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RESEARCH PAPER

Rheological Characterization and Comparative Evaluation of Herschel Bulkley model, Power law model, and Bingham plastic model for Arrowroot Starch Dispersions

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ABSTRACT

Rheological Characterization and Comparative Evaluation of different rheological models in describing the flow Properties of gelatinized arrowroot (*Maranta arundinacea L.*) starch dispersions prepared at concentrations of 5%, 10%, 15%, 20% and 25% (w/v). Flow measurements were conducted over a shear rate range of 0.08, 0.16, 0.4, 0.66, 1.06, 1.6, 2.66, 3.2, 5.33, 8, 13.33, 16, 26.66 and the experimental data were fitted to the Herschel Bulkley model, Power law model, and Bingham plastic model to evaluate their predictive performance. All dispersions exhibited non-Newtonian, shear-thinning nature, with flow behaviour index (n) values ranging from approximately 0.41 to 0.946, depending on concentration. A progressive increase in consistency coefficient (K) (0.156 to 8.3 Pa·s^n) and yield stress (τ_0) (1.278 to 5.357 Pa) was observed with increasing starch concentration, indicating enhanced structural interactions within the system. Comparative model analysis showed that the Herschel Bulkley model provided the best fit, with higher coefficients of determination (R^2) (0.98-1.00) and lower error values (MSE) (0.09-1.48), along with more uniform residual distribution. The Power law model demonstrated acceptable fitting at intermediate shear rates (R^2) (0.96-0.998) but failed to capture low-shear deviations, while the Bingham plastic model showed comparatively poorer performance with higher error values (MSE up to ~20). However, the Herschel Bulkley model is the most appropriate for representing the complex rheological behaviour of arrowroot starch dispersions, particularly in systems exhibiting yield stress and concentration dependent structural characteristics.

Keywords: Arrowroot starch dispersion, Rheological models, Model comparison, Herschel Bulkley model, Power Law Model, Bingham Plastic Model, Non-Newtonian flow, Yield stress, Shear thinning behaviour

The rheological properties of starch dispersions are influenced by several factors, including shear stress, concentration, temperature, and processing conditions. Under various shear conditions, starch dispersions may exhibit complex flow behaviours such as shear thinning, thixotropy, or anti-thixotropic characteristics, depending on the magnitude of applied stress Hundekari and Swami (2024) and Kaur *et al.* (2010). These responses are associated with structural rearrangements within the dispersion, including breakdown and reformation of molecular interactions.

Starch is widely utilized in the food industry due to its functional properties such as thickening, gelling, and

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film forming ability. The performance of starch in these applications is largely governed by its rheological behaviour, which determines how the material flows and deforms during processing. Therefore, to study the rheology of starch hydrocolloids is essential for their effective industrial application, particularly in systems involving interactions with various additives Ahmed *et al.* (2017) The rheological response can vary significantly depending on the solvent system, sample preparation, and starch composition Ikeda and Nishinari, (2001). For example, the stability and flow characteristics of starch dispersions can be altered in different solvent conditions, indicating the importance of molecular interactions between starch components and the continuous phase Copeland *et al.* (2009).

The composition of starch, particularly the ratio of amylose to amylopectin, plays a crucial role in determining its rheological properties. Amylopectin rich starches tend to form network structures in Xu *et al.* (2020); Vekhande and Swami, (2025) aqueous systems, while amylose contributes to intermolecular association and gel formation. During gelatinization, starch granules swell, lose their crystalline structure, and release amylose into the surrounding medium, leading to the formation of a weak three dimensional network responsible for viscoelastic behaviour Chiotelli *et al.* (2002).

Most starch dispersions exhibit non-Newtonian flow behaviour, where viscosity changes with shear rate. For Example, wheat starch dispersions have been reported to show non-Newtonian flow and dynamic viscoelasticity under aqueous conditions Singh et al., (2016). In many cases, shear-thinning behaviour is observed due to the alignment and disentanglement of polymer chains under shear. However, depending on structural conditions, starch systems may also exhibit shear-thickening or time-dependent characteristics Wang *et al.* (2011).

The rheological behaviour of starch dispersions is also strongly dependent on concentration and temperature. Increasing starch concentration enhances intermolecular interactions, leading to higher viscosity and, in some cases, the development of yield stress. Similarly, temperature influences gelatinization and molecular mobility, thereby affecting the flow properties of the system Kim and Yoo, (2009); Rao, (2007).

Arrowroot (*Maranta arundinacea*) starch has gained increasing attention as a non-conventional starch source due to its fine granule size, high purity, and neutral taste, making it suitable for specialized food and biodegradable applications. From a rheological perspective, arrowroot starch dispersions are particularly important because their flow and deformation pattern directly influence processing characteristics such as mixing, pumping, coating, and film formation. While gelatinization, arrowroot starch forms a structured dispersion in which swollen granules and leached amylose contribute to the development of viscosity, yield stress, and viscoelastic properties. These rheological attributes are highly sensitive to concentration and shear conditions. Peroni *et al.* (2006); Hoover, (2001). structural features such as the degree of polymerization of amylopectin can significantly influence viscosity and rheological characteristics Singh *et al.* (2018).

The complex flow behaviour of starch dispersions, empirical and semi empirical rheological models are commonly used. Among these, the Power law model, Herschel Bulkley model, and Bingham plastic model are widely used due to their simplicity and effectiveness in representing non-Newtonian systems. The Power law model is frequently applied to describe shear thinning nature at intermediate and high shear rates; however, it does not account for yield stress and may therefore be inadequate for structured dispersions Rao, (2007). In other hand, the Herschel Bulkley model incorporates a yield stress term along with a non-linear flow component, making it more suitable for materials that exhibit an initial resistance to flow followed by shear dependent viscosity Xu *et al.* (2020). The Bingham plastic model also includes yield stress but assumes a linear relationship between shear stress and shear rate after yielding, which limits its applicability for highly non-linear system such as gelatinized starch dispersions Guo *et al.* (2022). Therefore, a comparative evaluation of these models is essential not only to determine the best statistical fit but also to understand the physical significance of model parameters in relation to the internal structure of starch dispersions.

MATERIALS AND METHODS

Material

Fresh arrowroot (*Maranta arundinacea*) rhizomes were collected from the university farm at Central Research Station, Wakawali Dr. B.S.K.K.V. Dapoli. The rhizomes were cleaned and used for starch extraction immediately after harvesting to avoid quality deterioration. All reagents used during the study were of analytical grade, and distilled water was used throughout the experimentation.

Extraction of Arrowroot Starch

Arrowroot (*Maranta arundinacea*) starch was extracted using a wet extraction method adapted from procedures reported by Cruz and Dash (2004). Fresh arrowroot rhizomes were thoroughly washed under running water to remove adhering soil, dust and impurities. The cleaned rhizomes were manually peeled to eliminate the outer skin and then cut into small pieces approximate 3mm thicker. The sliced rhizomes were grinding with the addition of distilled water in a ratio of approximately 1:2 (w/v) to obtain a homogeneous slurry. The resulting slurry was filtered through a muslin cloth to separate fibrous material from the starch rich liquid extract. The filtrate was allowed to stand for sedimentation of starch granules. After complete settling, the supernatant liquid was carefully decanted, and the sedimented starch was collected. The washing and sedimentation steps were repeated two to three times to improve the purity of the extracted starch. The collected starch was then dried in a tray dryer at 40-45 °C until a constant moisture content was achieved. The dried starch was ground into fine powder and stored in airtight polythene bags.

Preparation of Arrowroot Starch Dispersions

Arrowroot starch dispersions were prepared at different concentrations of 5%, 10%, 15%, 20%, and 25% (w/v) by dispersing the required quantity of starch in 100ml distilled water. The mixtures were initially stirred to obtain uniform suspensions without lump formation. The suspensions were then heated in a water bath at 90 ± 2 °C for 20 minutes with continuous stirring to ensure complete gelatinization of starch granules. After heating, the gelatinized

Table 1: Shows Comparative Analysis of Rheological Models

Model	Statement	Fow Behaviour	Key Feature	Reference
Herschel Bulkley Model	$\tau = \tau_0 + K\gamma^n$	Non-linear	High R^2, Low RMSE values indicate better model fitting. This model captures both yield stress and non-linearity in the flow behaviour. Although it is slightly complex, it is highly suitable for gel-like and structured systems.	Steffe (1996)
Power Law Model	$\tau_0 = K\gamma^n$	Non-linear	Moderate R^2 and RMSE values are generally observed for this model. It cannot capture yield stress but is simple and widely applicable describing general non-Newtonian fluids.	Rao (2007)
Bingham Plastic Model	$\tau = \tau_0 + \mu\gamma$	Linear (after yield)	Low R^2 and RMSE are usually obtained with this model. It cannot describe non-linear behaviour. However, it is simple with yield stress concept making it suitable for simple suspensions or slurries.	Saha and Bhattacharya (2019)

(Where τ_0 - yield stress (Pa), K - consistency coefficient (Pa.s^n), n - flow index behaviour, τ - shear stress (Pa), γ - shear rate (s^{-1}), μ - plastic viscosity (cP))

dispersions were allowed to cool to approximately 50 °C, and rheological measurements were carried out immediately to avoid structural changes due to prolonged storage.

Measurement of Viscosity Using Brookfield Viscometer

The apparent viscosity of arrowroot starch dispersions was determined using a Brookfield Viscometer (Model DV-II+ Pro) with Spindle No. 07. Before starting the measurements, the instrument was carefully level to ensure accurate readings. About 500 mL of the gelatinized starch dispersion was poured into a 500 mL beaker. The spindle was then immersed in the sample up to the designated mark and kept at the centre to maintain uniform shear during measurement.

Viscosity was measured at a range of rotational speeds (0.3, 0.6, 1.5, 2.5, 4, 6, 10, 12, 20, 30, 50, 60, and 100 rpm). At each speed, readings were taken only after the values became stable, and both torque (%) and viscosity (cP) were recorded, following the method described by Hundekari and Swami (2024). All measurements were carried out in triplicate to improve reliability. The obtained viscosity data were later used to calculate shear rate and shear stress.

Determination of Shear Rate (γ) and Shear Stress (τ)

For rotational viscometers, the shear rate is directly related to the angular velocity of the spindle. In the present study on arrowroot starch dispersions, the average shear rate (γ) was calculated using the method described by Razavi *et al.* (2007):

$$\gamma = \frac{8}{\pi}\Omega \qquad \dots (1)$$

Where:

γ = Shear rate (s^{-1})

Ω = Angular velocity (rad s^{-1})

The angular velocity (Ω) was determined from the rotational speed (N, rpm) using:

$$\Omega = \frac{2\pi N}{60} \qquad \dots (2)$$

By combining the above equations, the shear rate was simplified as:

$$\gamma = 0.267N \qquad \dots (3)$$

This relationship was used to calculate the shear rate corresponding to each spindle speed during the viscosity measurements.

The shear stress (τ) imposed on the arrowroot starch dispersion was calculated from the apparent viscosity and shear rate using the following relationship:

$$\tau = \eta \times \gamma \qquad \dots (4)$$

Where:

τ = Shear stress (Pa)

η = Apparent viscosity (Pa·s)

γ = Shear rate (s^{-1})

Substituting the expression for shear rate, shear stress can also be expressed as:

$$\tau = \eta\left(\frac{8}{\pi}\Omega\right) \qquad \dots (5)$$

These equations were used to calculate the shear rate and corresponding shear stress values for arrowroot starch dispersions at different rotational speeds.

Rheological Models and Model Optimization

The experimental data were fitted to the following rheological models: Herschel Bulkley model, Power law model, Bingham plastic model. In this model include parameters such as consistency coefficient (K), flow behaviour index (n), and yield stress (τ_0) were determined using regression analysis.

Rheological Model Optimization

The performance of the selected rheological models was evaluated using statistical criteria to determine their suitability in describing the flow behaviour of arrowroot starch dispersions. The residual sum of squares (RSS), root mean square error (RMSE), and coefficient of determination (R^2) were used as statistical indicators to quantify the deviation between experimental and model predicted values.

The statistical evaluation of model fitting is presented in Fig. 1 (a). The Herschel Bulkley model showed the highest R^2 and lowest RMSE values across all concentrations, indicating the best fit. The Power law model showed moderate agreement, while the Bingham plastic model exhibited poor fitting due to its inability to represent non-linear flow behaviour. The residual plots in Fig. 1 (b) provide further insight into model performance. The Herschel–Bulkley model showed randomly distributed residuals around zero, indicating a good fit. In contrast, the Power law model showed slight deviations, while the Bingham plastic model exhibited a systematic pattern, confirming its poor suitability Moreira *et al.* (2012).

(1) Root Mean Square Error (RMSE)

$$\text{RMSE} = \frac{RSS}{Degree\ of\ freedom} = \frac{RSS}{N-M} \quad \ldots (6)$$

Where:

RMSE = Root mean square error

RSS = Residual sum of squares

N = Number of experimental observations

M = Number of model parameters

RMSE represents the average deviation between experimental and predicted values. Lower RMSE values indicate better model accuracy.

(2) Coefficient of Determination (R^2)

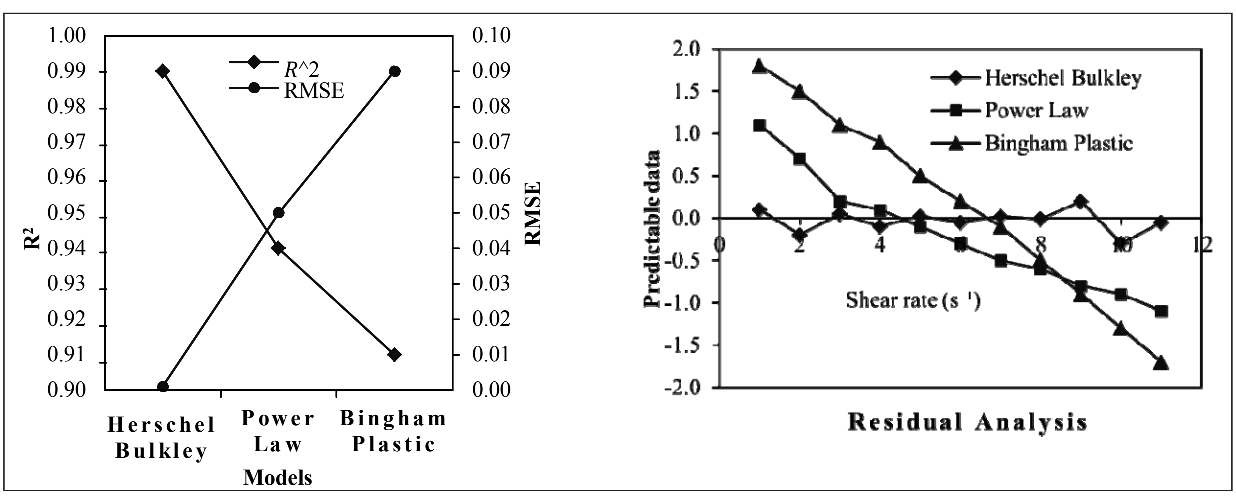
$$\text{R squared} = 1 - \frac{RSS}{TSS} \quad \ldots (7)$$

Where:

RSS = Residual sum of squares

TSS = Total sum of squares

The R^2 value indicates the degree of correlation between experimental data and model predictions. Values closer to unity represent a better fit of model.



(a) **(b)**

Fig. 1: General comparison of rheological model based performance **(a)** R^2, RMSE and **(b)** Residual analysis for arrowroot starch dispersions.

(3) Residual Analysis

$$\text{Residuals} = \tau - \tau' \quad \dots (8)$$

Where:

τ = Experimental shear stress

τ′ = Predicted shear stress

Residual analysis was carried out to examine the distribution of errors across the shear rate range. A random distribution of residuals indicates a good model fit, whereas systematic deviation suggests model inadequacy.

Statistical Analysis

The accuracy of model fitting was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). A model with higher R^2 and lower RMSE values was considered to provide a better representation of the experimental data. Data analysis was performed using standard software Systat 13.6.

RESULTS AND DISCUSSION

Flow Behaviour of Arrowroot Starch Dispersion

The relationship between shear stress and shear rate (0.3, 0.6, 1.5, 2.5, 4, 6, 10, 12, 20, 30, 50, 60 and 100 rpm) for arrowroot starch dispersions at different concentrations (5-25% w/v) is presented in Figure 2 For all samples, shear stress increased with increasing shear rate; however, the relationship was non-linear, confirming non-Newtonian behaviour. At lower shear rates (≤5 rpm), a comparatively significant increase in shear stress was observed, indicating higher resistance to flow due to the presence of swollen granules and intermolecular interaction of starch molecules.

As the shear rate increased beyond 10 rpm, the rate of increase in shear stress became less pronounced, reflecting structural breakdown and alignment of macromolecules in the direction of flow. This behaviour was more evident at higher concentrations (10%, 15%, 20% and 25%), where increased particle interactions and amylose leaching contributed to greater initial resistance and higher overall stress values. The observed trend is characteristic of shear-thinning systems, where internal structural elements are progressively disrupted under applied shear, leading to reduced flow resistance at higher deformation rates. Similar flow behaviour has been reported for starch-based dispersions under steady shear conditions Steffe, (1996); Rao, (2014).

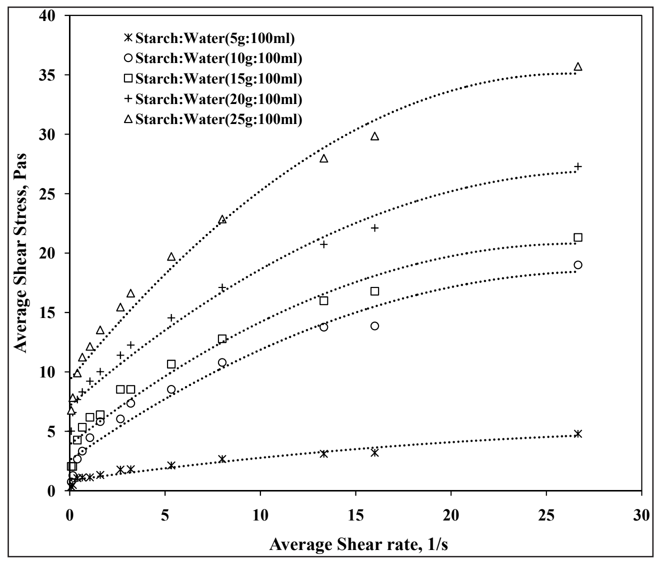


Fig. 2: Shear Stress (Pa) versus Shear rate (1/s) for Arrowroot starch

The variation of apparent viscosity with shear rate for arrowroot starch dispersions at different concentrations (5%, 10%, 15%, 20% and 25% w/v) is presented in Fig. 3. A continuous decrease in viscosity with increasing shear rate was observed for all samples, confirming shear-thinning (pseudoplastic) behaviour. At lower shear rates (≤5 rpm), the system exhibited higher viscosity due to strong intermolecular interactions, including hydrogen bonding and network formation of starch chains. At low shear rates, the system exhibits higher viscosity, which can be attributed to the presence of a temporary network formed by swollen starch granules and leached polysaccharide chains. These interactions contribute to resistance against flow, particularly at higher concentrations. As shear rate increases, this network undergoes alignment and partial breakdown, resulting in reduced internal resistance and lower apparent viscosity Rao, (2014); Steffe, (1996).

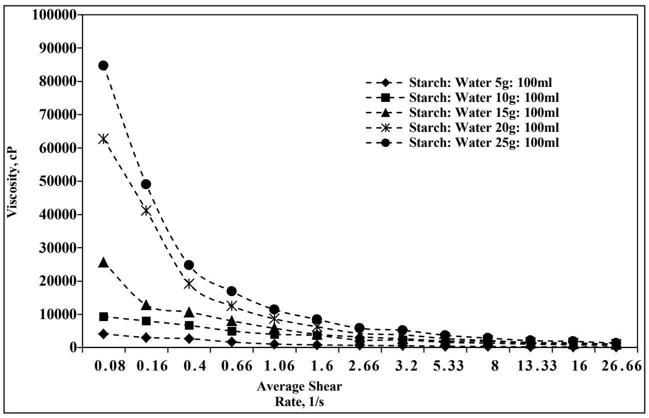


Fig. 3: Apparent Viscosity (cP) versus Shear rate (1/s) for Arrowroot starch

The magnitude of viscosity and its rate of decline are strongly influenced by concentration. Dispersions in the range of 15-25% (w/v) show significantly higher initial viscosity and a sharper reduction with shear rate, indicating a more developed structural network and stronger intermolecular associations. This response is consistent with concentrated biopolymer systems where entanglement density and particle interactions govern flow resistance Morris, (1990); Roberts *et al.* (2002). From a models perspective, the observed viscosity profiles support the application of shear-dependent rheological models. While the Power law model adequately captures viscosity reduction at higher shear rates, it fails to represent the structural resistance at low shear. In contrast, the Herschel-Bulkley model, through inclusion of a yield stress component, provides a more realistic description of the entire viscosity–shear relationship. Thus, the viscosity behaviour not only confirms the pseudoplastic nature of arrowroot starch dispersions but also highlights the importance of considering structural effects when selecting an appropriate rheological model Heidarinasab and Nanas, (2010).

The log-log representation of shear stress as a function of shear rate for arrowroot starch dispersions (5%, 10%, 15%, 20% and 25% w/v) provides a scaling perspective of the flow behaviour in Fig. 4. The data exhibit a near-linear trend over the intermediate shear region, indicating a power law type dependence where shear stress scales with shear rate according to $\tau \propto \gamma^n$. The slope of the linear segment corresponds to the flow behaviour index (n), which remains less than unity for all concentrations, confirming shear-thinning characteristics Rao, (2014); Steffe, (1996). Notably, the deviation from linearity at lower shear rates highlights the limitation of simple scaling models. The curvature observed in this region suggests the presence of a stress threshold associated with the breakdown of a weakly structured network. Such behaviour is typical of concentrated biopolymer dispersions and cannot be adequately captured by the Power law model, which assumes zero yield stress Barnes, (2000).

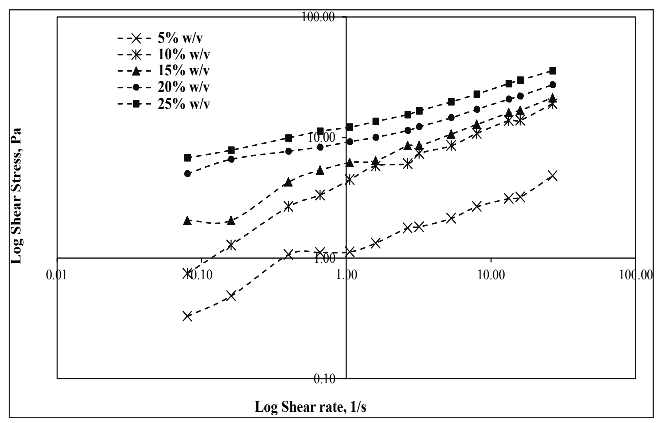


Fig. 4: Log-Log Plot of Shear stress (Pa) versus Shear rate (1/s) of Arrowroot starch

In contrast, the Herschel Bulkley model extends the relationship by considering a yield stress term, allowing it to accurately describe both the initial resistance to flow and the subsequent shear-dependent behaviour. This makes it particularly suitable for systems exhibiting structural integrity at low deformation rates Chhabra & Richardson, (2008). Additionally, the progressive upward shift of the curves with increasing concentration reflects enhanced intermolecular associations and network density. The increasing departure from linearity at low shear further indicates that yield stress becomes more significant as concentration increases, a behaviour widely reported in starch-based and other hydrocolloid systems Parker *et al.* (2001); Morris, (1990).

Herschel Bulkley Model

Table 2: Parameters of Herschel-Bulkley model of Arrowroot starch

Proportion (g: ml)	Parameters of Herschel-Bulkley model				
	τ_0	K	n	r^2	MSE
5:100	1.278	0.156	0.946	0.981	0.199
10:100	1.457	2.678	0.565	0.991	1.483
15:100	1.537	4.172	0.474	0.998	0.314
20:100	4.370	4.496	0.496	1.0	0.091
25:100	5.357	8.343	0.414	0.999	0.437

Table 2 shows the Herschel Bulkley model was applied to describe the flow behaviour of arrowroot starch dispersions across different concentrations. This model considers the presence of yield stress (τ_0), which represents the minimum stress required to initiate flow, along with the consistency coefficient (K) and flow behaviour index (n).

From the obtained results, the values of τ_0 increased with increasing starch concentration, indicating that higher concentrations develop a stronger internal structure that resists flow. Similarly, the consistency coefficient (K) also showed an increasing trend, reflecting higher viscosity and resistance at greater concentrations.

The flow behaviour index (n) remained less than 1 for all samples, confirming pseudoplastic (shear thinning) behaviour. The high coefficient of determination (R^2, 0.98-1.00) and comparatively low mean square error (MSE) values indicate that this model provides an excellent fit to the experimental data. This suggests that the Herschel Bulkley model effectively captures both yield stress and shear-dependent flow, making it suitable for describing structured systems such as gelatinized starch dispersions Rao, (2014) and Moreira *et al.* (2012).

Power Law Model

Table 3: Parameters of Power Law Model of Arrowroot starch

Proportion (g: ml)	Parameters of Power Law Model			
	K	n	r^2	MSE
5:100	0.853	0.516	0.959	0.393
10:100	3.882	0.480	0.989	1.552
15:100	5.331	0.421	0.998	0.390
20:100	7.868	0.377	0.997	0.865
25:100	11.068	0.357	0.998	0.726

Table 3 shows the Power law model was used to evaluate the shear dependent flow behaviour of arrowroot starch dispersions without considering yield stress. The model parameters include the consistency coefficient (K) and flow behaviour index (n). The results show that the value of K increases with concentration, indicating higher viscosity at higher starch content. The flow behaviour index (n) remained below unity, confirming shear-thinning characteristics across all concentrations.

Although the model provided relatively high R^2 values (0.96-0.99), it exhibited higher MSE compared to the Herschel Bulkley model, particularly at lower concentrations. This indicates that while the Power law model can adequately describe the flow behaviour at moderate to high shear rates, it fails to account for the initial resistance to flow observed at low shear rates. Therefore, the Power law model is limited in describing systems where yield stress plays a significant role M. E. Ojewumi *et al.* (2017); Rao, (2014).

Bingham Plastic Model

Table 3 shows the Bingham plastic model assumes a linear relationship between shear stress and shear rate after overcoming a yield stress. The model parameters include yield stress (τ_0) and plastic viscosity (μ). In this study, τ_0 values increased with starch concentration, indicating stronger structural resistance at higher concentrations. However, the

R^2 values for this model were comparatively lower (0.94-0.98), and the MSE values were significantly higher than those of the other models.

Table 4: Parameters of Bingham Plastic Model of Arrowroot starch

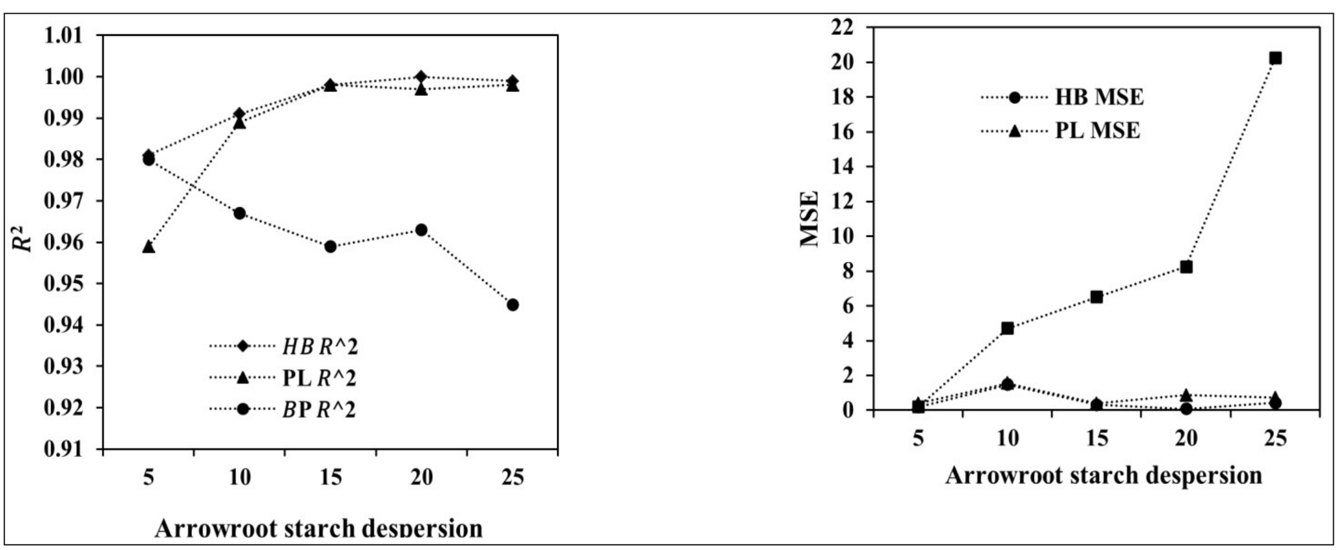
Proportion (g: ml)	Parameters of Bingham Plastic Model			
	μ	τ_0	r^2	MSE
5:100	1.358	0.128	0.980	0.183
10:100	5.940	0.501	0.967	4.715
15:100	7.870	0.524	0.959	6.497
20:100	11.272	0.624	0.963	8.251
25:100	15.617	0.792	0.945	20.230

This suggests that the Bingham model is not suitable for describing the non-linear shear thinning behaviour observed in arrowroot starch dispersions. The model oversimplifies the system by assuming linear flow beyond yield stress, which does not represent the actual rheological behaviour of starch-based systems. Dak *et al.* (2007); Chhabra & Richardson, (2008).

Comparative Analysis of Rheological Models

A comparative evaluation of the three models Herschel Bulkley model, Power law model, and Bingham plastic model was carried out based on statistical parameters such as R^2 and MSE shown in Fig. 5 (a) and (b) respectively.

The Herschel Bulkley model consistently showed the highest R^2 values (close to unity) and the lowest MSE across all concentrations, indicating superior predictive accuracy. The Power law model showed good agreement at higher shear rates but failed to accurately represent low shear behaviour due to the absence of a yield stress term. In contrast, the Bingham plastic model exhibited the lowest fitting accuracy, as indicated by lower R^2 and significantly higher MSE values. This is because the model assumes a linear flow region, which does not match the non-linear rheological behaviour of starch dispersions. Overall, the results clearly demonstrate that the Herschel Bulkley model is the most suitable for describing the rheological behaviour of arrowroot starch dispersions, as it accounts for both yield stress and shear-thinning characteristics. Similar findings have been reported for other starch-based and hydrocolloid systems Rao, (2014); R.A. Muhammad *et al.* (2013).



(a) (b)

Fig. 5: Combined evaluation of rheological models showing variation of **(a)** coefficient of determination (R^2) and **(b)** mean square error (MSE) with starch concentration.

CONCLUSION

The present work demonstrates that arrowroot starch dispersions prepared at 5%, 10%, 15%, 20%, and 25% (w/v) exhibit complex flow behaviour that cannot be adequately described by a single simplified rheological approach. The systematic comparison of models highlights that the choice of model significantly influences the interpretation of flow characteristics, particularly in systems where structural interactions and yield response are prominent.

When the models were compared using goodness of fit criteria, the Herschel Bulkley model consistently performed best, giving higher R^2 values (0.98-1.00) and lower RMSE (0.19-1.4) across all concentrations. The Power law model showed reasonable agreement in the mid-shear region (R^2 0.96-0.99) but did not capture the low-shear region adequately. The Bingham plastic model was less suitable overall, as reflected by comparatively lower R^2 (0.94-0.98) and higher RMSE, indicating its limitation for non-linear systems. The better performance of the Herschel Bulkley model can be linked to its ability to account for a yield stress component along with shear dependent changes in viscosity, which are key features of structured starch dispersions.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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