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Characterization and Biodegradation Test of Palm Kernel Meal Galactomanan-Based Bioplastics with Succinic Acid-Polyvinyl Alcohol Cross-Linking Agent

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Abstract. Environmental pollution caused by non-biodegradable plastic waste has become a major global concern, prompting the development of eco-friendly alternative materials. Bioplastics derived from natural polymers are considered a promising solution due to their biodegradability and renewability. A study has been conducted on the manufacture of bioplastics from palm kernel meal galactomannan, with the addition of succinic acid and PVA, as an effort to reduce pollution caused by plastic waste. This study aims to determine the characteristics of bioplastics, including tensile strength, elongation, Young's modulus, chemical structure, and biodegradation. Bioplastics were obtained by mixing galactomannan, PVA, and variations of succinic acid (0, 0.1, 0.2, and 0.3 g). The results showed a tensile strength of 3.61–8.76 MPa, elongation of 260.83–432.92%, and Young's modulus of 1.21–2.49 MPa. FTIR analysis confirmed the presence of ester bonds, indicating cross-linking, while the biodegradation test showed that all samples were completely degraded within 1 day. The 0.10 g variation produced the best tensile strength, while the control had the most stable surface. This galactomannan-based bioplastic has the potential to be an alternative to conventional plastic due to its good mechanical properties and very rapid degradation.

Keywords: *galactomannan, succinic acid, PVA, bioplastic, biodegradation*

Abstrak. Pencemaran lingkungan yang disebabkan oleh limbah plastik yang tidak dapat terurai secara hayati telah menjadi perhatian global utama, mendorong pengembangan material alternatif yang ramah lingkungan. Bioplastik yang berasal dari polimer alami dianggap sebagai solusi yang menjanjikan karena sifatnya yang dapat terurai secara hayati dan dapat diperbarui. Telah dilakukan penelitian mengenai pembuatan bioplastik dari galaktomanan bungkil inti sawit dengan penambahan asam suksinat dan PVA sebagai salah satu upaya untuk mengurangi pencemaran akibat sampah plastik. Penelitian ini bertujuan untuk mengetahui karakteristik bioplastik meliputi kuat tarik, elongasi, modulus Young, struktur kimia, dan biodegradasi. Bioplastik diperoleh melalui pencampuran galaktomanan, PVA, dan variasi asam suksinat (0; 0,1; 0,2; dan 0,3 g). Hasil penelitian menunjukkan kuat tarik sebesar 3,61–8,76 MPa, elongasi 260,83–432,92%, dan modulus Young 1,21–2,49 MPa. Analisis FTIR mengonfirmasi adanya ikatan ester yang menandakan proses penautan silang, sedangkan uji biodegradasi menunjukkan bahwa seluruh sampel terdegradasi sempurna dalam waktu 1 hari. Variasi 0,10 g menghasilkan kuat tarik terbaik, sedangkan kontrol memiliki permukaan paling stabil. Bioplastik berbasis galaktomanan ini berpotensi menjadi alternatif pengganti plastik konvensional karena memiliki sifat mekanik yang baik dan kemampuan degradasi yang sangat cepat.

Kata kunci: galaktomanan, asam suksinat, PVA, bioplastik, biodegradasi

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INTRODUCTION

Plastic is a material that is widely used in daily life due to its flexibility, strength, light weight, transparency, and resistance to corrosion. In addition, plastics are relatively inexpensive, especially for single-use products (Mukhlisien et al., 2021). However, most conventional plastics are derived from fossil-based synthetic polymers that are non-biodegradable, making them difficult to decompose in the environment and a major contributor to pollution (Saputra & Supriyo, 2022). Indonesia is currently facing serious challenges related to plastic waste. In 2021, the total national waste generation reached 28.6 million tons, with plastic waste accounting for 17.86% of the composition (KLHK, 2022). Plastic waste entering the ocean is estimated to reach 1.29 million tons per year. This condition is closely related to changes in consumption patterns, with society increasingly dependent on practical, single-use products.

Various efforts have been made to address this problem, such as recycling and reducing plastic use. However, these approaches have not been fully effective. Therefore, the development of bioplastics based on renewable resources has become a promising alternative because they are biodegradable and have the potential to reduce dependence on fossil-based plastics. Several types of bioplastics, such as starch-based plastics, polylactic acid (PLA), and polyhydroxyalkanoates (PHA), have been developed, but they still have limitations in terms of low mechanical strength, suboptimal biodegradability, and relatively high production costs (Hasibuan, 2021).

Galactomannan is a natural polysaccharide that is hydrophilic and has good film-forming ability, making it a potential base material for bioplastics (Cut, 2022). One abundant source of galactomannan is palm kernel meal (PKM), with a content of about 37.1% (Ihsan *et al.,* 2024). Along with the increasing production of Indonesian palm kernel oil, which reached 4.77 million tons in 2023 (GAPKI, 2023), the amount of PKM generated is also increasing. This makes PKM a promising raw material to be developed into bioplastics while simultaneously increasing the value of palm oil industry by-products. The use of biopolymers and natural-based reinforcing agents can produce bioplastics with improved mechanical performance without reducing their biodegradability. The incorporation of polyvinyl alcohol (PVA) as a plasticizer enhances hydrogen bonding interactions within the polymer matrix, leading to improved structural and mechanical characteristics (Hutagalung et al., 2024). Therefore, a similar modification approach is adopted in this study using galactomannan and PVA.

However, it is known that bioplastics based on pure galactomannan generally have low tensile strength. Several studies have reported that unmodified galactomannan films show tensile strength values of only about 1–2 MPa, depending on their molecular structure and composition (Santos *et al.,* 2015). This value is still far below the standards required for packaging applications. Therefore, efforts are needed to improve the mechanical properties through modifications such as cross-linking, blending with other polymers, or certain chemical treatments (Haghighi *et al.,* 2020).

PVA was selected as a co-polymer because it is hydrophilic and compatible with polysaccharides such as galactomannan. Unlike polyethylene (PE) and polypropylene

(PP), which are hydrophobic and thus have low affinity for galactomannan, PVA is able to form better intermolecular interactions and improve the structural homogeneity of bioplastics (Septiati & Karmini, 2023). In addition, succinic acid acts as a cross-linking agent that can form ester bonds between the hydroxyl groups of galactomannan and PVA. The resulting polymer network is expected to enhance mechanical strength and thermal stability while maintaining biodegradability, since succinic acid is readily biodegradable (Lusiana et al., 2021).

Succinic acid was selected as a cross-linking agent due to its ability to form ester bonds with hydroxyl groups present in galactomannan and PVA. The presence of two carboxyl groups enables the formation of a three-dimensional polymer network, which can significantly improve the mechanical strength, structural stability, and water resistance of the resulting bioplastic. In addition, succinic acid is biodegradable, non-toxic, and can be derived from renewable resources, making it suitable for sustainable material development. Previous studies have reported that the use of succinic acid as a cross-linking agent in polysaccharide-based bioplastics improves tensile strength and thermal properties while maintaining biodegradability (Lusiana et al., 2021; Zhou et al., 2021). Therefore, the incorporation of succinic acid in this study is expected to enhance the overall performance of galactomannan-based bioplastics.

MATERIAL AND METHODS

Materials

The materials used in this study included palm kernel meal (PKM), PVA (Mw 89,000–98,000, Sigma-Aldrich, USA), succinic acid ($C_4H_6O_4$), 1% acetic acid (CH_3COOH), sodium hydroxide (NaOH), sodium chloride (NaCl), isopropyl alcohol, ethanol (C_2H_5OH), Tween 80, humus soil, and distilled water.

Instrumentation

The instruments used in this study included an analytical balance, oven, homogenizer, thickness gauge, Universal Testing Machine/tensile strength analyzer (Instron 3365, USA), pH meter, and FTIR spectrophotometer (PerkinElmer Spectrum 100, USA).

Procedure

Extraction of galactomannan from palm kernel meal *(adapted from Teekanam et al., 2023)*

PKM was dried, ground, and sieved through a 70-mesh screen. A total of 500 g of sample was soaked in 5% NaCl solution adjusted to pH 3–5 for 48 h at 37 °C with periodic stirring. The mixture was then filtered using a cloth filter followed by filter paper. The filtrate was precipitated with an isopropyl alcohol–ethanol mixture (90:10, v/v) at a ratio of 3:1 and allowed to stand for 24 h. The resulting precipitate was collected by filtration and dried in an oven at 110 °C for 24 h. The galactomannan powder obtained was characterized using FTIR spectroscopy.

Galactomannan-based bioplastic production (Sari et al., 2019, with modifications by Lusiana et al., 2021)

A total of 1 g of galactomannan, 1 g of PVA, and succinic acid at varying amounts (0, 0.1, 0.2, and 0.3 g) were added into a beaker containing 30 mL of distilled water and 10 mL of 1% CH_3COOH. The mixture was stirred using a magnetic stirrer at 80 °C for 1 hour until homogeneous. The solution was then cast into

Petri dish molds previously coated with Tween 80 and dried at room temperature for 2–3 days.

Table 1. Variations in bioplastic mixing

Materials	Sample code			
	A0	A1	A2	A3
GM (g)	1	1	1	1
PVA (g)	1	1	1	1
Succinic acid (g)	0	0.1	0.2	0.3
CH_3COOH (1%) (mL)	0	10	10	10
Water (mL)	40	30	30	30

In this study, only the concentration of succinic acid was varied, while the amount of PVA was kept constant. This approach was used to specifically evaluate the effect of cross-linking density on the mechanical and biodegradation properties of the bioplastic. The PVA concentration was fixed to maintain a consistent polymer matrix and to avoid overlapping effects from multiple variables.

***Characterization of bioplastics** (Lusiana et al., 2021)*

a. FTIR analysis

The synthesized bioplastics were analyzed using an FTIR spectrophotometer (PerkinElmer Spectrum 100) to identify functional groups.

b. Mechanical properties test

The mechanical tests included tensile strength, elongation at break, and Young's modulus measurements.

c. Tensile strength test

The tensile strength (σ) was calculated using Equation (1):

$$\sigma = \frac{F}{A} \qquad (1)$$

σ = Mechanical strength (MPa),
F = Tensile strength (N),
A = surface area (mm^2).

d. Elongation Test

The elongation (%) was calculated using equation (2):

$$\text{Elongation (\%)} = \frac{l - l_0}{l_0} \times 100 \qquad (2)$$

l = initial sample length(mm),
l_0= sample length to break (mm)

e. Young's modulus

Young's modulus (E) was calculated using Equation (3):

$$E = \frac{\sigma}{\varepsilon} \qquad (3)$$

E = Elastic modulus (N/m^2),
σ = tensile strength/tension,
ε = Elongation/strain

f. Biodegradation test (soil burial test)

The percentage of mass loss was calculated using Equation (4):

$$\%M = \frac{M_{initial} - M_{final}}{M_{initial}} \times 100 \qquad (4)$$

RESULT AND DISCUSSION

Extraction and Purification of Galactomannan from Palm Kernel Meal

Galactomannan extraction was carried out to separate the polysaccharide fraction from palm kernel meal through a dissolution and alcohol precipitation process. A total of 500 g of sample was dried and ground to obtain a uniform particle size in order to increase the surface area and enhance solvent penetration. According to Teekanam et al. (2023), reducing particle size can improve extraction efficiency by accelerating the release of polysaccharides from the plant tissue matrix.

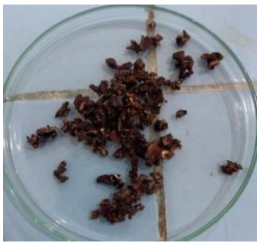

Figure 1. Galactomannan from PKM

Soaking in a 5% NaCl solution at pH 3–5 facilitated the dissolution of galactomannan and its separation from impurities such as fibers, lignin, and proteins. Precipitation using isopropyl alcohol at a ratio of 3:1 (v/v) reduced the solubility of the polysaccharides, leading to the formation of a solid galactomannan fraction. The obtained extract appeared as a brownish granular solid with a mass of 4 g, indicating that the product was still a crude extract. The brown color suggests the presence of residual impurities such as lignin, phenolic pigments, and proteins. Teekanam et al. (2023) reported that further-purified galactomannan typically appears pale yellow to white in color.

Infrared spectrum of extracted Galactomannan

The successful extraction of galactomannan was confirmed by FTIR analysis. The spectrum of the extracted sample exhibited a broad O–H stretching band around 3346 cm⁻¹, comparable to the characteristic band of standard galactomannan at 3450 cm⁻¹, indicating the presence of hydroxyl groups typical of polysaccharides. Aliphatic C–H stretching vibrations were observed at 2932 cm⁻¹, which are associated with the carbohydrate backbone.

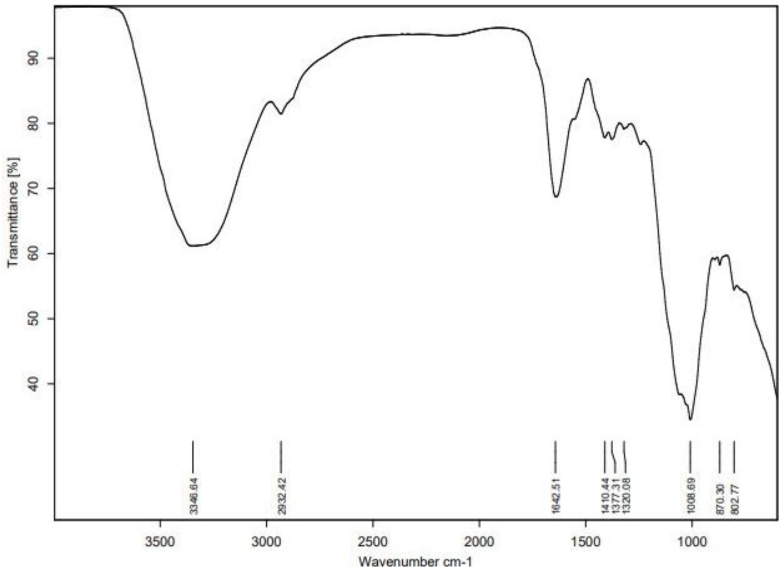

Figure 2. FTIR results of galactomannan from palm kernel cake

Glycosidic C–O and C–O–C vibrations appeared in the region of 1320–1008 cm⁻¹, while the bands at 870–803 cm⁻¹ indicate β-glycosidic linkages. These results confirm that the chemical structure of the extracted material is consistent with that of standard galactomannan (Tako et al., 2018), although minor differences may arise from residual moisture and impurities.

Bioplastic Formation and Physical Appearance

Bioplastics were prepared by blending the extracted galactomannan with PVA and adding succinic acid as a cross-linking agent. The control sample (A0) produced a homogeneous film with a relatively fast drying time. This condition is consistent with the findings of Sari et al. (2019), who reported that the combination of galactomannan and PVA can form stable films during drying due to the absence of compounds that significantly increase water retention.

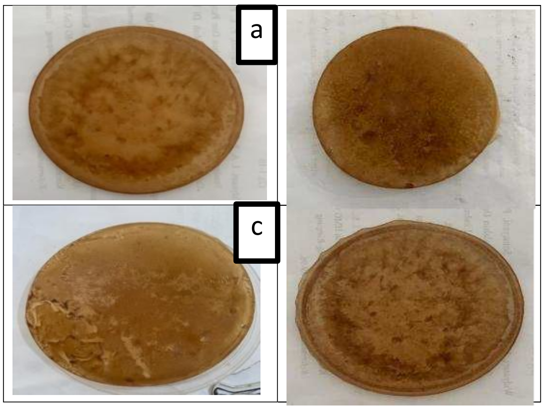

Figure 3. Bioplastics (a) control (b) A1 (c) A2 (d) A3.

At a low concentration of succinic acid (A1, 0.1 g), changes in surface characteristics began to appear, indicating partial interactions between the –COOH groups of succinic acid and the –OH groups of the polymers. At higher concentrations (A2 and A3), the drying time increased, and surface heterogeneity became more pronounced due to the excess of hydrophilic groups that retain water. These results are in agreement with Lusiana et al. (2021), who reported that increasing succinic acid content enhances water affinity and leads to changes in film surface characteristics. The formation of inter-chain bonding increases the mechanical properties of bioplastics because the matrix structure becomes denser and stronger. In addition, interactions among hydroxyl (–OH) groups between film components also affect physical properties such as solubility and swelling. This is evidenced by FTIR characterization and mechanical tests, which show that changes in bioplastic composition lead to changes in mechanical properties and water resistance of the film (Nurwidiyani et al., 2022).

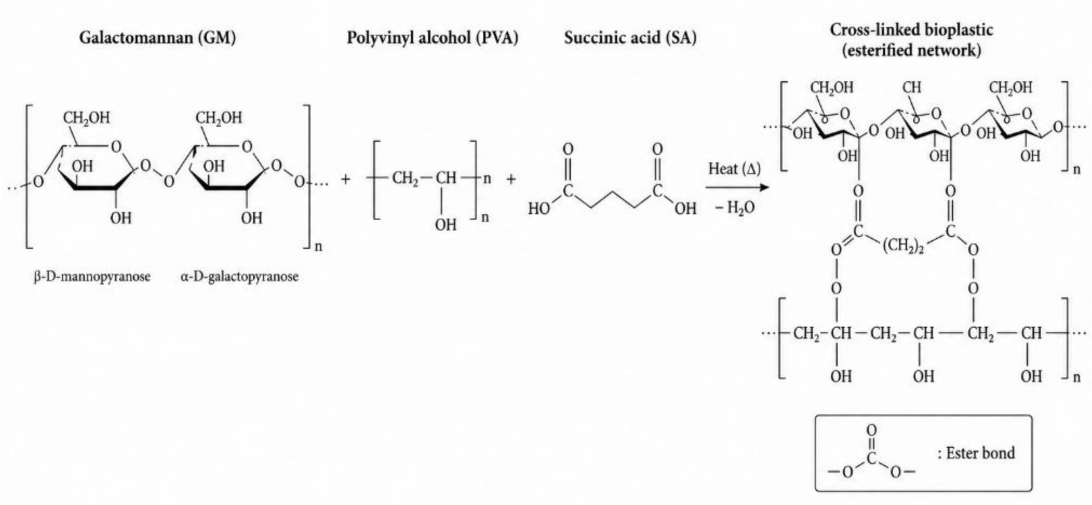

Figure 4. Reaction Scheme (drawn using KingDraw application version 35.8 on iOS 18.4)

IR Analysis of Bioplastics

The FTIR spectra of the bioplastic samples (A0–A3) exhibited a broad O–H stretching band in the region of 3200–3500 cm⁻¹ (Figure 5). A slight shift of the O–H peak from 3282 cm⁻¹ (A0) to 3269 cm⁻¹ (A3) was observed, accompanied by a decrease in intensity, indicating reduced free hydroxyl groups due to esterification. A distinct carbonyl (C=O) band appeared in the range of 1710–1730 cm⁻¹, with increasing prominence from A0 to A3, confirming the formation of ester linkages between succinic acid and the polymer matrix. This suggests that the cross-linking reaction became more extensive with higher succinic acid content. Additionally, changes in the C–O and C–O–C stretching regions (1000–1300 cm⁻¹) were observed, indicating structural modifications in the polymer network. These findings confirm successful cross-linking, which contributes to the improved structural properties of the bioplastic, in agreement with Lusiana et al. (2021).

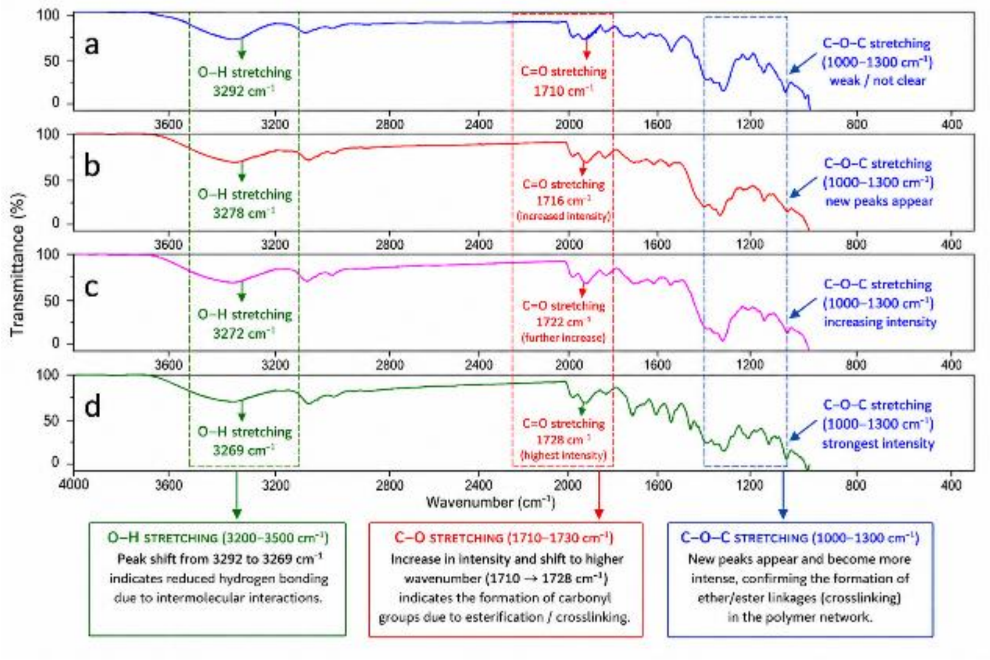

Figure 5. FTIR spectra of bioplastics: (a) control; (b) A1 (0.1 g succinic acid); (c) A2 (0.2 g succinic acid); (d) A3 (0.3 g succinic acid).

Mechanical Properties

Tensile strength

The tensile strength increased from 3.61 MPa (A0) to 8.76 MPa with the addition of 0.1 g succinic acid (A1), indicating an optimum crosslinking condition. However, further increases in succinic acid content (A2 and A3) resulted in a decrease in tensile strength to 7.40 MPa and 5.05 MPa, respectively (Figure 6). This reduction is likely due to the presence of excess unreacted acid, which disrupts the homogeneity of the polymer matrix and weakens intermolecular interactions.

These findings are in agreement with previous studies, which reported that the incorporation of organic acid as a crosslinking agent enhances tensile strength up to an optimum concentration, beyond which the mechanical properties tend to deteriorate due to phase separation or structural inhomogeneity.

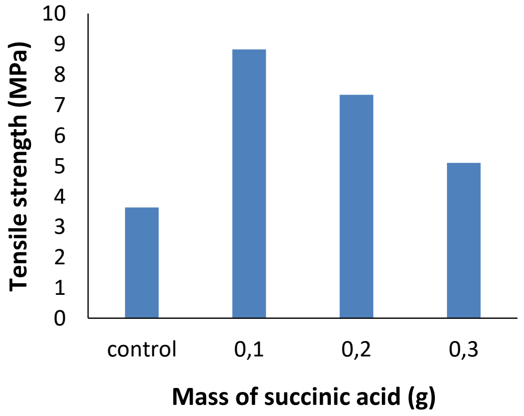

Figure 6. Tensile strength of bioplastics

Elongation

The elongation value of A0 (260.83%) increased sharply in A1 (432.92%), indicating enhanced flexibility due to a balanced cross-linking effect. At higher concentrations, elongation decreased in A2 to 297.08% and then increased again in A3 to 417.08% (Figure 7). These results are consistent with the report by Kartika and Saepudin (2022), who stated that in cellulose–PVA–based polymer systems with the addition of a cross-linking agent, elongation does not always decrease linearly. After decreasing at a certain concentration, elongation can increase again at subsequent compositions due to the emergence of a new balance between cross-link density and polymer chain mobility. This indicates that in sample A3, the increase in elongation occurred because the polymer chains still retained sufficient flexibility to adapt despite the higher amount of cross-linking agent (Figure 8).

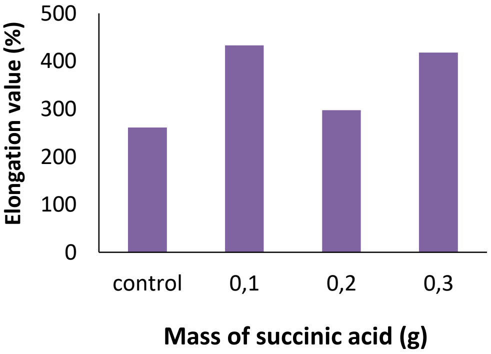

Figure 7. Elongation value of bioplastics

Observation

Sample A3 showed brittle fracture behavior. The sample broke suddenly with very little plastic deformation.

Figure 8. Tensile testing of bioplastic sample A3 (0.3 g succinic acid)

Young's Modulus

The Young's modulus of A0 was 1.38 MPa and increased to 2.02 MPa in A1, reaching a maximum at A2 (2.49 MPa), before decreasing in A3 to 1.21 Mpa (Figure 9). This trend suggests that the addition of succinic acid enhances the stiffness of the bioplastic up to an optimum crosslinking density. However, excessive addition of the crosslinking agent may induce a plasticizing effect or structural inhomogeneity, leading to reduced intermolecular interactions and decreased rigidity.

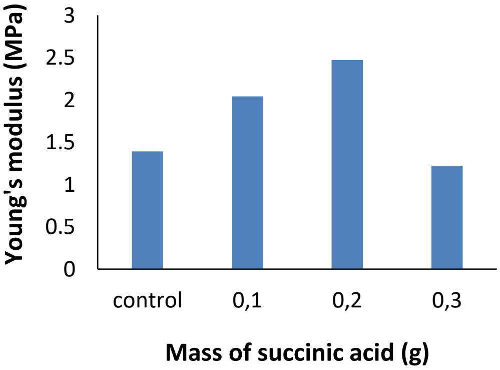

Figure 9. Young's modulus value

This finding is in agreement with the results reported by Kartika and Saepudin (2022), who observed that the elastic modulus increases up to an optimum concentration of crosslinking agent, followed by a decline due to structural disruption within the polymer network.

Biodegradation Test

The soil burial test showed that all samples were completely degraded within 24 h. The hydrophilic nature of galactomannan and PVA facilitates water absorption and microbial attack. These results are in agreement with previous studies on galactomannan-based bioplastics, which show rapid degradation due to their hydrophilic nature (Sari et al., 2019) and Lusiana et al (2021).

CONCLUSION

FTIR analysis confirmed the presence of characteristic polysaccharide functional groups as well as the formation of ester linkages due to the addition of succinic acid. Mechanical testing showed that the incorporation of PVA and succinic acid increased the tensile strength of the bioplastics compared to the control sample. The best formulation was obtained for A1 (0.10 g succinic acid), which exhibited the highest tensile strength of 8.76 MPa while maintaining a very rapid biodegradation rate. These results indicate that galactomannan-based bioplastics derived from palm kernel meal have strong potential for application as biodegradable packaging materials that require a balance between mechanical strength and degradability.

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