



Non-Newtonian Characterization of Gelatinized Corn Starch Dispersions with Magnetic Particle Enhancement Under Shear Stress

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ABSTRACT

Starch-based dispersions continue to be of interest as non-Newtonian fluids because of their availability, biodegradability and sensitivity to applied shear stress. It is significant that one understands how their flow behaviour can be altered with the help of particulate additives both in characterizing materials and in feasibility studies due to their applications. The steady-shear rheological behaviour of gelatinized corn starch-water dispersions using locally sourced yellow and white varieties of corn was studied in this work, at a fixed formulation of 20 g starch in 350 mL of water. The loading levels of 0 g, 2 g and 4 g of iron filings were added and the rheological measurements were done under the influence of a static magnetic field using a rotational viscometer. The power-law model was used to analyse the data on apparent viscosity to quantify shear dependence through the flow behaviour index (n) and consistency parameter ($\ln\mu$). All fixed formulations of the starch were non-Newtonian and shear thinning, and all flow behaviour indices were found to be less than one under the conditions considered. The iron filings had a quantifiable effect on the viscosity and consistency, and this means that the resistance to flow under shear was increased. These findings offer controlled rheological insight into magnetically modified corn starch systems and also in their plausibility as shear-dependent, energy-dissipating media for further investigation in applied material systems.

Keywords: Non-Newtonian, Gelatinization, Shear thinning, Rheology, Power law model.

INTRODUCTION

Chemical Composition of Corn Starch

Corn starch, which is a carbohydrate obtained from maize (*Zea mays* L.) is commonly used with diverse applications in food processing, pharmaceuticals and engineered material systems. The behaviour of starch in water bodies is controlled by its molecular architecture and interaction with the water and it is therefore a common topic in the investigation of non-Newtonian fluids and complex dispersions (BeMiller and Whistler, 2009). Corn starch is a polysaccharide in structure and is mainly made of two glucose-based polymers namely amylose and amylopectin whose proportions have a strong impact on gelatinization behaviour and rheological response (Araújo *et al.*, 2020).

Amylose is a predominantly linear polymer and typically constitutes a smaller fraction of corn starch. During heating in excess water, amylose leaches from swollen granules and contributes to viscosity development and gel formation (Hoover, 2001). Systems with higher amylose contribution exhibit apparent shear-dependent viscosity reduction under stress, which is associated with pseudoplastic flow behaviour (Xie *et al.*, 2009). Amylopectin, on the other hand, is a highly branched polymer that forms the bulk of the starch granule structure. Its branched structure encourages the swelling of the granules and the formation of networks in the process of gelatinization which can increase resistance to flow depending on shear conditions and concentration (BeMiller & Whistler, 2009).

The process of gelatinization involves the swelling of the granules and melting of crystalline regions. These changes are the main source of the non-Newtonian behaviour that governs gelatinized corn starch dispersions and forms the structural foundation of rheological response to steady shear (Barnes, 2000).

Rheological Behaviour

Gelatinized corn starch dispersions are commonly known to be non-Newtonian fluids whose apparent viscosity varies with the applied shear rate. Starch pastes when in the hydrated form have both viscous and elastic nature due to the polymer entanglement, granule residues and the inter-molecular interaction in the continuous phase (Barnes, 2000). These systems usually exhibit shear-thinning behaviour under steady-shear conditions with viscosity declining with shear rate, especially when the concentration is moderate (Xie *et al.*, 2009).

The extent of shear dependence depends on the starch concentration, the degree of gelatinization, temperature, and the structure of the polymer network. Empirical models, especially the power-law model have been extensively used to characterise the flow behaviour of gelatinized starch dispersions, as they are simple and effective in capturing non-Newtonian trend (Rao, 2014). The flow behaviour index is a quantitative value to determine the non-Newtonian flow and is often applied to compare starch systems prepared under varying conditions (Falana *et al.*, 2025).

Rheological response can also be altered by the addition of particulate additives by increasing the resistance of the flow and altering the consistency. These modifications are especially applicable in cases where external fields do affect the particle distribution or contact with the starch matrix, making the necessity of controlled rheological characterization especially important in the process of assessment of modified starch systems.

Rheological Relevance

Increasing interest in sustainable and bio-based materials has renewed attention in starch-based systems to be used in situations where flexible mechanical response is required. Corn starch is attractive due to its low cost, biodegradability and availability. From a rheological standpoint, the shear-dependent viscosity of gelatinized corn starch dispersions provides a basis for considering their relevance in systems where increased resistance to deformation under stress is desirable (Rao, 2014).

Recent research focuses on employing rheological parameters such as power-law indices, as indirect indicators on the capacity of a material to dissipate energy by viscous processes during deformation (Falana *et al.*, 2025). Although none of these parameters is a direct measure of impact or ballistic resistance, they provide necessary prior information on flow resistance and structural response to shear. As a result, steady-shear rheological test serves as a screening method that can be used to identify starch-based systems that may warrant further investigation under dynamic or application-specific loading conditions.

Problem Statement

Gelatinized corn starch dispersions have been proposed to be used in protective textile systems like military uniforms because of their non-Newtonian nature and the possibility of a shear-dependent response. Nevertheless, it is unclear whether the exact rheological behaviour of locally prepared corn starch systems is known especially when the systems are modified with iron filings and affected by magnetic fields. There is a need to experimentally determine their steady-shear behaviour using parameters such as the power-law flow behaviour index and consistency index. Without such characterization, the real-world usefulness of

magnetically modified corn starch dispersions in military uniform systems would be largely hypothetical, and it highlights the need for controlled rheological investigation.

Research Objective

The objective of this study is to characterize the steady-shear rheological behaviour of gelatinized corn starch-water dispersions modified with iron filings, with emphasis on quantifying shear-dependent viscosity and

power-law flow parameters. This research aims to evaluate the feasibility of gelatinized corn starch dispersions as shear-responsive rheological systems through steady-shear characterization and magnetic particle modification.

Research Hypothesis

Hypothesis 1: Power-law model can satisfactorily explain the rheological behaviour of gelatinized yellow and white corn starch-water dispersions at the chosen concentration, and these findings can validate the non-Newtonian flow behaviour.

Hypothesis 2: Introduction of a constant magnetic field with iron filings into gelatinized corn starch dispersions also changes the flow behaviour and consistency indices of such dispersions suggesting their usefulness as shear-dependent, energy-dissipating materials like military uniforms.

METHOD AND MATERIALS

Sample Preparation

Yellow and white corn varieties were obtained from local sources. The maize kernels were washed and steeped in water, which softened the endosperm, then wet-milled into a slurry by mechanical grinding. The slurry that resulted was mixed with distilled water and passed through a fine mesh sieve to get starch. The filtrate was left to settle under gravity over a few hours after which the supernatant was carefully decanted. The starch sediment which was recovered was dried at room temperature. To every formulation, 20 g of corn starch was measured on a calibrated analytical scale with precision of ± 0.01 g. 350 mL of deionized water was prepared and approximately 50 mL was used to pre-disperse the starch into a fine suspension. The rest of the water was boiled (100 °C) and gradually added to the slurry with constant stirring to induce gelatinization of the slurry. The resulting gelatinized starch paste was mixed until homogenous dispersion. Iron filings were added at loading levels of 0 g, 2 g and 4g and mixed all the mixtures again to make the particles even. Gelatinized dispersions were left to cool down to ambient laboratory temperature (25 °C) before testing to reduce any artefacts due to viscosity from thermal gradients. The samples were made fresh for each experimental run.

Apparatus

Steady-shear rheological measurements were carried out with an 8-speed rotational viscometer, configured for apparent viscosity measurements of high-viscosity fluids. The instrument was run at discrete rotational speeds of 600, 300, 200, 100, 60, 30, 6, and 3 rpm. Apparent viscosity was determined from the measured torque transmitted through the spindle using the calibration constants of the instrument. A standard viscometer cup was used to test the samples and it was ensured that the depth of the spindle immersion was consistent. Before testing all measuring devices were calibrated according to the specification of the manufacturer.

Testing Procedure

Each gelatinized corn starch samples were transferred into a 350 mL viscometer test cup and firmly positioned on the viscometer platform to avoid mechanical instability. The spindle was immersed to the calibration mark and then measurements started. In order to enhance uniformity of the sample, the rotation speed of the spindle was set to 600 rpm and allowed to rotate 5 s. Then the viscosity was measured at decreasing rotational speeds of 300, 200, 100, 60, 30, 6 and 3 rpm. At each speed, readings were taken after the torque signal stabilized, typically within 10-15 s. The final low-shear, which was 3 rpm was sustained at 10 s to record the gel-like behaviour of the dispersion. All the measurements were conducted at room temperature. In order to ensure reproducibility, two independent experimental runs were carried out with the entire testing protocol, and freshly prepared samples were used in each experimental run.

Magnetic Setup

In tests that involved magnetic influence, iron-modified samples were placed in the presence of a static magnetic field using a permanent magnet placed outside the wall of the viscometer cup. The first samples with 2g iron filings were made, then additional 2g of iron filings was applied and measurements made again with a total loading of 4g of iron filings. Samples which did not contain iron filings served as control specimens and were subjected to the same rheological conditions without exposure to any magnetic field. This set up allowed the assessment of the influence of iron loading and magnetic interaction on the steady-shear rheology of the gelatinized corn starch dispersions.

Analysis

The non-Newtonian flow of the corn starch is described to be

$$\tau = \mu \left(\frac{du}{dy} \right)^n$$

$\tau =$ shear stress, $\mu =$ consistency parameter,

$\frac{du}{dy} =$ shear rate, $n =$ power law exponent

Taking the natural logarithm of both sides gives

$$\ln \tau = \ln \left(\mu \left(\frac{du}{dy} \right)^n \right)$$

$$\ln \tau = \ln \mu + n \ln \left(\frac{du}{dy} \right) \rightarrow 1$$

This has similar structure as a simple linear equation

$$y = mx + c \rightarrow 2$$

Comparing equations 1 and 2

$$y = \ln \tau, \quad m = n,$$

$$x = \ln \left(\frac{du}{dy} \right), \quad c = \ln \mu$$

RESULTS AND DISCUSSION

The shear rate applied during rheological testing was determined from the rotational speed of the Brookfield viscometer using the R1B1 spindle configuration, R1 is the spindle speed and B1 is the spindle speed configuration.

Table 1: Brookfield Viscometer Configuration

Shear rate range	R1B1
Shear rate constant, k_p (sec^{-1} per RPM)	1.7023

Shear rate(sec^{-1}) 3RPM	5.11
6RPM	10.21
30RPM	51.07
60RPM	102.14
100RPM	170.23
200RPM	340.46
300RPM	510.69
600RPM	1021.38

For all samples, shear stress was recorded in two independent experimental runs at each rotational speed. The average shear stress was measured at every shear rate and it was taken as the representative value to be used in the analysis later. Natural logarithms of the shear rate and the average shear stress were then calculated to enable power-law modelling.

Rheological Behaviour of White Corn Starch Dispersions

The steady-shear rheological response of white corn starch dispersions is presented in Tables 2–4, which list the measured shear stresses from two runs, the averaged shear stress values, and the corresponding logarithmic terms used for the analysis.

Table 2: Shear stress and shear rate data for white corn starch without iron filings

S/N	RPM	Shear Rate (s^{-1})	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	$\ln(du/dy)$	$\ln(\tau)$
1	600	1021.38	18	16	17	6.92891	2.83321
2	300	510.69	11	12	11.5	6.23576	2.44235
3	200	340.46	9.5	10	9.75	5.83030	2.27727
4	100	170.23	8	8	8	5.13715	2.07944
5	60	102.14	6	6.5	6.25	4.62634	1.83258
6	30	51.07	4	5	4.5	3.93320	1.50408
7	6	10.21	3.5	4	3.75	2.32337	1.32176
8	3	5.11	3	3	3	1.63120	1.09861
9	10 seconds coil strength	-	7	7	7	-	1.94591

Table 3: Shear stress and shear rate data for white corn starch with 2g of iron filings

S/N	RPM	Shear Rate (s ⁻¹)	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	ln(du/dy)	ln(τ)
1	600	1021.38	18	18	18	6.92891	2.89037
2	300	510.69	12	14	13	6.23576	2.56495
3	200	340.46	11	11	11	5.83030	2.39790
4	100	170.23	10	9	9.5	5.13715	2.25129
5	60	102.14	8	8	8	4.62634	2.07944
6	30	51.07	6	7	6.5	3.93320	1.87180
7	6	10.21	5	6	5.5	2.32337	1.70475
8	3	5.11	5	5	5	1.63120	1.60944
9	10 seconds coil strength	-	4	8	6	-	1.79176

Table 4: Shear stress and shear rate data for white corn starch with 4g of iron filings

S/N	RPM	Shear Rate (s ⁻¹)	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	ln(du/dy)	ln(τ)
1	600	1021.38	19	20	19.5	6.92891	2.97041
2	300	510.69	11	16	13.5	6.23576	2.60269
3	200	340.46	10	13	11.5	5.83030	2.44235
4	100	170.23	9	11	10	5.13715	2.30259
5	60	102.14	8	9	8.5	4.62634	2.14007
6	30	51.07	7	8	7.5	3.93320	2.01490
7	6	10.21	6	7	6.5	2.32337	1.87180
8	3	5.11	6	6	6	1.63120	1.79176
9	10 seconds coil strength	-	5	10	7.5	-	2.01490

Log–log plots of shear stress against shear rate derived from these tables produced linear relationships for all iron loading levels, confirming non-Newtonian behaviour. The resulting fitted equations are:

- 0 g iron: $\ln(\tau) = 0.3335 \ln(du/dy) + 0.3735$
- 2 g iron: $\ln(\tau) = 0.2552 \ln(du/dy) + 0.9751$
- 4 g iron: $\ln(\tau) = 0.2289 \ln(du/dy) + 1.1901$

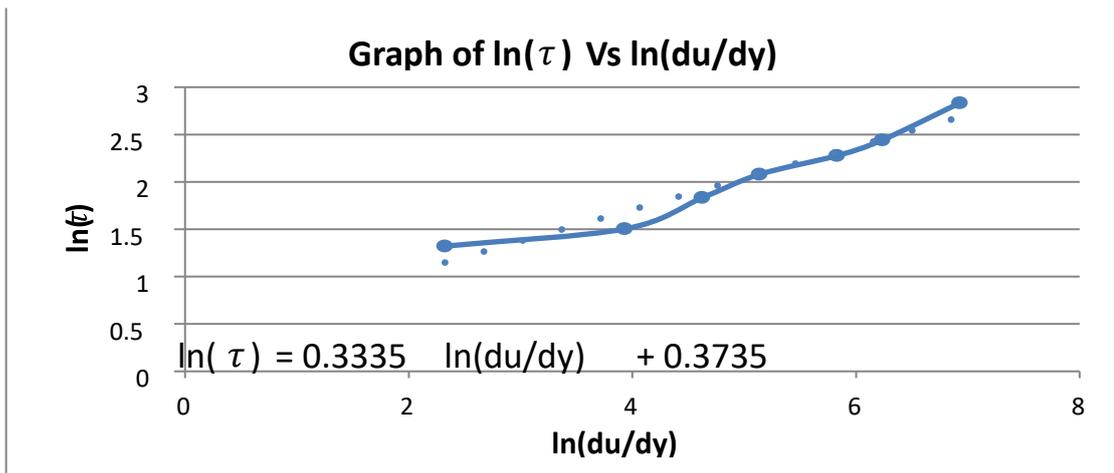


Figure 1: Graph of $\ln(\tau)$ against $\ln(du/dy)$ for white corn starch without iron filings

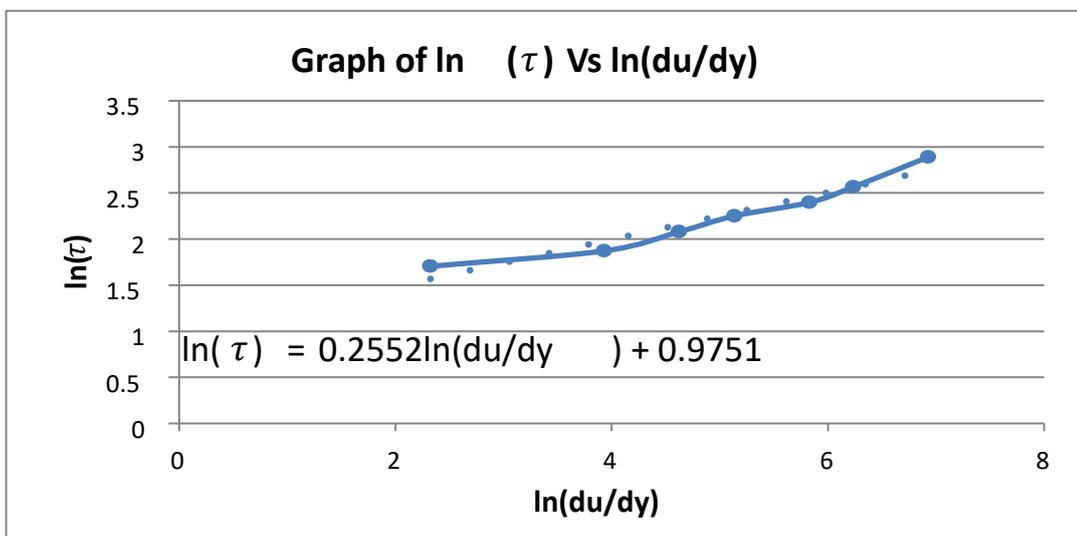


Figure 2: Graph of $\ln(\tau)$ against $\ln(du/dy)$ for white corn starch with 2g of iron filings

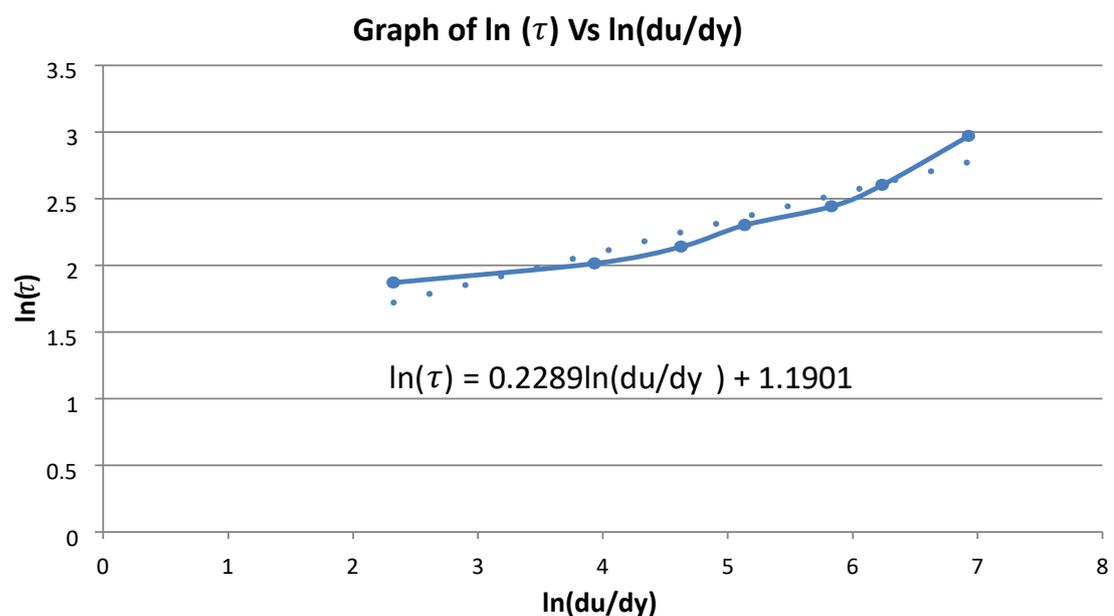


Figure 3: Graph of $\ln(\tau)$ against $\ln(du/dy)$ for white corn starch with 4g of iron filings

In all cases, the flow behaviour index (n) is less than one, indicating shear thinning behaviour. Increasing iron loading results in a progressive decrease in n and an increase in the intercept, reflecting enhanced shear dependence and increased resistance to flow.

Rheological Behaviour of Yellow Corn Starch Dispersions

A similar analytical approach was applied to yellow corn starch dispersions. The measured and averaged shear stress data along with their natural logarithms, are presented in Tables 5-7.

Table 5: Shear stress and shear rate data for yellow corn starch without iron filings

S/N	RPM	Shear Rate (s^{-1})	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	$\ln(du/dy)$	$\ln(\tau)$
1	600	1021.38	15	18	16.5	6.92891	2.80336
2	300	510.69	9	13	11	6.23576	2.39790
3	200	340.46	8	11	9.5	5.83030	2.25129
4	100	170.23	6	9	7.5	5.13715	2.01490
5	60	102.14	5	7.5	6.25	4.62634	1.83258
6	30	51.07	4	6	5	3.93320	1.60944
7	6	10.21	3	5	4	2.32337	1.38629
8	3	5.11	2	4	3	1.63120	1.09861
9	10 seconds coil strength	-	6	9	7.5	-	2.01490

Table 6: Shear stress and shear rate data for yellow corn starch with 2g of iron filings

S/N	RPM	Shear Rate (s^{-1})	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	$\ln(du/dy)$	$\ln(\tau)$
1	600	1021.38	18	20	19	6.92891	2.94444
2	300	510.69	11	14	12.5	6.23576	2.52573
3	200	340.46	10	12	11	5.83030	2.39790
4	100	170.23	9	11	10	5.13715	2.30259
5	60	102.14	7	8	7.5	4.62634	2.01490
6	30	51.07	5	7	6	3.93320	1.79176
7	6	10.21	5	6.5	5.75	2.32337	1.74920
8	3	5.11	5	6	5.5	1.63120	1.70475
9	10 seconds coil strength	-	3	9	6	-	1.79176

Table 7: Shear stress and shear rate data for yellow corn starch with 4g of iron filings

S/N	RPM	Shear Rate (s ⁻¹)	Shear Stress 1	Shear Stress 2	Average Shear Stress (τ)	ln(du/dy)	ln(τ)
1	600	1021.38	22	24	23	6.92891	3.13549
2	300	510.69	20	17	18.5	6.23576	2.91777
3	200	340.46	19	14	16.5	5.83030	2.80336
4	100	170.23	18	12	15	5.13715	2.70805
5	60	102.14	18	10	14	4.62634	2.63906
6	30	51.07	17	9	13	3.93320	2.56495
7	6	10.21	16	8	12	2.32337	2.48491
8	3	5.11	15	7	11	1.63120	2.39790
9	10 seconds coil strength	-	9	10	9.5	-	2.25129

The corresponding log–log plots yielded the following relationships:

- 0 g iron: $\ln(\tau) = 0.3037 \ln(du/dy) + 0.5229$
- 2 g iron: $\ln(\tau) = 0.2589 \ln(du/dy) + 0.9517$
- 4 g iron: $\ln(\tau) = 0.1346 \ln(du/dy) + 2.0773$

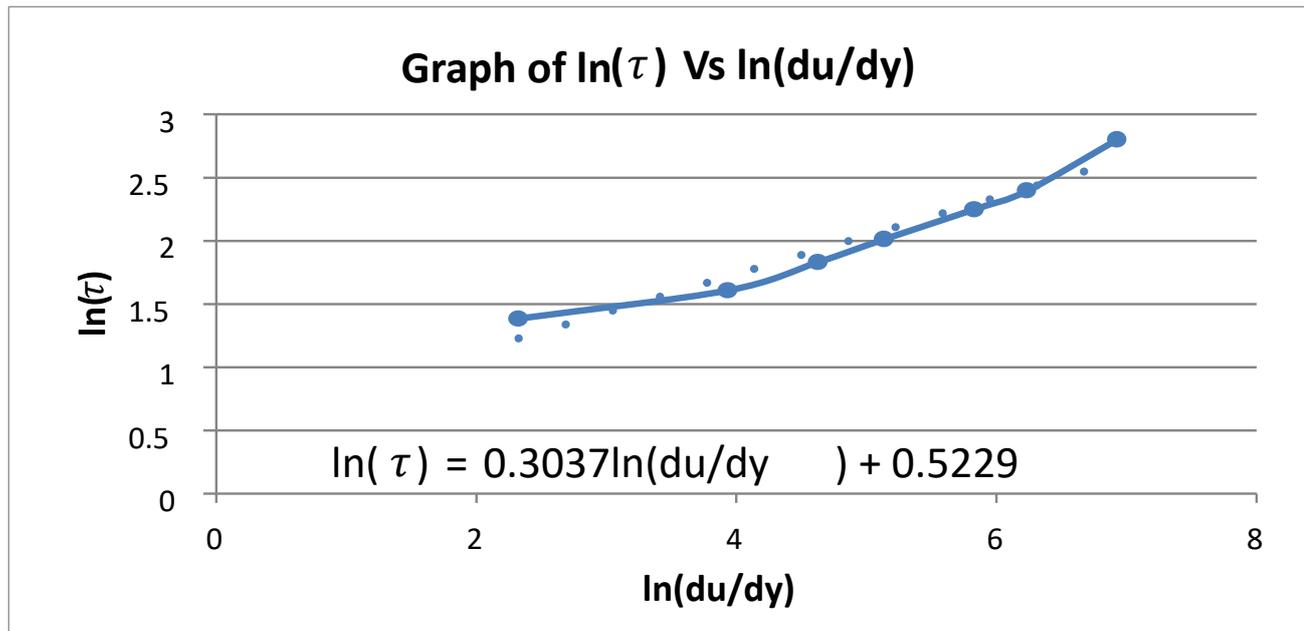


Figure 4: Graph of ln(τ) against ln(du/dy) for yellow corn starch without iron filings

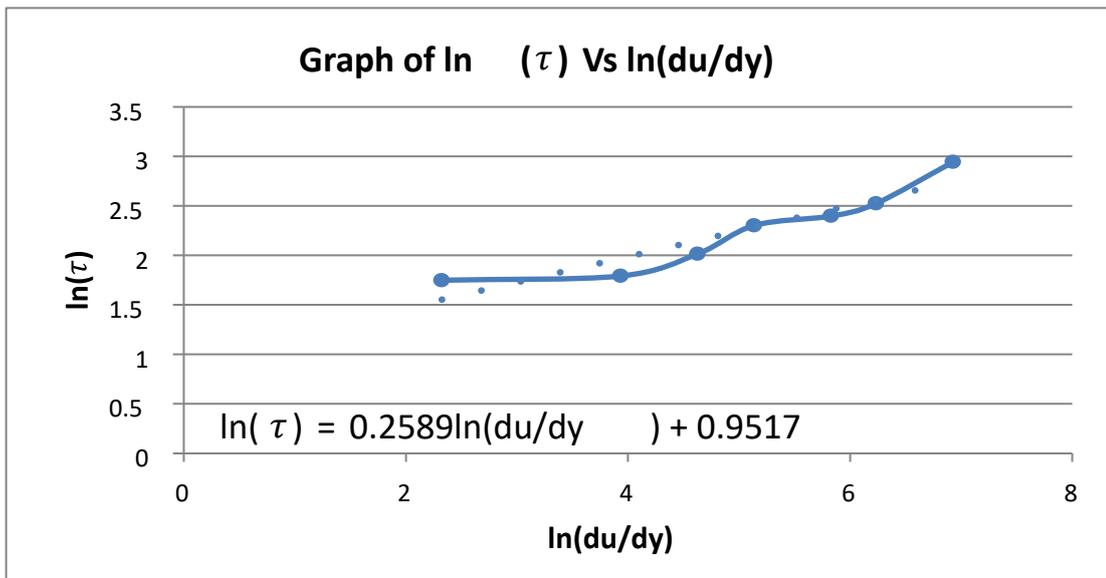


Figure 5: Graph of $\ln(\tau)$ against $\ln(du/dy)$ for yellow corn starch with 2g of iron filings

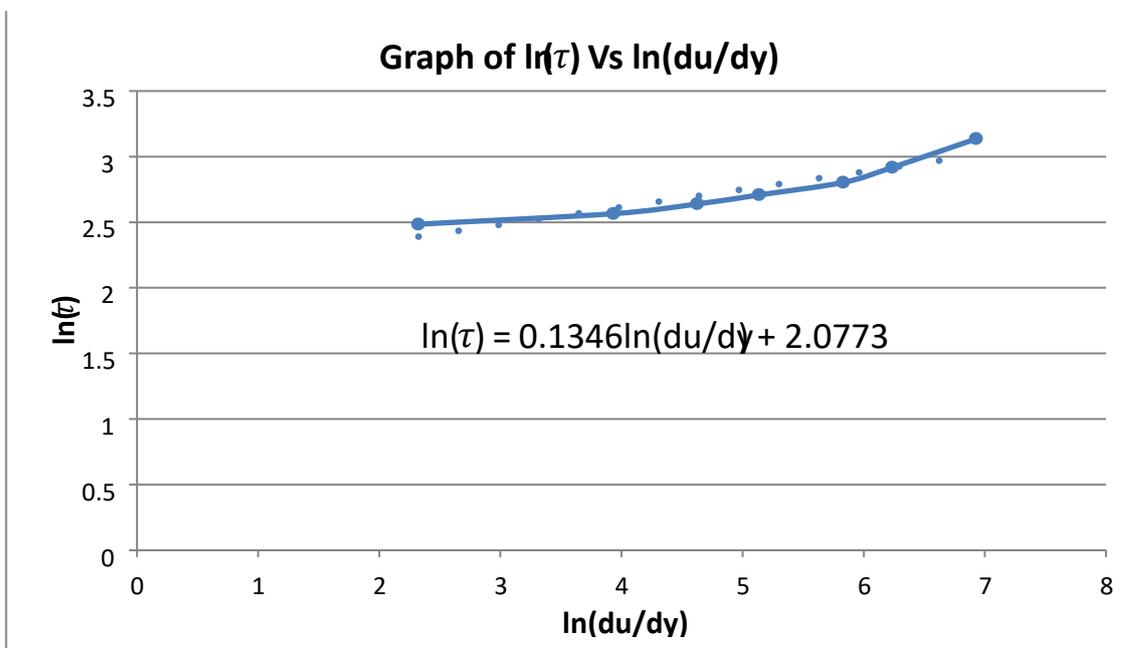


Figure 6: Graph of $\ln(\tau)$ against $\ln(du/dy)$ for white corn starch with 4g of iron filings

As observed for white corn starch, all yellow corn starch formulations exhibit shear thinning behaviour. However, the reduction in the flow behaviour index with increasing iron loading is more pronounced for the yellow corn starch which suggests a stronger modification of shear-dependent response.

Effect of Iron Loading and Implications for Shear-Dependent Behaviour

The influence of iron loading on the rheological behaviour of gelatinized corn starch dispersions is well depicted in the changes in power-law parameters. For both corn varieties, increasing iron content from 0 g to 4g results in a decrease in the flow behaviour index (n) and a corresponding rise in the consistency parameter. In the white corn starch, n in the unmodified sample is 0.3335 and at 4 g of iron loading, n is 0.2289; in yellow corn starch, n in the unmodified sample is 0.3037, and n in the 4 g of iron loading is 0.1346. These decreases represent an enhancement of shear thinning behaviour with increasing iron content.

This simultaneous reduction in n and increase in consistency indicates that addition of iron improves internal structural interactions inside the gelatinized starch matrix. The reinforced microstructure under applied shear

needs a greater stress to maintain flow. The stronger response in yellow corn starch, especially at increased iron loading suggests varietal differences in how starch networks interact with particulate additives. Varying ratios of amylose and amylopectin and gelatinized network strength can affect the degree to which iron particles can cause resistance to flow and shear sensitivity.

Though the current analysis has been conducted in steady-shear conditions, the trends in rheology directly apply to material behaviour that is shear-dependent. A reduced flow behaviour index and a higher consistency level is preferable in systems that are being used to withstand deformation with increasing stress and are also processable at low shear. The rheological response observed suggests potential relevance to protective textile applications such as military uniforms.

Evaluation of Research Hypotheses

Hypothesis 1: Power-law model can satisfactorily explain the rheological behaviour of gelatinized yellow and white corn starch-water dispersions at the chosen concentration, and these findings can validate the non-Newtonian flow behaviour.

Reflection and Validation

This hypothesis is supported by the results obtained from the steady-shear analysis. In both yellow and white corn starch dispersions, the log-log plots of shear stress versus shear rate showed linear relationships, which showed that the power-law model adequately describes the flow behaviour of the systems during the investigated conditions. The flow behaviour indices calculated using the fit equations were always lower than one across all of the samples, which validated shear thinning behaviour and non-Newtonian flow.

The results indicate that gelatinized corn starch dispersions prepared with a fixed concentration have predictable non-Newtonian response which can be quantitatively described using empirical power-law parameters. The consistency in the values between the experimental data and the power-law model thus confirm the validity of the power-law model for describing the steady-shear rheology of the investigated systems supporting Hypothesis 1.

Hypothesis 2: Introduction of a constant magnetic field with iron filings into gelatinized corn starch dispersions also changes the flow behaviour and consistency indices of such dispersions suggesting their usefulness as shear-dependent, energy-dissipating materials like military uniforms.

Reflection and Validation

This hypothesis is evidently supported by the results of the experiment. In both types of corn, there was a systematic decrease in flow behaviour index and corresponding increase in consistency as iron loading advanced from 0 g to 4 g. This trend shows improved shear dependence and resistance to flow when particulate is added to it. The effect was observed for both the yellow and white corn starch dispersions though the change was more pronounced in the yellow corn starch.

The observed modification of rheological parameters suggests that iron particles contribute to internal structural reinforcement within the gelatinized starch matrix, particularly under the influence of a static magnetic field. Although dynamic and impact testing were not included in this study, the changes in powerlaw parameters provide quantitative rheological indicators of increased viscous energy dissipation under shear. As such, the results confirm the conceptual feasibility of magnetically modified corn starch dispersions as shear-responsive materials which validates Hypothesis 2.

CONCLUSION

The steady-shear rheological behaviour of gelatinized corn starch–water dispersions prepared from yellow and white corn varieties was successfully characterised using power-law modelling. All the samples were non-Newtonian and shear-thinning, with the flow behaviour indices smaller than one, which is why the power-law model is appropriate to explain the flow response of the samples.

The addition of iron filings under the effect of a static magnetic field resulted in a decrease in the flow behaviour index and an increase in consistency which demonstrates an increase in shear dependence and resistance to deformation. The differences in the extent of these effects between the two varieties of corn indicate that the composition of starch has an effect on the rheological reaction to particulate modification.

Despite the fact that the work was reduced to steady-shear analysis, the trends can be used as indicators of shear-dependent energy-dissipating behaviour and support the theoretical viability of magnetically modified corn starch dispersions to be used as shear-responsive material such as protective textiles.

RECOMMENDATIONS

Guidance for Future Research

Further research to examine the steady-shear analysis should incorporate dynamic and impact-loaded conditions of the sample to analyse the energy-dissipation potential of the magnetically modified corn starch dispersions under application-relevant stresses. Investigations of how the concentration of starch, temperature, and strength of the magnetic field influence rheological response would further improve understanding of the tunability of rheological response. Microstructural analysis techniques can also be used to explain the processes that take place between particles and starch.

Practical Application

The rheological trends observed in this study suggest that gelatinized corn starch dispersions modified with iron filings may be suitable for use in shear-responsive material systems. Although direct performance validation is necessary, the findings indicate potential relevance to protective textile applications, including military uniforms, in which controlled resistance to deformation under stress is required. Further development should focus on material integration strategies compatible with textile systems.

Contribution to Knowledge

This study presents experimental results of the rheological behaviour of gelatinized corn starch dispersions as well as evidence of how magnetic particulate modification can affect power-law flow parameters. The work contributes to the body of knowledge on bio-based, non-Newtonian materials by establishing the relationship between iron loading and shear-dependent behaviour. It also supports the use of rheological characterisation as a screening tool for shear-responsive systems.

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