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Rheological Characterization of Sugar Palm Fruits (*Arenga pinnata*) at Different Maturity Levels and Concentrations

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***Abstract*— Aren is a versatile crop with significant economic potential in tropical regions, particularly Southeast Asia. While young fruits are commonly processed into kolang-kaling, the industrial potential of both young and matured fruits, especially about their rheological and structural properties for edible packaging, still needs to be explored. This study investigates palm fruits' rheological and structural properties at different maturity stages and evaluates their potential for industrial applications, specifically in developing edible films. Rheometer testing revealed that young fruits exhibit pseudoplastic flow behavior (n < 1), whereas matured fruits display Newtonian flow behavior (n = 1). The consistency index (K) increased as concentration. Dynamic rheological measurement showed that young fruits experienced a decrease in LVR and matured fruits showed an increase at higher concentration. The storage modulus (G') of matured fruits was higher than that of young fruits, indicating better mechanical stability in the former Both young and matured fruit had a loss factor < 1 and G' greater than G", indicating elastic behavior predominance. X-ray diffraction (XRD) analysis showed that matured fruits have a crystalline structure, while young fruits are semi-crystalline. The crystalline properties of matured fruits make them suitable for applications requiring mechanical stability, such as edible film production. In contrast, the semi-crystalline nature of young fruits is better suited for flexible packaging applications. These findings open new opportunities for utilizing palm fruit as an innovative base material in developing eco-friendly edible packaging for the food industry**.

***Keywords*— Flow Behaviour; Rheology; Sugar Palm Fruits; Viscoelasticity; X-ray diffraction**

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I. INTRODUCTION

Arenga pinnata commonly known as sugar palm, is a versatile tropical plant native to Southeast Asia. It has been widely utilized for various commercial products, such as palm sugar and *kolang-kaling* (sugar palm fruit jelly), derived from its young fruits. However, the utilization of matured sugar palm fruits remains highly limited despite their significant economic potential and relevance for industrial applications, particularly in the food sector [1]. In the growing global awareness of the importance of biodegradable and environmentally friendly raw materials, further exploration of the potential of sugar palm fruits becomes increasingly critical. Using sugar palm fruits as a sustainable natural resource can provide a viable solution to industrial needs, particularly in reducing dependence on synthetic materials and plastics, especially in the food industry.

One of the key components of sugar palm fruits is their heteropolysaccharide content, particularly galactomannan, composed of galactose and mannose units. The galactomannan in sugar palm fruits exhibits a unique structure, where mannopyranose units are linked by β-(1-4) bonds, while galactopyranose units are connected via α-(1-6) bonds [2]. The ratio of mannose to galactose in galactomannan depends on the plant species and the fruit's maturity level. For instance, sugar palm fruits aged 8–12 months have a mannose-to-galactose ratio of 3:1, while at 22–24 months, this ratio increases to 5:1 [3]. This ratio significantly impacts the material's characteristics, including its rheological properties.

Rheological properties of galactomannan play a crucial role in determining the flow behaviour, deformation, and stability of materials during production and storage processes. For example, galactomannan rheology affects the final product's texture, viscosity, and mechanical strength. A previous study demonstrated that increasing the concentration of galactomannan from *Arenga pinnata* results in higher viscosity [3]. Additionally, galactomannans from other plants, such as *Gleditsia sinensis*, *Gleditsia triacanthos*, *Prosopis ruscifolia*, guar gum, and lotus gum, exhibit pseudoplastic flow behaviour, where viscosity decreases with increasing shear stress [3];[4];[5].

Additionally, the material's crystalline structure plays a pivotal role in determining its mechanical properties and stability. The microscopic structure of natural materials such as sugar palm fruits contributes significantly to their durability and flexibility, which are crucial for various industrial applications. Therefore, further investigation into the structural properties of sugar palm fruits, both young and matured, is necessary to understand and optimize the potential of this material for industrial applications.

II. Material and Methods

A. *Material*

Young and matured sugar palm were sourced from West Java, Indonesia. The young and matured sugar palm fruits were sourced from West Java, Indonesia. The first step involved boiling the fruits for 3 hours, followed by peeling off the thin skin. The skin of the young fruits is yellow, while the skin of the matured fruits is black. After peeling, the fruits were thoroughly washed.Young sugar palm was mixed with distilled water at four different concentrations (5, 10, 15, 20% w/v). The mixture was then blended and stirred at 60 °C for 1.5 hours and subsequently stored at 4 °C for 12 hours. The preparation of matured sugar palm followed the same procedure as that of the young sugar palm

B. *Methods*

X-ray diffraction (XRD) Analysis

Young and matured sugar palm fruits were analyzed using X-ray diffraction (XRD) patterns. The XRD diffractometer (D8 Advance, Bruker Co., Karlsruhe, Baden-Württemberg, Germany), equipped with a Cu-Kα anode, operating at 40 kW and 30 mA, recorded wide-angle X-ray diffraction patterns. The diffraction angle range (2θ) was set between 10° and 90°, with a resolution of 0.02° at room temperature [6]

Viscosity Measurement

The flow properties of the prepared samples from both matured and young *Arenga pinnata* F\fruits were measured using an MCR 92 Rheometer (Anton Paar, GmbH, Germany) equipped with a cone and plate geometry (diameter = 50 mm, angle = 2°). A sample volume of 5.0 mL was applied to the plate surface with a gap of 0.1 mm between the plate and the cone. The instrument was operated at a shear rate range of 0.01 - 1000 s^{-1} and a temperature of 25 °C [7]. Data points were set at 51 points with a logarithmic increase profile, an initial time of 10 seconds, and a final time of 1 second. Flow curve analysis was performed using RheoCompass™ software, and each sample measurement was repeated twice. The information obtained included shear rate, shear stress, and viscosity, which were used to determine flow behaviour. The experimental data were fitted using the power-law model (Equation 1), where τ is the shear stress (Pa), ($\dot{\gamma}$) is the shear rate (s^{-1}), n is the dimensionless flow behaviour index, and k is the consistency index ($Pa{\cdot}s^n$). The slope of the flow behaviour curve plotted as log τ vs log $\dot{\gamma}$ indicates the flow behaviour index (n). The results demonstrate typical Newtonian flow if n = 1, shear-thinning behaviour if 0 < n < 1, and shear-thickening behaviour if n > 1.

$$\tau = K\dot{\gamma}^{n} \qquad (1)$$

Viscoelasticity Measurement

Viscoelasticity measurements were conducted using an Anton Paar MCR 92 Rheometer. Amplitude sweep tests were performed over a strain range of 0.01 - 100.00 % with an angular frequency of 10 rad/s at a temperature of 25 °C. The amplitude sweep test was used to understand how the elastic modulus (G') and viscous modulus (G") change with variations in strain amplitude. Frequency sweep measurements were carried out within the Linear Viscoelastic Region (LVR) over a frequency range of 0.1 to 100.0 rad/s at a temperature of 25 °C. The frequency sweep test was utilized to examine the material's response to frequency variations, aiding in the characterization of the material's viscoelastic properties [6]

Statistical Analysis

This study employed a Completely Randomized Design (CRD) with two replicates for each treatment. The resulting data were analyzed using Analysis of Variance (ANOVA) with IBM SPSS Statistics 27 software. The analysis was conducted at a significance level (alpha) of 5 %.

III. Result and Discussion

A. *X-Ray Diffraction of Matured and Young Sugar Palm*

X-ray diffraction analysis data of matured and young palms in Fig. 1. X-ray diffraction of matured and Young Sugar Palms. hows that matured sugar palm fruits exhibit several higher intensity peaks at specific positions, such as around 16°, 20°, and 23° (2θ). This indicates that specific crystalline structures are more dominant. At the same time, young sugar palm fruits display several peaks with lower intensity than matured fruits, suggesting a lower degree of crystallinity or a higher presence of amorphous phases in the young fruits. Crystallinity in a material influences the final product's mechanical and chemical properties. More crystalline materials tend to have higher mechanical strength and excellent resistance to environmental changes (such as temperature or humidity).

In contrast, more amorphous materials are more susceptible to changes but exhibit higher solubility [6]. Due to its higher crystallinity, a matured sugar palm may require more intensive processing, such as prolonged heating, grinding, or extraction at higher temperatures, to break down or modify its crystalline structure. In contrast, with its higher amorphous component, young sugar palm is more accessible to extract or dissolve in milder chemical processes, yielding natural products that are processed more quickly.

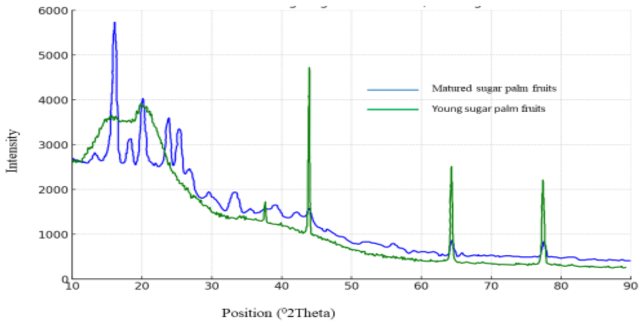


Fig. 1. X-ray diffraction of matured and Young Sugar Palm

B. *Flow Curve Behavior*

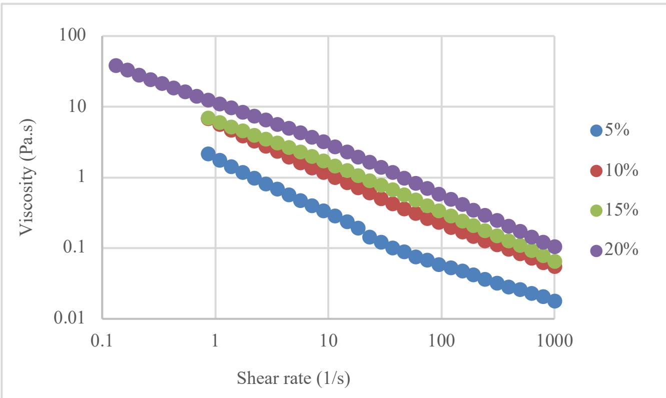
The rheological behavior of young and matured palm fruits at different concentrations in **Figure 2**, shows different flow characteristics. Young palm fruits, aged 8-12 months, showed shear thinning behavior with a flow behavior index (n) less than 1, as shown in Table 1, indicating pseudoplastic flow. This behavior was consistent across all concentrations. On the other hand, matured palm fruits aged 22-24 months showed Newtonian behavior with a flow behavior index (n) equal to 1, as shown in **Table 1**, indicating a constant viscosity regardless of shear rate.

The rheological properties of the young sugar palm fruit showed pseudoplastic behavior due to its semi-crystalline structure, as observed in the X-ray diffraction analysis in **Fig. 1** In a stationary state, this structure is typically entangled and interacts randomly. This random arrangement increases the viscosity under conditions of low or no shear. However, when shear force or pressure is applied, the polymer chains or molecules within the amorphous material align and disentangle from intermolecular interactions. This realignment reduces internal flow resistance, making the material easier to flow. Consequently, the viscosity decreases with increasing shear rate, resulting in pseudoplastic behavior. Similar results were reported by [8], who demonstrated that an amorphous structure facilitates more effortless flow under shear conditions.

The galactomannan content in sugar palm fruits also plays a crucial role in determining rheological properties. Galactomannan is a polysaccharide with hydrophilic properties that aids in water absorption and provides structural support during germination [9]. Furthermore, [10] stated that the ratio of galactose to mannose influences polymer complexity, with a high mannose-to-galactose ratio leading to long, unsubstituted mannan blocks, which results in aggregate formation and affects viscosity. Additionally, the branching structure of galactomannan, as observed in species like *Crotalaria*, contributes to increasing its viscosity [11]. The number of side groups in the polymer structure also plays a role in viscosity, where a reduction in side groups initially increases viscosity. Still, excessive reduction can lead to a decrease in viscosity [12].

The rheological data from the matured sugar palm fruit (22-24 months) showed a flow behavior index (n) of 1, indicating Newtonian behavior where the viscosity remains constant with increasing shear rate. This occurs because the matured sugar palm fruit has a crystalline structure, as shown in Fig. 1 . A crystalline structure causes atoms or molecules to be arranged in an orderly and tightly packed manner. Due to this order, intermolecular forces (such as Van der Waals forces or covalent bonds) act uniformly throughout the material. When shear stress is applied to this material, the molecules do not undergo significant deformation or change in orientation.

Additionally, the low galactose content in matured sugar palm leads to a more straightforward polymer structure, reducing the density and order in the solution. Studies on other plant species, such as *S. japonica* and *Gleditsia triacanthos*, also showed similar rheological behavior, where the ratio of galactose to mannose significantly influences viscosity [13]. Moreover, the unchanging flow behavior index across different solution concentrations suggests that the viscosity remains consistent regardless of shear rate and concentration [14]. This viscosity stability across various concentrations aligns with findings in other galactomannan-rich seed, such as *Bauhinia monandra* and *Cassia pleurocarpa*, where the polysaccharide composition is largely composed of galactose and mannose [15];[16]. The structural properties of galactomannan, influenced by the ratio of mannose to galactose, play a pivotal role in determining the rheological behavior of the solution [13].



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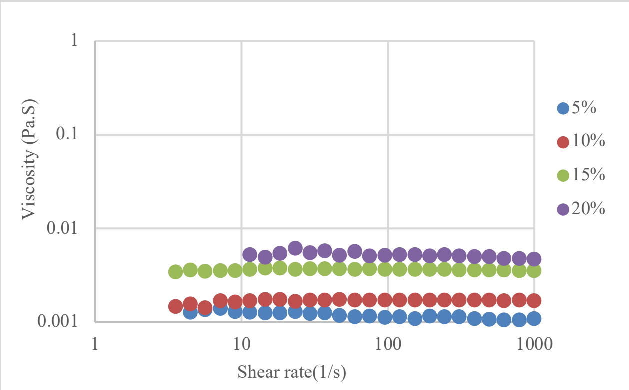


(b)
Fig. 2 Flow curve behaviour (a) young sugar palm fruits (b) matured sugar palm fruits

TABLE 1. FLOW BEHAVIOUR INDEX (N) VALUES FOR YOUNG AND MATURED SUGAR PALM FRUITS

Concentration (%)	Index (n) values	
	Young sugar palm fruits	Matured *sugar palm fruits*
5	0,313^{a} ± 0,0473	0,955^{a} ± 0,018
10	0,314^{a} ± 0,046	0,998^{b} ± 0,003
15	0,333^{a} ± 0,043	0,998^{b} ± 0,007
20	0,340^{a} ± 0,026	0,977^{b} ± 0,007

Values are mean ± standard deviation (n=2). Different superscript letters indicate significantdifferences between N sample values (one-way ANOVA; Duncan's test: P≤0.05).

The increase in the Consistency Index (K) value for young palm sugar fruits with increasing concentration **(Table 2)** indicates a significant influence of concentration variation on the K value. This phenomenon is attributed to a more disordered molecular structure, which leads to the formation of a more flexible polymer network, as shown in **Figure 1**. This network contributes to higher viscosity at higher concentrations, but it can also experience a decrease in viscosity under pressure due to its semi-crystalline structure. Additionally, the galactomannan present in these fruits also plays a role. The amorphous structure of galactomannan, such as that found in young palm sugar, is rich in galactose, which promotes molecular chain interactions through hydrogen bonds and other linkages [4]. These interactions form a more organized and dense network in the solution, increasing its viscosity [4].

Furthermore, Van der Waals interactions between atoms or molecules within the galactomannan chains contribute to the rigidity and stability of the molecular structure in solution, which further affects viscosity at higher concentrations [4]. Studies on other plant-based sources of galactomannan, such as *Gleditsia sinensis*, *Gleditsia triacanthos*, *Prosopis ruscifolia*, guar gum, and lotus gum, have also shown similar viscosity behavior due to the presence of galactomannan [4]. Galactomannan is known for its ability to form high-viscosity solutions even at low concentrations, making it valuable as a thickening agent in various industries [17]. The rheological properties of galactomannan, including its impact on viscosity, have been extensively studied, highlighting its significance in influencing solutions flow behavior and consistency [18].

Data from the study on matured palm sugar fruits revealed significant differences in the Consistency Index (K) values across different concentrations, with low K values observed at lower concentrations. This phenomenon occurs due to a more ordered and crystalline molecular structure, as shown in **Figure 1**. This structure does not form networks that can enhance viscosity, so the viscosity remains very low even with increasing concentration. [19] found that matured palm sugar fruits have a mannose-to-galactose ratio of 5:1. [20] explained that the lower galactose content leads to lower viscosity in galactomannan solutions due to weaker molecular interactions caused by the lack of hydrogen bonds. This is supported by [21], who discussed the impact of weak molecular interactions among galactomannan molecules on viscosity.

Studies on young and mature sugar palm (*Arenga pinnata*) fruits have demonstrated distinct rheological properties, where the young palm fruits exhibit pseudoplastic viscosity. In contrast, the matured palm fruits display newtonian behavior. These properties make sugar palm fruits highly promising for applications in the food industry, such as the production of edible films. For example, the intrinsic viscosity and shear rheology of galactomannans from various sources, such as *Gleditsia caspica*, guar gum, carob bean gum, fenugreek gum, and tara gum, which exhibit pseudoplastic flow behavior, have been extensively studied. These studies reveal that the molecular structure of galactomannan significantly influences its flow behavior and film-forming ability [22];[23].

TABLE 2 CONSISTENCY INDEX (K) VALUES FOR YOUNG AND MATURED SUGAR PALM FRUITS.

Concentration (%)	Index (n) values	
	Young sugar palm fruits	Matured sugar palm fruits
5	1,572^{a} ± 1,052	0,001^{a} ± 0,000
10	5,523^{b} ± 1,407	0,002^{a} ± 0,000
15	7,069^{bc} ± 2,293	0,003^{b} ± 0,000
20	11,75^{c} ± 2,419	0,058^{c} ± 0,007

Values are mean ± standard deviation (n=2). Different superscript letters indicate significant differences between K values at various concentrations (one-way ANOVA; Duncan's test: P≤0.05).

Viscoelastic Properties

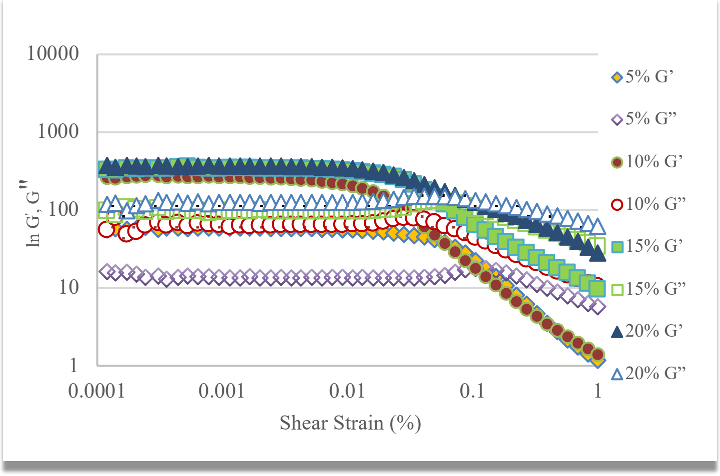
Viscoelasticity is a fundamental material property that combines elasticity and viscosity. The storage modulus (G′) and loss modulus (G″) are key parameters characterizing viscoelastic materials. The storage modulus reflects the energy stored in the material during deformation, indicating its elastic behavior and ability to return to its original form. Conversely, the loss modulus measures the energy lost as heat or dissipated during periodic deformation. This parameter is related to the material's viscosity component, showing how much force the material absorbs and dampens during deformation. The higher the loss modulus, the greater the energy dissipation, indicating a material with significant viscous characteristics, representing the material's viscosity component [24]. In a study involving young and matured sugar palm fruits, the storage modulus (G′) was more significant than the loss modulus (G″) during amplitude sweep tests. This observation suggests that the material exhibits more dominant elastic than viscous behavior [25].

Newtonian flow behavior is characterized by constant viscosity and no significant elastic response. However, in the case of matured sugar palm fruits, which exhibit newtonian flow with a crystalline structure, high G′ can emerge because the crystalline structure provides better resistance to deformation (**Figure 3).** This means that, despite showing Newtonian behavior, the crystalline structure contributes to the material's elastic strength, resulting in higher G′. Here, viscoelasticity is more related to the internal structure than to flow properties. In contrast, young sugar palm fruits exhibit pseudoplastic flow (shear thinning) and a decrease in viscosity as the shear rate increases. In materials with a semi-crystalline structure, due to the lack of regular particle arrangement, as seen in the crystalline structure, pseudoplastic materials tend to deform more efficiently and have lower elasticity. This explains why G′ is lower in semi-crystalline pseudoplastic materials because their structure is less regular and more flexible.

Furthermore, the 1:5 ratio of galactomannan found in matured sugar palm fruits [3] contains longer mannose chains with fewer galactose branching disturbances, forming a denser, interconnected polymer network. This network significantly contributes to viscoelasticity as energy can be stored and released more efficiently. In contrast, young sugar palm fruits, with a 1:3 galactose-to-mannose ratio and more galactose branching, make the network "looser" and less effective in storing mechanical energy.

This material is more crystalline in matured sugar palm fruits, with a regular molecular structure as shown by the XRD analysis, resulting in lower viscosity but more dominant elastic properties (higher G′). This material behaves like an elastic solid because its molecules are arranged more orderly and rigidly. In contrast, young sugar palm fruits are more semi-crystalline, resulting in higher viscosity and lower elasticity modulus (lower G′ and higher G″). Young sugar palm fruits are more flexible and liquid-like because their molecules are more irregular and mobile. This flexibility allows the material to store elastic energy (as shown by G′) and increases the viscosity of the solution at low shear rates.

The Linear Viscoelastic Region (LVR) relates to the linear viscoelastic response of the material to small deformations or low frequencies. It represents the molecular response on a small scale, where high shear rates do not significantly disrupt the material's internal structure. While matured sugar palm fruits exhibit Newtonian behavior at high shear rates and young sugar palm fruits show pseudoplastic behavior at low-frequency ranges (LVR), their linear viscoelastic responses may be similar because the underlying internal structure reacts similarly to small deformations [27]. Testing to determine the LVR is typically conducted at lower strains or frequencies, where even materials with different flow behaviors can display similar linear viscoelastic behavior. This is because the gel-like or fluid internal structure is not sufficiently disrupted to show significant differences in behavior. As a result, the internal structure of matured (Newtonian) and young (pseudoplastic) sugar palm fruits is well organized at the molecular level, allowing them to exhibit similar viscoelastic responses at LVR. At small deformations, the gel network or molecular arrangement in both types of sugar palm fruits responds the same way, resulting in similar LVR (**Table 3).**



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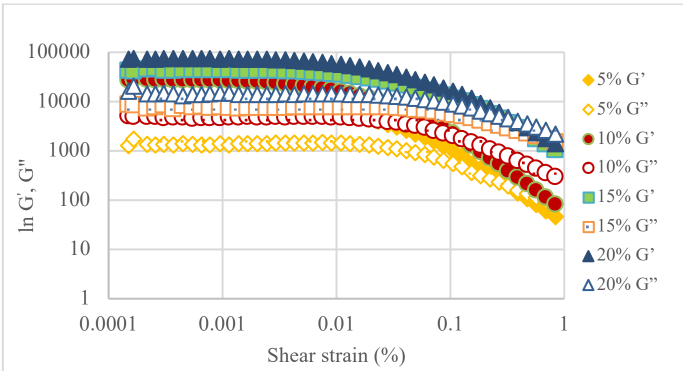

(b)

Fig. 3. Amplitude sweep spectrum rheology (a) young sugar palm fruits (b) matured sugar palm fruits

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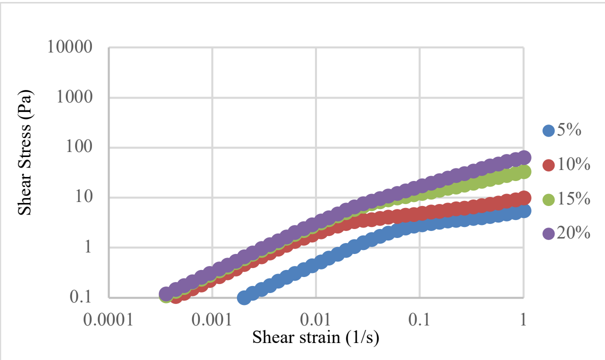
TABLE 3. LINEAR VISCOELASTIC REGION (%) FOR YOUNG AND MATURED SUGAR PALM FRUITS

Concentration (%)	**Linear viscoelastic region (%)**	
	Young sugar palm fruits	**Matured sugar palm fruits**
5	$0{,}153^{b} \pm 0{,}000$	$0{,}016^{a} \pm 0{,}000$
10	$0{,}0342^{a} \pm 0{,}037$	$0{,}023^{ab} \pm 0{,}002$
15	$0{,}0342^{a} \pm 0{,}037$	$0{,}034^{ab} \pm 0{,}01$
20	$0{,}0194^{a} \pm 0{,}000$	$0{,}049^{b} \pm 0{,}01$

Values are mean ± standard deviation (n=2). Different superscript letters indicate significant differences between LVR values at various concentrations (one-way ANOVA; Duncan's test: P≤0.05).



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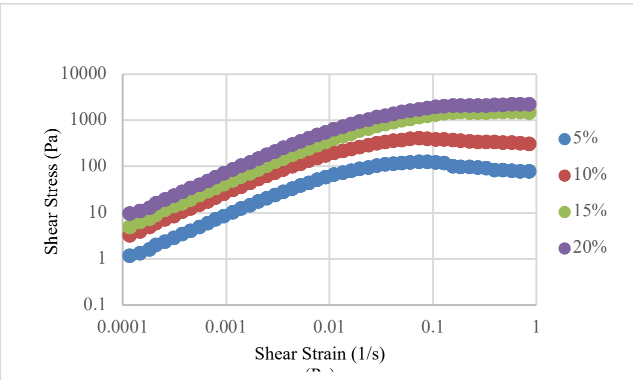


(b)

Fig. 4. Yield stress values (a) young sugar palm fruits (b) matured sugar palm fruits

The increase in yield stress with increasing solution concentration, observed in young and matured sugar palm fruits (**in Figure 4** and **Table 4)**, can be attributed to the closer proximity of polymer chains at higher concentrations. This proximity enhances chain interactions, leading to a denser, stiffer, and stronger three-dimensional network, increasing resistance to deformation [28]. Moreover, higher concentrations result in more molecules per unit volume that can interact through various physical bonds, such as hydrogen bonds and Van der Waals forces, thus increasing yield stress [28].

The difference in yield stress between young and matured sugar palm fruits is due to structural variations in the fruits. Younger fruits, with a semi-crystalline structure, reduce network strength and lower yield stress. In contrast, the more crystalline structure of matured fruits facilitates stronger interactions and the formation of a more coherent network, requiring higher pressure to initiate flow. Furthermore, young sugar palm fruits consist of galactomannan with a 3:1 mannose-to-galactose ratio. As a side branch, galactose weakens interactions between mannose chains because these branches hinder the formation of strong polymer networks. As a result, the material has a weaker structure and requires lower stress to initiate flow (lower yield stress). Matured sugar palm fruits, with a galactomannan content having a 1:5 mannose-to-galactose ratio [3], have fewer galactose branches, and the mannose chains form longer, interconnected structures through hydrogen bonds. This results in a stronger, denser polymer network that requires more energy to initiate plastic deformation (higher yield stress) [28]. These findings are consistent with previous research by [27] on seed galactomannan, which highlights how variations in galactose content affect network strength and yield stress [28].

TABLE 4. YIELD STRESS (PA) VALUES FOR YOUNG AND MATURED SUGAR PALM FRUITS

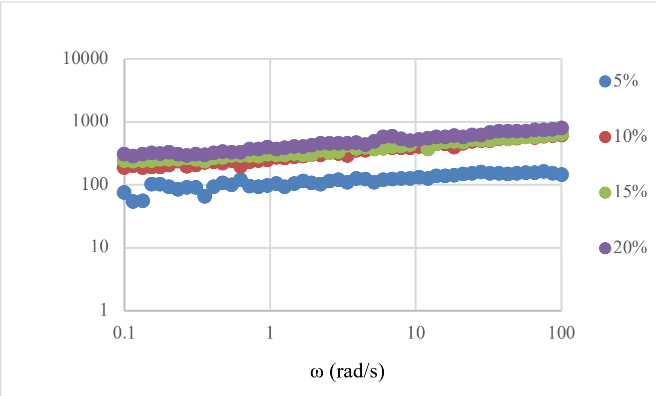
Concentration (%)	**Yield stress (Pa) Values**	
	Young sugar palm fruits	**Matured sugar palm fruits**
5	$3{,}2407^{a} \pm 1{,}374$	$84{,}806^{a} \pm 208{,}401$
10	$4{,}0289^{ab} \pm 4{,}756$	$379{,}78^{ab} \pm 452{,}138$
15	$10{,}535^{bc} \pm 2{,}227$	$1521{,}7^{bc} \pm 122{,}824$
20	$17{,}280^{c} \pm 2{,}321$	$2171{,}3^{c} \pm 588{,}755$

Values are mean ± standard deviation (n=2). Different superscript letters indicate significant differences between Yield stress values at various concentrations (one-way ANOVA; Duncan's test: P≤0.05).

The results presented in **Figure 5** show that the storage modulus (G') remains stable across both low and high frequencies, indicating that both young and matured sugar palm fruits exhibit minimal changes in their elastic behavior as frequency increases. This suggests that both young and matured fruits are capable of maintaining their elasticity across various oscillation time scales. At low frequencies, the material has more time to respond to deformation, while at high frequencies, the response time is shorter. The stability of G' indicates that the material remains elastic over a wide range of frequencies, regardless of how quickly the deformation occurs.

The particles are arranged in a regular, rigid three-dimensional network in matured palm sugar fruits with crystalline structures. During frequency sweep tests at high oscillation frequencies, crystalline materials have a more remarkable ability to store energy in the form of elasticity. This occurs because the ordered arrangement of crystalline particles allows the material to resist deformation better, and the power applied through oscillation is more efficiently absorbed and recovered by the material. Therefore, G' increases at higher frequencies. At low frequencies, while crystalline materials may not show a drastic increase in G', their ordered structure still provides more excellent elastic stability than semi-crystalline materials. This is because the more vital intermolecular forces in the crystalline arrangement make the material more elastic, even at low frequencies.

In contrast, young palm sugar fruits with a semi-crystalline structure have a random and disordered particle arrangement, which makes them more flexible but less elastic. At low frequencies, semi-crystalline pseudoplastic materials tend to absorb deformation energy as viscous energy, meaning torn energy is lost as heat rather than being recovered as elasticity. This results in a lower G' compared to matured fruits. At high frequencies, the semi-crystalline material lacks the internal structure needed to efficiently store elastic energy. Instead, at higher frequencies, semi-crystalline materials tend to behave more viscously (fluid-like), causing G' to remain low or even decrease compared to crystalline materials. Similar findings were reported in the study by [28].



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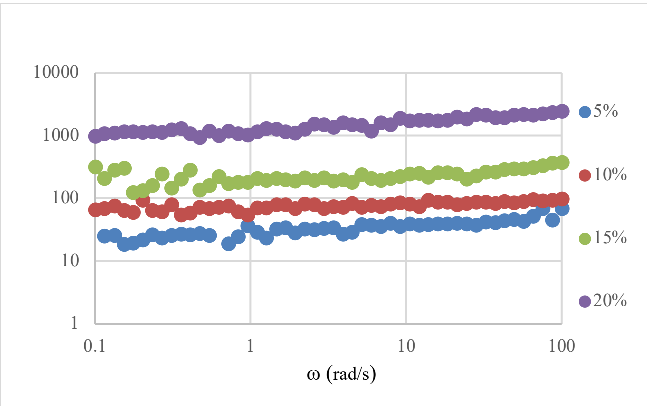
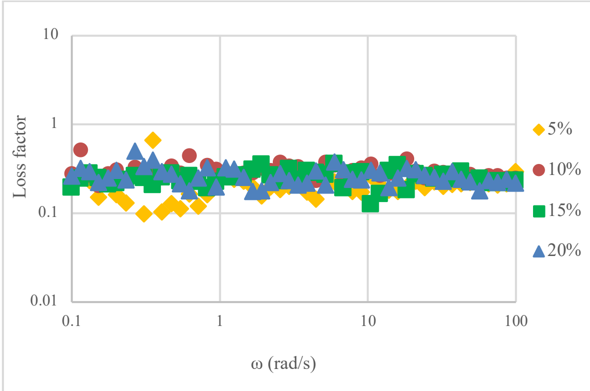


(b)

Fig. 5. Frequency sweep spectrum rheology (a) young sugar palm fruits (b) matured sugar palm fruits



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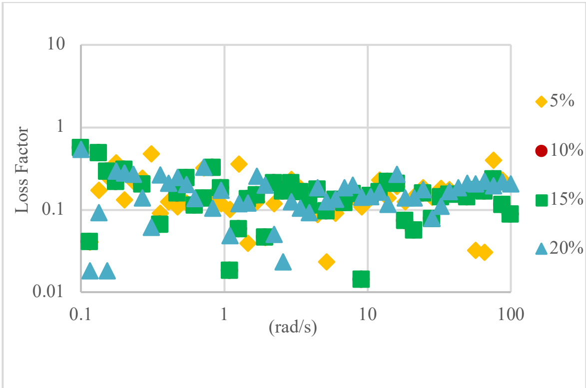

(b)

Fig. 6. Frequency sweep spectrum loss factor (a) young sugar palm fruits (b) matured sugar palm fruits

The research data in **Figure 6** shows that the loss factor values for matured and young sugar palm fruits are less than 1, with the loss factor values within the same range. This indicates that despite one material being Newtonian with a crystalline structure and higher G', and the other being pseudoplastic with a semi-crystalline structure and lower G', the loss factor (tan δ) within the same range suggests that both materials have a similar balance between the energy stored as elasticity and the power dissipated as viscosity. While the structural differences and flow types may affect G' and G", the ratio between them (which determines tan δ) remains balanced. This demonstrates that both materials exhibit a well-balanced viscoelastic response within the same frequency range, even though their physical and flow properties differ. Matured and young sugar palm fruits are dominated by the elastic component rather than the viscous component, indicating good elastic energy storage and the ability to return to their original shape after deformation [28]. Furthermore, values approaching 1 indicate a more viscous gel component [29].

Studies on various seeds have also elucidated the viscoelastic properties of these materials. For example, research on chia seeds has shown that the storage modulus is higher than the loss modulus, increasing with frequency [30]. Additionally, investigations on mixtures of *Lepidium perfoliatum* seed gum and xanthan gum have highlighted the impact of seed crosslink density on viscoelastic properties, demonstrating frequency-dependent behavior at different temperatures [31]

The study on young and matured sugar palm (*Arenga pinnata*) fruits showed that the elastic modulus (G') was more significant than the viscous modulus (G"), indicating that the elasticity was more dominant than the viscosity. Based on amplitude sweep and frequency sweep analyses, these findings suggest the potential application of sugar palms in edible film production. Similar properties have been observed in other galactomannan sources, such as guar gum, as reported [32]; [33]

IV. Conclusion

The findings of this study highlight significant differences in the internal structure and rheological behavior between young and matured sugar palm fruits. Matured palm sugar fruits exhibit higher crystallinity, while young palm sugar fruits possess a semi-crystalline structure. The young fruits display shear-thinning behavior, with a flow behavior index(n) of less than one across various concentrations, with no significant difference ($P > 0.05$). In contrast, the consistency index of matured palm sugar fruits increases significantly with concentration ($P < 0.05$), exhibiting Newtonian behavior ($n = 1$). Moreover, matured fruits show significant differences in the consistency index across concentrations ($P < 0.05$), with an initially low value that increases with concentration.

In the Linear Viscoelastic Region (LVR) tests, young palm sugar fruits showed a significant decrease in LVR with increasing concentration ($P < 0.05$), while matured fruits exhibited a substantial increase in LVR ($P < 0.05$). However, the LVR range for both young and matured fruits remained similar. Yield stress values for both types of palm sugar fruits increased significantly with concentration ($P < 0.05$), indicating more excellent resistance to deformation at higher concentrations. Additionally, the loss factor (tan δ) for both young and matured fruits remained below one across all concentrations, indicating that their elastic component rather than viscosity dominates both materials.
Matured palm sugar fruits exhibit a higher G′ than young fruits, indicating better stability in resisting deformation, particularly at low and high frequencies. This suggests that matured fruits can retain their shape better and exhibit Newtonian behavior at higher shear rates due to their stable crystalline network, which resists breakdown. In contrast, with their more flexible and less stable structure, young fruits are less effective at storing elastic energy, particularly at higher frequencies. They tend to show pseudoplastic (shear-thinning) behavior as their structure breaks down more efficiently at high shear rates.

These insights are critical for the development of edible packaging materials. The excellent structural stability and elasticity of matured palm sugar fruits make them potentially more suitable for applications requiring rigidity and resistance to deformation. These properties are beneficial in packaging materials that must maintain their shape under stress. On the other hand, the better flow characteristics and flexibility of young palm sugar fruits, due to their pseudoplastic nature, make them more appropriate for applications requiring materials that can adapt and flow easily, such as films or coatings for food products. Understanding these rheological properties allows for optimizing palm sugar-based materials in various edible packaging applications, balancing the need for elasticity, viscosity, and stability based on specific usage requirement

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Conflict of Interest

The authors declare no conflicts of interest or personal relationships with other people or organizations that can inappropriately influence this work.

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