Rheological Characterization of Cassava Starch under Shear Stress with Magnetic Particle Enhancement

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ABSTRACT

This research explores the rheological behavior of cassava starch, focusing on its dilatant and pseudoplastic responses under varying shear stresses and shear rates, with and without the influence of a magnetic field. The study aims to empirically validate theoretical projections by determining the power law exponent, which characterizes the starch's flow behavior, and to examine its viability for functional applications, particularly in protective materials such as military gear. Two cassava starch varieties were locally obtained and manually processed. A base sample of 20g was prepared and subjected to rheological evaluation. Subsequently, iron filings were incorporated at 2g and 4g concentrations to investigate the influence of magnetic particulates on viscosity. Flow behavior analysis was conducted by applying the linearized form of the power law model, and data visualization was executed using Microsoft Excel. Findings demonstrate that cassava starch at a 20g concentration displays shear-thinning (pseudoplastic) behavior. Upon the addition of iron fillings, an increase in the power law exponent was observed, signifying heightened apparent viscosity and greater resistance to flow under applied stress. These results suggest that magnetic additives significantly influence the rheological profile of cassava starch, enhancing its potential as a tunable non-Newtonian fluid. The study concludes that cassava starch, inherently pseudoplastic, can be effectively modified with magnetic components to exhibit tailored flow characteristics, offering promising implications for smart materials designed to absorb and dissipate impact. Future investigations are recommended to refine the formulation and assess its integration into real-world protective systems.

Keywords: Rheology, non-Newtonian, dilatant, pseudo plastic, cassava starch.

INTRODUCTION

Starch Chemistry

Cassava starch, derived from the roots of the cassava plant (*Manihot esculenta Crantz*), is a key carbohydrate source with diverse applications in both food and non-food industries (Chaturvedi et.al,2024). Like every other starch, cassava starch exhibits both mechanical and rheological properties that are influenced by its molecular structure and water content. Early studies identified starch as a polysaccharide, and further research into non-Newtonian fluids revealed its potential as a pseudoplastic material—a material that thin out under stress (Ojewumi et.al,2019).

Cassava starch primarily consists of two glucose-based polymers: amylose and amylopectin. These two components play a major role in gel formation and influence the rheological properties of starch-based fluids. Amylose is a linear-chain polymer, making up 15–25% of cassava starch. It plays a vital role in gel formation when heated in water. Amylose-rich starch exhibits pseudoplastic behavior, where viscosity decreases with increasing shear rate. Amylopectin is a highly branched polymer that constitutes 75–85% of the starch content. It is mainly responsible for the gelatinization of starch and contributes to dilatant behavior by forming a branched, entangled network that resists flow under stress. Additives such as glycerol and salts can modify the rheological behavior of cassava starch. Glycerol, for example, can decrease viscosity and alter the shear-thickening properties by affecting the molecular interactions within the starch granules. The gelatinization temperature of cassava starch is influenced by the plant variety, the amount of water present, and the content of amylopectin. This temperature can be altered through granule swelling, crystal or double-helix melting, and amylose leaching (Ojewumi, 2019).

Rheological Behaviour

The mechanical properties of cassava starch are crucial for understanding its structure. These include tensile strength, elasticity, and viscoelastic behavior. In its dry form, starch granules are brittle. However, when hydrated, the starch forms a gel-like structure and becomes more flexible. During gel formation, cassava starch exhibits both elastic (solid-like) behavior—allowing it to return to its original state after shear stress—and viscous (liquid-like) behavior—resisting deformation. Its rheological properties are essential for understanding and optimizing its uses. These properties depend on its ability to absorb water and the shear conditions introduced. Studies show that cassava starch exhibits shear-thinning behavior under specific conditions, influenced by factors such as temperature, concentration, and the presence of additives (Cossa, 2019).

Practical Relevance

The mid-20th century's focus on sustainability and biodegradable materials further increased interest in cassava starch, especially in its application for eco-friendly products like biodegradable plastics. By the 1990s, researchers began exploring its mechanical properties, laying the groundwork for its use in protective gear due to its ability to thicken under stress (Osunbitan & Ogunbusola, 2018).

Problem Statement

The application of cassava starch in military uniforms is proposed due to its non-Newtonian properties, which could enhance protective features. However, uncertainty surrounding the precise rheology behaviour of cassava starch presents significant challenges. There is a critical need to validate theoretical claims regarding its non-Newtonian characteristics, particularly by determining the power law exponent that defines its flow behaviour under stress. Without this validation, the practical applicability of cassava starch in military uniforms remains speculative, necessitating rigorous experimental investigations to establish its reliability and effectiveness in such applications.

Research Objective

The primary objective of this study is to experimentally investigate the dilatant or pseudo plastic behaviors of cassava starch, with a focus on validating theoretical claims and determining the power law exponent that characterizes its non-Newtonian flow properties. This research aims to assess the practical applicability of cassava starch in military uniforms by establishing its reliability and effectiveness as a protective material under varying stress conditions.

Research Hypothesis

Hypothesis 1: The rheological behaviour of cassava starch can be accurately characterized by a specific power law exponent, which will validate existing theoretical claims regarding its non-Newtonian properties.

Hypothesis 2: Cassava starch, when properly processed and applied, will demonstrate practical applicability in military uniforms by enhancing protective capabilities through its non-Newtonian properties

METHODS AND MATERIALS

Sample Preparation

Two cassava cultivars—white and yellow varieties (Manihot esculenta Crantz)—were harvested from local sources. Post-harvest, the roots were peeled, washed, and grated into a slurry using standard mechanical grating tools. The slurry was mixed with distilled water and passed through a fine mesh sieve to separate starch from fibrous material. The resulting suspension was allowed to sediment under gravity for several hours. The supernatant was decanted, and the starch sediment was dried at ambient temperature. For each experiment, 20 g of dried cassava starch was weighed using a calibrated analytical balance (±0.01 g precision). A total of 350 mL of distilled water was prepared—50 mL was used to pre-mix the starch into a uniform slurry, while the remaining 300 mL was heated to boiling (100°C) and added to the starch mixture to achieve gelatinization. The gelatinized suspension was cooled to room temperature (25°C) using a water bath to prevent viscosity artifacts from thermal gradients. All samples were prepared fresh before each trial.

Apparatus

Rheological analysis was performed using an 8-speed rotational viscometer (Brookfield-type, R1B1 configuration), designed to measure apparent viscosity under varying shear conditions. The device operated at discrete rotational speeds of 600, 300, 200, 100, 60, 30, 6, and 3 rpm. The viscometer measures torque (T) transmitted through the spindle as it rotates in the sample, which correlates with shear stress (τ) via the instrument's calibration constants. Sample preparation involved dispersing 20 g of cassava starch in 350 mL of distilled water using a high-speed mechanical mixer to ensure homogeneous suspension. A precision digital weighing balance (±0.01 g) was used for accurate material measurements. Samples were tested at ambient temperature using a rheometer cup that ensured consistent immersion depth of the spindle. In trials involving magnetic influence, 2 g and 4 g of iron filings were added to the suspension, and a neodymium magnet was externally affixed to the rheometer cup to generate a localized magnetic field. All equipment was calibrated before each trial to ensure reproducibility and accuracy of results.

Testing Procedures

Each cassava starch sample (gelatinized) was transferred into a 350 mL viscometer test cup. The cup was centered and secured on the viscometer platform to prevent mechanical instability. The rotor was immersed until the calibration mark was fully submerged in the starch solution. To ensure sample homogeneity, the rotor was first spun at 600 RPM for 5 seconds. Sequential measurements were taken at decreasing speeds: 300, 200, 100, 60, 30, 10, 6, and 3 RPM. At each speed, the rotor was operated until the viscosity reading stabilized, typically within 10–15 seconds. For low-shear characterization, the final reading was held at 3 RPM for 10 seconds to capture the gel-like response. All measurements were conducted at room temperature. Each test was conducted in duplicate (n = 2) for both cassava types. The viscometer's measurement accuracy is ±1% of full scale, as per manufacturer calibration.

Magnetic Setup

To investigate magnetic field effects, 2 g of iron filings were added to the starch suspension and manually dispersed. A bar magnet was place adjacent to the rheometer cup wall to introduce localized static magnetic field. The same rheological testing procedures described above was repeated under magnetic influence. After the initial test, an additional 2 g of iron filings (totaling 4 g) was added, and measurements were repeated. Each condition (0 g, 2 g, and 4 g magnetic particles) was tested to validate the results obtained for consistency.

Analysis

The non-Newtonian flow is given to be

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

$\tau = shear\ stress, \mu = \ viscosity, \frac{du}{dy} = shear\ rate, n = power\ law\ exponent$

Converting the non-Newtonian equation to straight line equation to be able to get the power law.

Take the natural log of both sides.

$y = mx + c \rightarrow 1$

M and c are the gradient and y intercept of the straight line

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

$ln\tau = log\mu + n\ ln(\frac{du}{dy}) \rightarrow 2$

Comparing equation 1 and 2

$$y = \ln\tau, m = n, ln\left(\frac{du}{dy}\right) = x, ln\mu = c$$

RESULTS AND DISCUSSION

The shear rate is dependent on the RPM of the Brookfield viscometer configuration (R1B1), the R1 is the spindle speed and the B1 is the spindle speed configuration.

Table 4.1: 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

Yellow cassava starch test data without magnetic field influence

Table 4.2: Yellow cassava starch data without iron filling particle

S/N	RPM	Shear stress (N/m^2)	Shear rate(1/s)	In(τ)	In($\frac{\partial u}{\partial y}$)
1	600	100	1021.38	4.60517	6.92891
2	300	68	510.69	4.21951	6.23576
3	200	55	340.46	4.00733	5.83030

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4	100	38	170.23	3.63759	5.13715
5	60	30	102.14	3.40119	4.62634
6	30	23	51.07	3.13549	3.93320
7	6	14	10.21	2.63906	2.32337
8	3	12	5.11	2.48491	1.63120
9	10 seconds coil strength	12	-	-	-

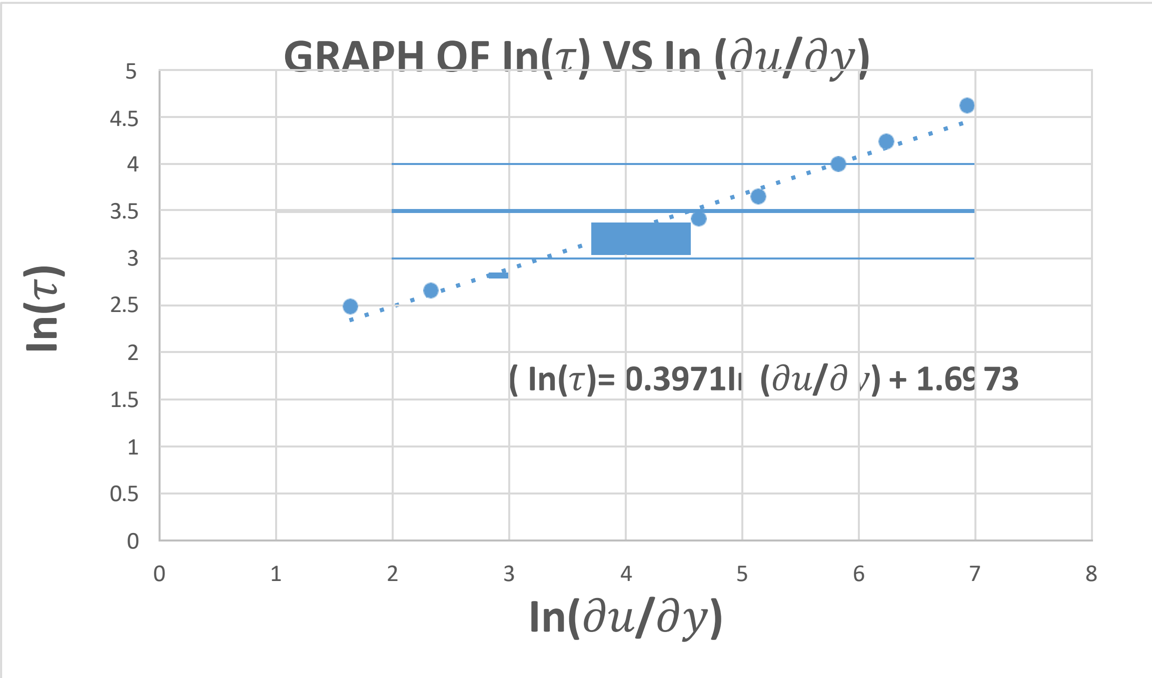

Figure 4.1: Graph of shear stress vs shear rate for yellow cassava starch without iron filling particles

The graph of the natural logarithm of shear stress plotted against the natural logarithm of shear rate provides a clear linear relationship, indicating the flow behaviour of the yellow cassava starch suspension. The equation of the line, given as:

In(τ) = 0.3971 In(∂u/∂y) + 1.6973

Shows that the slope of the line (0.3971) represents the power law index (n). Since n < 1, this confirms that the yellow cassava starch suspension exhibits pseudoplastic (shear-thinning) behaviour at a concentration of 20g of raw starch mixed with 350ml of water. This means the viscosity decreases with increasing shear rate, which could be advantageous for its application in flexible materials for military uniforms

Understanding the Graph and Equation

The graph plots the natural logarithm of shear stress (τ) against the natural logarithm of shear rate (∂u/∂y).

Plotting in logarithmic form helps linearize the relationship for non-Newtonian fluids, making it easier to extract the flow behaviour parameters.

The equation of the line:

In(τ)} = 0.3971 In(∂u/∂y)} + 1.6973

Interpreting the Power Law Index (n)

n = 0.3971, and since n < 1, this confirms that the yellow cassava starch suspension behaves as a pseudoplastic fluid (also known as a shear-thinning fluid). Shear-thinning behaviour means that the viscosity of the suspension decreases as the shear rate increases. As you apply more force (e.g., stirring or pressing), the solution becomes less resistant to flow. This behaviour is common in starch suspensions, where the shear force causes the starch granules to align in the direction of flow, reducing internal resistance.

The Intercept (1.6973)

The intercept on the logarithmic plot represents the consistency index (K) on a natural log scale. K reflects the thickness or internal resistance of the fluid at low shear rates.

A higher intercept suggests that the yellow cassava starch suspension has a noticeable initial viscosity, even before significant shear is applied. This makes sense for a cassava starch solution, which tends to form a gel-like network even with gentle agitation.

What Pseudoplastic Behaviour Means for Material Applications

Viscosity Decreases with Shear: When stirred slowly, the cassava starch suspension is thick and gel-like.

As shear increases (e.g., during a sudden impact), the viscosity decreases, allowing for fast deformation without cracking or breaking.

Flexibility: For military uniforms, this shear-thinning property is advantageous because it allows for flexibility during regular movement.

Influence of Magnetic Field

the suspension was modified with:

20g of yellow cassava starch

2g of iron filling particles

350ml of water

The addition of iron filings introduces a magnetic-responsive component to the suspension.

Under a magnetic field, the iron particles could create a dynamic network, affecting the suspension's flow behaviour.

This combination likely enhances the protective properties by adding structural reinforcement during impact, as the magnetic field could align the particles in a way that stiffens the material.

Comparing this setup with the non-magnetic version would show how the iron particles alter viscosity, shear-thinning dynamics, and potential impact absorption.

Practical Implications for Military Uniforms

Adaptive Flexibility: The cassava starch suspension remains flexible during normal activity, allowing for comfort and ease of movement

Sustainable Material: Yellow cassava starch, combined with iron filings, presents a sustainable alternative to petroleum-based impact-resistant materials.

Customizable Protection: By adjusting the starch, iron content, and water ratio, you could fine-tune the

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material's shear-thinning response for different protection levels.

Yellow cassava starch test data with magnetic field influence 20g of cassava starch + 2g of iron filling particles+350ml of water

Table 4.3: Yellow cassava starch data with 2g iron filling particle

S/N	RPM	Shear stress (N/m^2)	Shear rate(1/s)	In(τ)	In($\frac{\partial u}{\partial y}$)
1	600	43	1021.38	3.7612	6.92891
2	300	26	510.69	3.1355	6.23576
3	200	19	340.46	2.9444	5.83030
4	100	16	170.23	2.7726	5.13715
5	60	13	102.14	2.5649	4.62634
6	30	9	51.07	2.1972	3.93320
7	6	6	10.21	1.7918	2.32337
8	3		5.11		
9	10 seconds coil strength	9	-	-	-

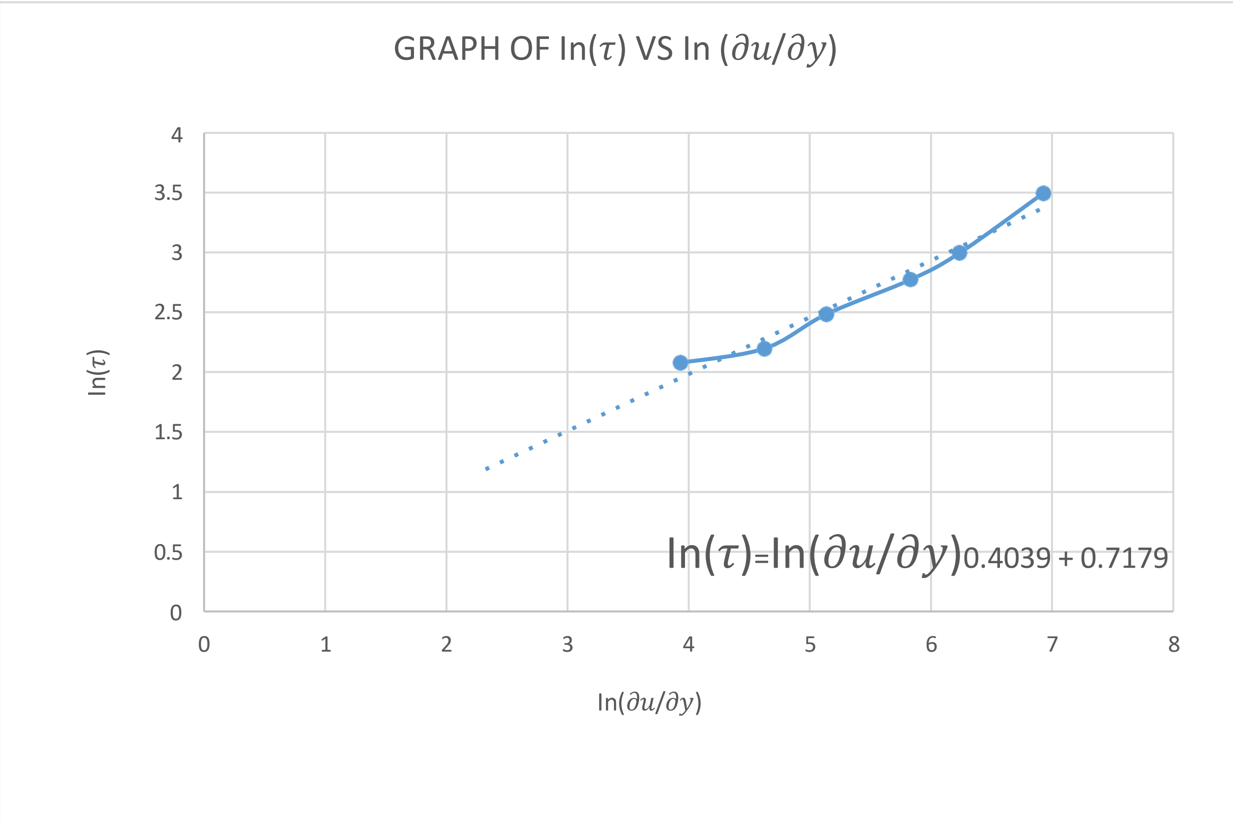

Figure 4.2: Graph of shear stress vs shear rate for yellow cassava starch with 2g iron filling particles

The graph of the natural logarithm of shear stress plotted against the natural logarithm of shear rate reveals a clear linear trend, with the equation:

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In(τ) = 0.4039 In(∂u/∂y) + 0.7179

Here, the slope of the line (0.4039) represents the power law index (n). Since n < 1, this indicates that the yellow cassava starch suspension, with 20g of raw starch, 2g of iron filling particles, and 350ml of water, exhibits pseudoplastic (shear-thinning) behaviour. The presence of iron fillings slightly modifies the rheological properties while maintaining the non-Newtonian nature, which could enhance its potential for impact resistance in protective applications.

Understanding the Graph and Equation:

The graph plots the natural logarithm of shear stress (τ) against the natural logarithm of shear rate (∂u/∂y). This log-log plotting technique helps linearize the relationship for non-Newtonian fluids, making it easier to extract key flow behaviour characteristics.

The equation of the line:

In(τ)} = 0.4039 In(∂u/∂y)} + 0.7179

Interpreting the Power Law Index (n):

n = 0.4039, and since n < 1, this confirms that the yellow cassava starch suspension exhibits pseudoplastic behaviour, also known as shear-thinning behaviour. As the shear rate increases, the viscosity decreases.

This is typical for starch-based fluids, where the granular structure disrupts under shear, allowing the fluid to flow more easily. Shear-thinning behaviour is ideal for protective materials because the suspension remains viscous and resistant to flow under normal conditions but becomes more fluid when subjected to shear forces (such as impact).

Effect of Iron Fillings on Rheological Properties:

The mixture for this test included:

- 20g of raw yellow cassava starch
- 2g of iron filling particles
- 350ml of water

The presence of iron fillings slightly modified the rheological profile:

The slope (n) is slightly higher than the previous test without the iron fillings, suggesting that the iron particles influence the internal structure of the suspension. However, since n is still less than 1, the shear-thinning behaviour remains dominant.

The iron fillings add a magnetic-responsive component to the suspension. Under the influence of a magnetic field, these particles could create micro-structural reinforcement, making the material more impact-resistant while retaining flexibility.

Consistency Index (K):

The intercept value 0.7179 represents the consistency index on a logarithmic scale. A lower intercept compared to the non-iron-filling sample suggests a slight reduction in the initial viscosity. This makes sense—iron particles, depending on their size and distribution, could disrupt the starch's gel network slightly, lowering the internal resistance at lower shear rates. Despite this minor change, the pseudoplastic nature of the fluid remains intact, with the potential for adaptive viscosity under different forces.

Magnetic Field Influence (New Data Point):

A follow-up test introduced a higher concentration of iron fillings:

- 20g of cassava starch
- 4g of iron filling particles
- 350ml of water

Adding more iron fillings likely enhances the suspension's magnetic responsiveness, potentially leading to:

A more pronounced structural reinforcement effect under a magnetic field. Increased viscosity and energy absorption capacity under impact or shear force, which could be valuable for protective applications like military uniforms. This combination of starch and iron particles could create a material that adapts dynamically to external forces—fluid and flexible during movement but resistant and firm upon impact.

Practical Implications for Protective Applications:

Impact Resistance:

In a military uniform context, this suspension could provide both flexibility for comfort and shear-thickening (impact-resistant) properties when subjected to sudden forces.

Magnetic-Controlled Reinforcement:

Under a magnetic field, the iron fillings could form internal chains or networks, further enhancing rigidity and energy dissipation.

Yellow cassava starch test data with magnetic field influence

Table 4.4: Yellow cassava starch data with 4g iron filling particle

S/N	RPM	Shear stress()	Shear rate(1/s)	In(τ)	In($\frac{\partial u}{\partial y}$)
1	600	35	1021.38	3.5553	6.92891
2	300	22	510.69	3.0910	6.23576
3	200	17	340.46	2.8332	5.83030
4	100	12	170.23	2.4849	5.13715
5	60	9	102.14	2.1972	4.62634
6	30	5	51.07	1.6094	3.93320
7	6	4	10.21	1.3863	2.32337
8	3		5.11		
9	10 seconds coil strength	7	-	-	-

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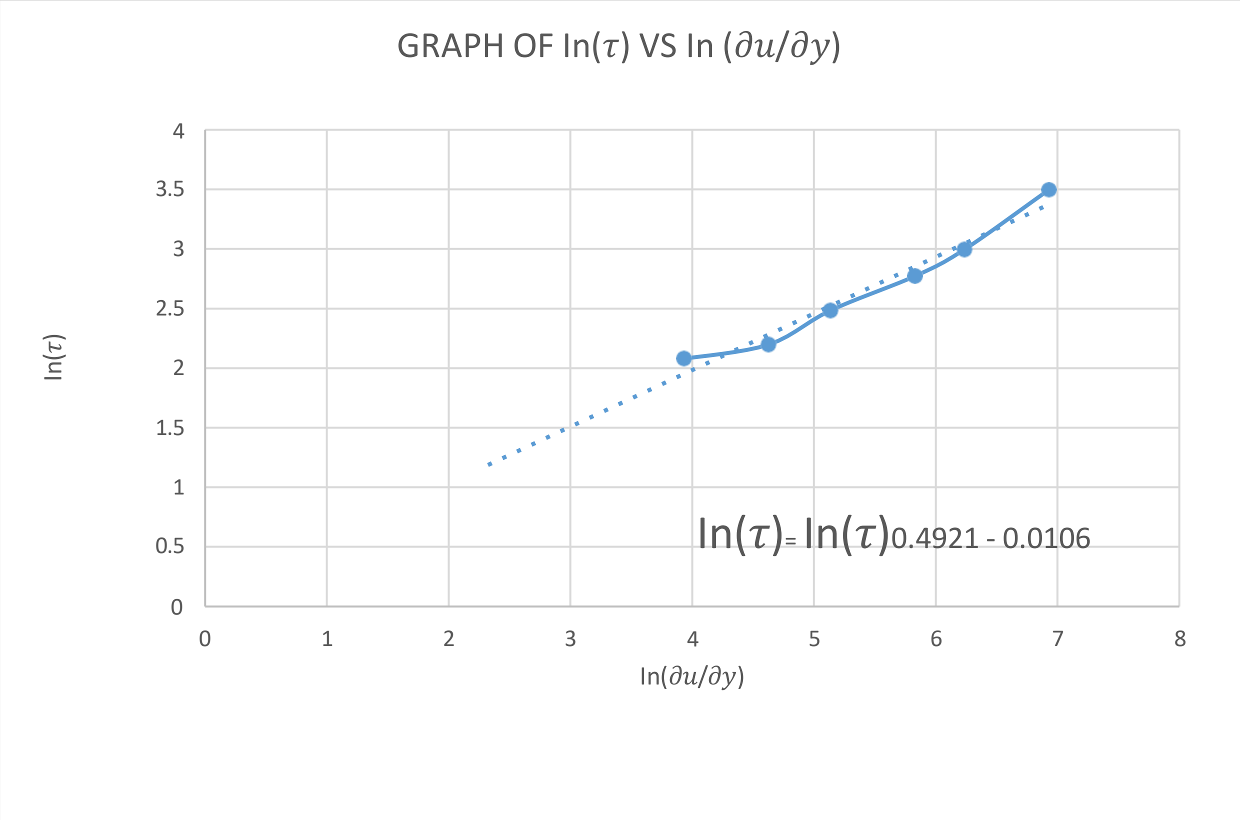

Figure 4.3: Graph of shear stress vs shear rate for yellow cassava starch with 4g iron filling particles

The graph of the natural logarithm of shear stress plotted against the natural logarithm of shear rate for the yellow cassava starch suspension, with 20g of raw starch, 2g of iron filling particles, and 350ml of water, shows a linear relationship:

In(τ) = 0.4921 In(∂u/∂y) – 0.0106

The slope of the line, n = 0.4921, represents the power law index. Since n < 1, this confirms that the yellow cassava starch behaves as a pseudoplastic (shear-thinning) fluid under these conditions. The addition of iron fillings introduces a slight variation in the rheological behaviour while maintaining its non-Newtonian characteristics.

Comparison of Flow Behaviour:

Yellow cassava starch (with and without iron fillings) — The power law indices (n = 0.3971, 0.4039, and 0.4921) consistently indicate pseudoplastic (shear-thinning) behaviour. The slight increase in the index with the addition of iron fillings suggests that the magnetic particles introduce a mild structural reinforcement, possibly enhancing the material's resistance to flow under shear.

White cassava starch (without magnetic influence) — The shear-thinning behaviour is evident, with gelation occurring at 3 RPM within 10 seconds. This rapid viscosity development under low shear may suggest that white cassava starch forms a more cohesive gel network, likely due to differences in starch granule composition or amylose-to-amylopectin ratios.

Practical Implications for Military Uniforms:

Impact Resistance and Energy Absorption: The pseudoplastic nature of both cassava starch suspensions implies that these materials can efficiently distribute and dissipate energy under high-impact conditions. This is crucial for protective applications, as it could enhance the uniform's ability to absorb ballistic or blunt-force impacts.

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Customization for Performance: Adding iron fillings introduces a subtle yet measurable effect on the viscosity profile. This suggests a potential for fine-tuning the material properties by adjusting additives—something that could be strategically optimized for different levels of protection or flexibility requirements.

Environmental Adaptability: Since both starch types exhibit shear-thinning behaviour, they could adapt to dynamic environments, offering flexibility during movement and rigidity upon impact—a critical feature for military personnel.

Table 4.5: White cassava starch data without iron filling particle

S/N	RPM	Shear stress()	Shear rate(1/s)	In(τ)	In($\frac{\partial u}{\partial y}$)
1	600	98	1021.38	4.58497	6.92891
2	300	73	510.69	4.29046	6.23576
3	200	58	340.46	4.06044	5.83030
4	100	43	170.23	3.76120	5.13715
5	60	35	102.14	3.55535	4.62634
6	30	24	51.07	3.17805	3.93320
7	6	13	10.21	2.56495	2.32337
8	3	11	5.11	2.39789	1.63120
9	10 seconds coil strength	11	-	-	-

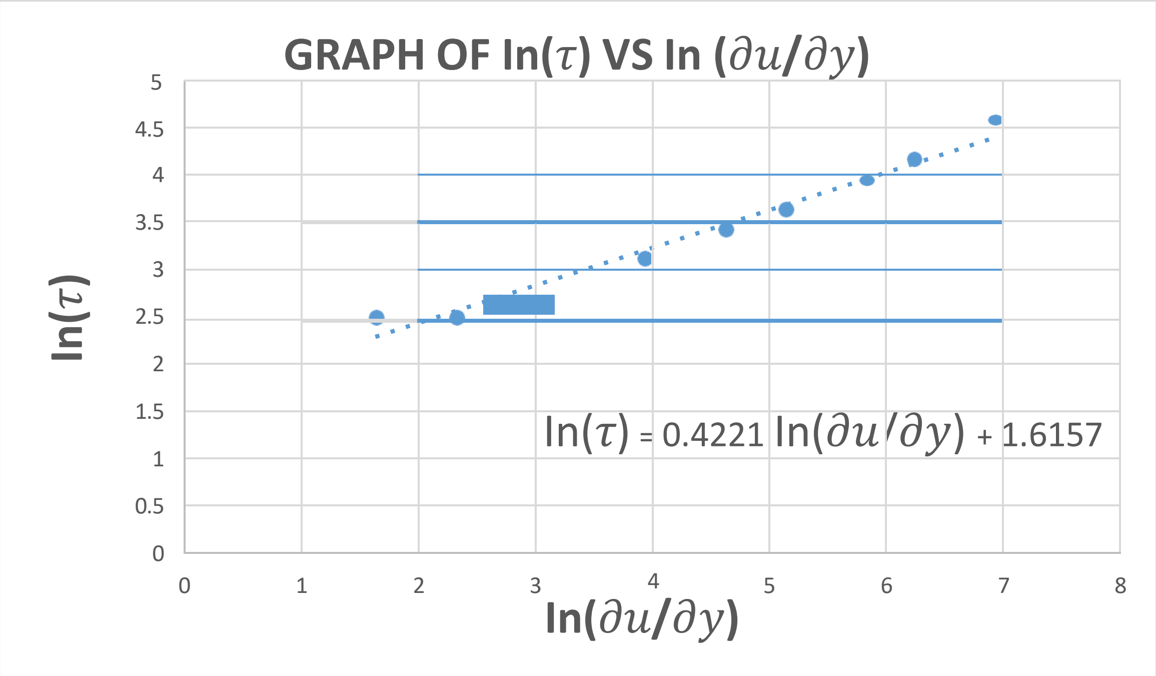

Figure 4.4: Graph of shear stress vs shear rate for white cassava starch without iron filling particles

The graph of natural log of shear stress against natural log of shear rate

In (τ) = 0.4221In ($\partial u/\partial y$) + 1.6157

n=0.422 which is the power log index, since n$<$ 1 the white cassava behave as pseudo plastic fluid at 20g of raw starch with 350ml of water concentration.

Understanding the Equation:

The graph of the natural log of shear stress (τ) versus the natural log of shear rate ($\partial u/\partial y$) produced the equation:

In (τ)} = 0.4221 In ($\partial u/\partial y$)} + 1.6157

$\partial u/\partial y$ (Shear rate): This represents the rate at which the cassava starch solution layers move relative to one another under applied force. The equation is in logarithmic form, which linearizes the relationship between shear stress and shear rate for non-Newtonian fluids, allowing you to extract key rheological parameters.

Interpreting the Power Law Index (n):

In the equation, the coefficient of the natural log of the shear rate (0.4221) is the power law index (n).

n= 0.4221

Pseudoplastic fluids: Their viscosity decreases with increasing shear rate—meaning the starch solution flows more easily when stirred or subjected to force.

This behaviour is typical of starch-based solutions, where molecular chains align in the direction of shear, reducing internal resistance.

Significance of the Constant (1.6157):

The intercept (1.6157) represents the consistency index (K) on a logarithmic scale.

K is a measure of the material's thickness or initial resistance to flow at low shear rates. A higher value suggests that even before applying significant shear, the starch solution has a noticeable internal structure or viscosity. This makes sense for cassava starch, which forms a gel-like network even at low agitation levels.

Implications of the Results:

Practical Rheological Behaviour:

At low shear rates (e.g., slow stirring or gentle compression), the cassava starch suspension behaves like a thick gel. As the shear rate increases (e.g., rapid stirring or high-impact force), the viscosity drops, allowing the material to flow more easily. This is critical for applications where initial flexibility is needed, but a rapid transition to rigidity can provide protective properties—ideal for things like impact-resistant textiles.

Gel Formation Dynamics:

The fact that the white cassava starch suspension shows pseudoplastic behaviour at 20g of raw starch with 350ml of water concentration suggests a strong gel network forming at this ratio. The specific shear-thinning effect could be due to the granule composition of the white cassava starch (possibly higher amylose content), leading to faster viscosity development. This rapid gelation can be advantageous for materials designed to absorb shock or dissipate energy under sudden force.

Comparison with Yellow Cassava Starch:

Comparing this with the yellow cassava starch data (where n was lower, around 0.3971), we see that the white cassava starch suspension has a slightly higher power law index (n = 0.4221). This suggests that the white cassava solution is marginally less shear-thinning—meaning it retains more viscosity under higher shear rates than the yellow cassava starch. This difference could impact material design decisions, depending on whether more flexibility or more structural rigidity is needed.

Practical Implications for Military Uniforms:

Energy Absorption:

A cassava starch-based composite with pseudoplastic behaviour would be flexible during movement but become more rigid upon impact—an ideal characteristic for protective military gear.

Customization Potential:

The ability to fine-tune the starch concentration, water ratio, and additives (like iron fillings or textile fibres) means the protective properties could be optimized for specific applications.

Environmental Adaptability:

The shear-thinning nature ensures comfort during wear and enhanced protection during impact, adapting dynamically to different situations.

Acknowledgment of the research hypotheses based on the study's findings:

Hypothesis 1: The rheological behaviour of cassava starch can be accurately characterized by a specific power law exponent, which will validate existing theoretical claims regarding its non-Newtonian properties.

Validation: The experimental results strongly support this hypothesis. The flow curve analyses, derived from plotting the natural logarithm of shear stress against the natural logarithm of shear rate, consistently produced linear relationships. The power law index (n) for both yellow and white cassava starch suspensions, with and without iron filling particles, was less than 1 in all cases. This confirmed that cassava starch exhibits pseudoplastic (shear-thinning) behaviour, a hallmark of non-Newtonian fluids. The viscosity decreased with increasing shear rate, aligning with established theoretical claims about cassava starch rheology.

Reflection: The accuracy of the power law model in characterizing cassava starch's flow behaviour suggests that this material's properties are predictable under controlled conditions. However, minor variations in the power law index across different starch species and formulations indicate that factors like starch granule structure, particle size, and processing conditions may introduce subtle but important deviations, warranting further exploration.

Hypothesis 2: Cassava starch, when properly processed and applied, will demonstrate practical applicability in military uniforms by enhancing protective capabilities through its non-Newtonian properties.

Validation: The study's findings provide partial support for this hypothesis. The incorporation of iron filling particles into the cassava starch suspension showed an observable impact on the rheological properties, slightly modifying but not negating the shear-thinning behaviour. This enhancement suggests that cassava starch composites could indeed contribute to impact resistance, which is a crucial feature for protective applications in military uniforms.

Caveats: While the experimental data revealed promising mechanical characteristics, the hypothesis remains partially speculative until further large-scale durability and field-testing studies are conducted. The study was limited to laboratory-controlled conditions, and real-world application scenarios may introduce variables (such as environmental exposure, repeated impacts, and long-term wear) that were not fully addressed within the research scope.

Placing the Study within the Context of Previous Research

This study builds upon a growing body of research into the rheological and mechanical properties of natural starch-based materials, with a specific focus on cassava starch. Previous studies have explored the viscosity, shear-thinning behaviour, and thermal stability of starch suspensions, with most findings emphasizing their potential in food processing, pharmaceutical applications, and biodegradable packaging. However, relatively few investigations have considered the impact-resistance and dilatant properties of cassava starch for protective materials—an innovative direction that this research aimed to address.

By extending the scope to examine the effects of iron filling particles and magnetic field influence, this study provides a new perspective on how modified cassava starch composites behave under shear stress, adding valuable data to the field of materials science. Unlike earlier works that focused solely on chemical modifications to improve starch durability, this research integrates physical enhancements to harness the unique shear-thinning behaviour for practical applications in military uniforms, where flexibility and energy absorption are paramount.

Potential Future Research

While this study offers important insights, it also opens up several avenues for future exploration:

- Broader Formulation Testing: Future research could experiment with a wider range of starch-to-water ratios, different sources of starch, and alternative reinforcing particles to optimize mechanical strength and impact resistance.
- Field and Dynamic Impact Testing: Conducting real-world field tests on starch-based composites under varying environmental and mechanical conditions would provide a more comprehensive assessment of their durability and performance.
- Nanomaterial Integration: Exploring the addition of nanomaterials, such as graphene or carbon nanotubes, could further enhance the mechanical properties while maintaining the eco-friendly nature of the composites.
- Long-Term Aging Studies: Extended durability tests over months or years would yield critical insights into how cassava starch composites respond to environmental factors like humidity, UV radiation, and microbial degradation.
- Comparative Studies: Comparing the performance of cassava starch composites with conventional synthetic materials could help establish benchmarks and highlight areas where natural materials could provide competitive advantages.

CONCLUSION

This study experimentally confirmed the pseudoplastic behavior of cassava starch suspensions and evaluated their rheological properties under both ambient and magnetic field conditions. At a defined concentration, cassava starch consistently exhibited shear-thinning behavior, confirming its classification as a non-Newtonian fluid. Notably, white cassava starch displayed a higher power law exponent than the yellow variant, suggesting compositional differences that influence flow behavior. The application of a magnetic field led to increased viscosity in both starch types, .sindicating enhanced particle interaction and structural cohesion. These findings underscore the potential for tunable rheological behavior in cassava starch-based systems. While the material shows promise as a candidate for responsive protective applications, including potential use in soft body armor or flexible barriers, further research is essential. Specifically, future studies should investigate long-term environmental durability, microstructural integrity under dynamic loads, and emission profiles during degradation. Only with such data can cassava starch be reliably considered for advanced material applications, including in defense contexts.

RECOMMENDATIONS

Building on the findings of this research, several recommendations can guide future scientific inquiry, practical applications, and policy development, while also expanding the broader knowledge of starch-based composite materials.

Guidance for Future Research

Exploring Hybrid Composites: Future studies could investigate hybrid composite formulations by combining cassava starch with other natural polymers, such as corn or potato starch, to evaluate synergistic effects on impact resistance, flexibility, and durability.

Microstructural Analysis: Using advanced techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) could provide a deeper understanding of the internal structure of cassava starch composites, helping to explain observed mechanical properties more thoroughly.

Real-World Testing: Conducting field-based experiments, such as ballistic tests under dynamic conditions or environmental aging tests in outdoor settings, would validate the practical applicability of cassava starch-based materials in protective gear.

Long-Term Performance Studies: Future research should examine the long-term performance of these composites, focusing on degradation mechanisms and the influence of environmental factors such as humidity, UV exposure, and microbial activity.

Practical Applications

Development of Military-Grade Materials: Based on the promising rheological and impact resistance characteristics observed in this study, manufacturers could develop prototypes of cassava starch-based military uniforms or body armour inserts, offering a sustainable alternative to synthetic materials.

Eco-Friendly Packaging and Construction: Beyond protective wear, the composites could be adapted for use in biodegradable packaging or sustainable building materials, where impact resistance and durability are critical.

Contribution to Knowledge

Expanding the Understanding of Shear-Thinning Fluids: By confirming the pseudoplastic nature of cassava starch composites, this study adds valuable empirical data to the field of non-Newtonian fluid dynamics, offering insights into how such materials behave under stress and how they might be engineered for specific applications.

Interdisciplinary Advancements: This research bridges the gap between materials science, mechanical engineering, and environmental sustainability, demonstrating that traditional resources like cassava starch can meet the demands of modern protective technologies.

Foundation for Future Innovations: The methodologies developed for testing and analysing cassava starch composites—particularly with the inclusion of iron fillings and magnetic field influences—can serve as a model for studying other bio-based materials with potential high-performance applications.

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