' of 8% (w/w) DAM solution has a greater value than G'' in the LVER zone and before the flow crossover point (G_f = 63.89 Pa, = 13.0%), indicates the dominant elastic behavior (gel-like structure) in solution and the intermolecular interactions and bonds in the hydrocolloid conformation are stronger [17]. The crossover point is used to measure the elapsed time before the network first appears or as a measure of gelation time [34]. The G_f was considered a good indicator when the yield stress is exceeded, the structure breaks, and the flow behavior begins [35].

G' remains constant until the strain reaches a critical point, then G' starts to decrease sharply, representing that the deformability of mucilage occurs. G' decrease indicates a decrease in the elastic properties of the DAM, which shows the disruption of the gel-forming tissue in the mucilage. After the G_f, G' and G'' indicate that the DAM solution transitions from elastic to viscous characteristics. The G' value continued to decrease with adding the strain up to 100%, exhibiting that the DAM solution has viscous characteristics.

3.3.2 Frequency sweep test

The frequency sweep test was carried out on the LVER, which was used to characterize or classify the dispersion [36]. Figure 4a-c shows changes in G', G''', tanδ, and η* as a function of f of 8% (w/w) DAM solution at 30 °C. The 8% (w/w) DAM solution had a weak gel-like behavior where the values of G' and G'' increased with increasing frequency. $G'$was greater than G'' before the G_f. The 8% (w/w) DAM solution behaved like a gel-elastic at low frequencies and liquid-like at high frequencies. The results show a transition from an elastic-gel-like structure to a liquid-like structure. This behavior can be found in other DAM solutions, such as 0.1–1% quice seed gum solution [16].



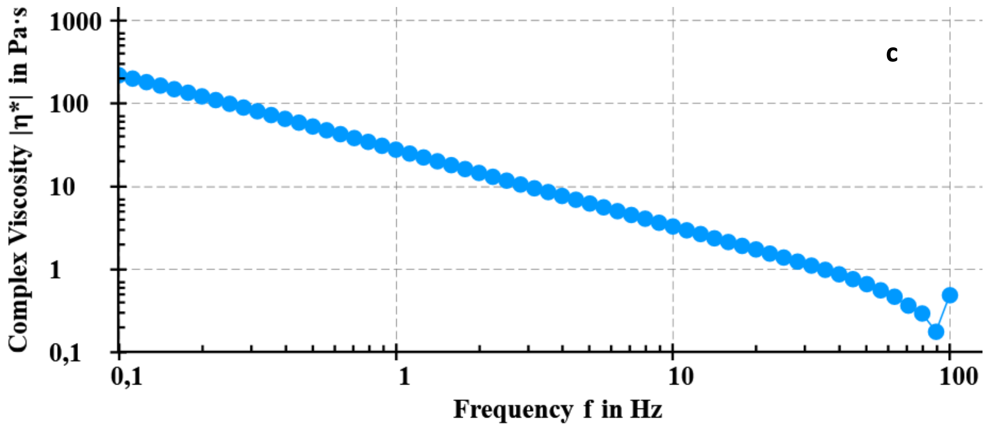


Fig. 4 Strain sweep frequency G' and G'' (a), tanδ (b), η* (c) 8% w/w of *Dioscorea alata* mucilage solution (f = 0.1–100 Hz, strain = 1%, 30 °C).

The frequency at which the curves G' and G'' intersect, or the frequency at which the elastic and viscous responses are same, is known as the f* [12]. The f* indicates gelation reaction kinetics [37] and, is an important rheological parameter and is inversely related to relaxation time [38]. Relaxation time is the time required for the sample to relax the received stress or for complete rearrangement of the polymer chain configuration between cross-links [39, 40]. The G_f (30 °C) occurs at a very high frequency of 83.70 Hz, which represents a meager relaxation time (0.012 seconds), with the G_f (G'= G'') being 92.745 Pa and f* of 0.25 Pa s (Figure 4a). The time interval is insufficient to break the intermolecular and intramolecular bonds and then re-form the molecules at high frequencies, so the chains of the ubiquitous DAM solution are not strongly bonded. The character of the 8% w/w DAM gel will change to a viscous character and begin to flow at the yield point (τ =1.324 Pa; G' = 97.89 Pa).

The power law model was used to model the relationship of $G'$and G'' to the angular frequency of the logarithmic plot in equations 17 and 18. The value of b in the log-log plot of G' versus was related to the strength and properties of the gel [36], including covalent gels if b = 0 while physical gels if b > 0. A low b value is a characteristic of an elastic gel, while for a b value close to 1, the system behaves as a viscous gel. At *a* value of b close to zero, G' does not change with frequency. The value of b slope G' was 0.079 (R^2 = 0.988), and the value of d slope G'' was 0.329 (R^2 = 0.989), which indicates the characteristic of 8% w/w DAM solution was an elastic gel. The intercept parameter k' (132.62) value was much higher than k'' (11.589), represents the rigidity of the continuous phase due to the effect of the hydrocolloid thickener, and confirms the gel-like behavior of DAM.

On the double logarithmic scale plot (Fig. 5c), the viscosity of the η^* decreased linearly with increasing frequency, indicating that the DAM solution had a non-Newtonian shear-thinning behavior. One of the techniques that shows gel strength is the slope of η^* versus f, where high slope values indicate more and stronger interactions in weak gel structures [35, 41]. The slope of the f - η^* of the 8% w/w DAM solution was 0.854. The DAM gel formed by overlapping and entangled flexible random coil chains has a weal gel characteristic, as shown by the complex's viscosity with a slope near to 0.8 [42]. Similar behavior was shown in 3% basil seed gum solution ($\eta^* = -0.84$) [35], *Plantago major* 1% seed gum solution ($\eta^* = -0.75$) [41], and 1.5% solution of *Lepidium perfoliatum* seed gum ($\eta^* = -0.76$) [36].

3.3.3 Temperature ramp

Regarding the effect of temperature on the DAM viscous properties, for concentrations of 8% (w/w) at 10 and 100 s^{-1} shear rate (Figure 5), range from 30 to 90°C using a heating rate of 2 °C/min. The DAM solution had a higher initial viscosity at a $\dot{\gamma}$ of 10 s^{-1} (1.916 Pa s) than at a $\dot{\gamma}$ of 100 s^{-1} (0.401 Pa s); this result is nearly identical to the steady shear viscosity in Figure 1. The viscosity of the 8% DAM solution is dramatically affected by temperature. The $\dot{\gamma}$ parameter of 100 s^{-1} was chosen because it is typical for food processing, including flow via pipes in industry, stirring, and mastication processes [43].

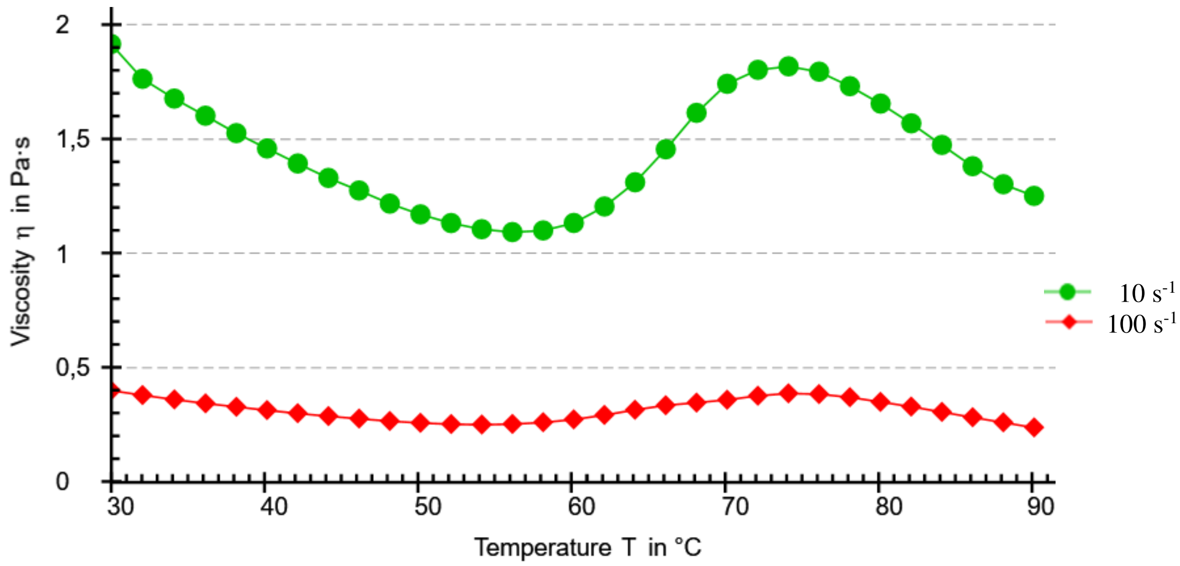


Fig. 5 Effect of temperature from 30°C to 90 °C using a heating rate of 2 °C/min on the viscosity of *Dioscorea alata* mucilage (8% w/w) at the shear rate of 10 and 100 s^{-1}

Table 3 shows that the *Ea* was positive and decreased with increasing $\dot{\gamma}$ at a temperature of 58–74 °C, in agreement with the results reported [44]. The activation energy indicates the viscosity's sensitivity to temperature changes. The higher activation energy means that the DAM solution's viscosity was relatively more sensitive to temperature changes. The activation energy at 30–56 °C and 76–90 °C was negative, which is called a non-inhibitory reaction, where an increase in temperature resluts in a decrease in the probability of the mucilage molecules colliding with each other. Viscosity decreases with increasing temperature. More energy is needed to break bonds and make molecules flow because liquids are made up of molecules linked by hydrogen bonds. However, these bonds will be broken at high temperatures by heat transfer.

Table 3: Relationship between 1/T and ln η for 8% (w/w) *Dioscorea alata* mucilage solution.

Temp (°C)	Shear rate 10 s^{-1}				Shear rate 100 s^{-1}			
	Ea/R	Ea (KJ mol^{-1})	R^2	RMSE	Ea/R	Ea (KJ mol^{-1})	R^2	RMSE
30–56	2154.23	-17.91	0.991	0.017	1872.65	-15.57	0.999	0.025
58–74	-4306.16	35.80	0.972	0.033	-2912.85	24.22	0.987	0.017
76–90	3358.76	-27.92	0.993	0.010	4365.87	-36.30	0.984	0.020

4 Conclusion

This research has studied the rheological behavior of DAM solution (1–8% w/w). Steady shear viscosity measurements of all DAM solutions showed non-Newtonian shear-thinning behavior, which was well-fitted using the Carreau model. The dynamic viscoelasticity study shows that the 8% DAM solution has a characteristic elasticity behavior, weak gel characteristics and mainly elastic and recoverable molecular structural deformation. The rheological characteristics of the mucilage solution are affected by concentration and temperature. The concentration of the DAM solution increases, which will increase the viscosity and shear-thinning properties. The concentration of DAM solution and different shear rate treatments affected the apparent viscosity of the DAM solution. This research on the rheological properties of DAM can provide useful information about the use of DAM as a source of hydrocolloids in food and non-food applications.

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