Utilization of Microcrystalline Cellulose (MCC) from Kepok Banana Pseudostem (*Musa acuminata*) as A Filler and Glycerol as A Plasticizer in Starch-Based Bioplastics from Cassava Peels (*Manihot esculenta*)

Erlikasna Sembiring [a,1], Halimatuddahliana Nasution [a,2,*], Erni Misran [a,3]

[a] Department of Chemical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia
[1] theresiaerlikasna@gmail.com; [2] halimatuddahliana@usu.ac.id*; [3] erni2@usu.ac.id
* corresponding author

ARTICLE INFO

Article history
Received January 07, 2026
Revised July 09, 2026
Accepted July 09, 2026

Keywords
Bioplastics
Cassava Peels
Glycerol
Microcrystalline Cellulose

ABSTRACT

The use of agricultural residues as renewable reinforcing materials offers a sustainable strategy to enhance the performance of biodegradable bioplastics. This study aims to characterize Microcrystalline Cellulose (MCC) derived from the pseudostem of kepok banana and to analyze its effects on the characteristics and mechanical properties of bioplastics. In this study, 10 g of starch was used, with MCC concentrations of 0%, 2.5%, 5%, 7.5%, 10%, and 15% (%w/w) and glycerol at 20%, 30%, and 40% (%v/w) relative to the mass of starch. The process of isolating MCC from kepok banana pseudostem is by hydrolysis with 50% H_2SO_4. The highest tensile strength value was 2.5 MPa in bioplastics filled with 5% MCC and 30% glycerol, with an elongation percentage of 7.92% and a Young's modulus of 48.68 MPa. FTIR analysis of bioplastics showed C-H, -OH, and C=C functional groups, confirming the presence of starch and cellulose. The addition of 5% MCC can increase tensile strength, as supported by SEM test results showing a denser, non-porous, non-cracked bioplastic surface. The results of the biodegradation test using the soil burial method, with an MCC-to-glycerol ratio of 5:30, showed 20% degradation in 15 days. The open-air test method yielded 12.5% degradation. These results demonstrate that MCC derived from kepok banana pseudostem can effectively enhance the mechanical performance of cassava peel starch-based bioplastics while providing a sustainable approach for the valorization of agricultural residues.

1. Introduction

Plastics possess distinctive properties, including being inexpensive, lightweight, water-resistant, durable, and readily available, which make them an integral part of daily life. These distinctive properties cause plastics to persist in the environment and accumulate as solid waste. Therefore, the development of environmentally friendly bioplastics is being pursued as an alternative to conventional petroleum-based plastics. Bioplastic production reached 2.18 million tons in 2023, with a projected significant increase to approximately 7.43 million tons by 2028 [1]. Bioplastics are already widely used for packaging, compostable shopping bags, and in the agricultural, automotive, electronics, and biomedical sectors [2]. Bioplastics are environmentally friendly materials that can be decomposed by microorganisms into carbon dioxide and water, thereby reducing the accumulation of plastic waste in the environment, and are derived from renewable raw materials such as starch, cellulose, and protein [3]. One of the potential raw materials for bioplastic production is cassava peel, which contains 44-59% starch [4]. However, starch-based bioplastics have the disadvantage of low water resistance due to starch's hydrophilic nature, which compromises their stability and mechanical properties. To overcome this, mixing with cellulose is carried out because cellulose has a structure similar to starch, high tensile strength, and strong binding ability [5]. Microcrystalline cellulose (MCC) is the result of

purifying partially depolymerized cellulose. MCC is non-toxic, renewable, and biodegradable, with high mechanical strength and surface area [6]. Natural sources that can be used as MCC include wood pulp, cotton fiber, teff straw, and orange peel [7], [8]. One of the most promising sources is the kepok banana pseudostem, as it is abundantly available as agricultural waste, has a high cellulose content, and is more economical and environmentally friendly, making it an efficient raw material for MCC [9]. In addition to strengthening the mechanical properties of bioplastics, the addition of glycerol acts as a plasticizer, enhancing their flexibility and elasticity [10].

Research on the production of bioplastics from starch with MCC filler has already been conducted. Maulida *et al.*[11] reported that the highest tensile strength was obtained with the addition of 6% MCC and 20% sorbitol, amounting to 9.12 MPa. Bioplastics with 0% MCC and 30% sorbitol content produced an elongation percentage of 23%. Abdullah *et al.*[12] reported that the addition of 20% MCC showed the highest tensile strength of 16.7 MPa, Young's modulus of 1300 MPa, elongation percentage of 1.31%, and biodegradability of bioplastics of more than 60% after 21 days. Othman *et al.*[13] reported that adding 1% MCC resulted in a bioplastic with a tensile strength of 20.74 MPa, an elongation at break of 35.12%, and a 16.72% increase in moisture content with the addition of 3.5% MCC. Overall, previous studies have demonstrated that incorporating MCC as a reinforcing filler enhances the physicochemical and mechanical properties of starch-based bioplastics. However, the optimal MCC content varies with the starch matrix and formulation.

So far, research on cassava peel-based bioplastics with variations in the addition of MCC from kepok banana pseudostem and glycerol, as well as biodegradation testing using soil burial and open-air methods, has not been conducted. This study evaluates the effects of varying MCC concentrations and glycerol plasticizers on the characteristics, physical properties, mechanical properties, and biodegradability of cassava starch-based bioplastics.

2. Research Methodology

2.1. Materials

The materials used in this study were kepok banana pseudostem collected from a local plantation, cassava peels obtained from a traditional market in Medan, North Sumatra, Indonesia, aquadest, NaOH (Merck, 99%), NaOCl (Merck, 12%), and H_2SO_4 (PA, 98%). The instruments used were an oven, hot plate, magnetic stirrer, pH meter, filter paper, 100 mesh sieve, acrylic mold, Particle Size Analysis (PSA, Fritsch Analysette 22), X-ray Diffraction (XRD, Rigaku Miniflex), Scanning Electron Microscope (SEM, Hitachi), and Fourier Transform Infrared (FTIR, Shimadzu Ir-Spirit).

2.2. Methods

The analysis was conducted using a descriptive-comparative method to compare test results across variations in bioplastic composition. Each sample was prepared and tested in triplicate to ensure data consistency and validity. The results are presented as mean values, accompanied by error bars to indicate the degree of variation for each parameter analyzed.

1) Procedure for isolating cellulose from kepok banana pseudostem

Kepok banana pseudostems are cleaned, cut into 1-2 cm pieces, and dried in the sun for 2-3 days, then soaked in water for 3 days, with the water changed every 24 hours. The soaked banana pseudostems are dried again. After reaching a constant weight, the banana pseudostems are cut into small pieces. Kepok banana pseudostems were treated with a 10% NaOH solution at a solid-to-liquid ratio of 1:20 (w/v) for delignification, with 1 g of dried pseudostems mixed with 20 mL of NaOH solution. The bleaching process was carried out by treating the material with a 4% NaOCl solution at a solid-to-liquid ratio of 1:20 (w/v), with 1 g of material mixed with 20 mL of NaOCl solution. The mixture is stirred and heated at 100°C for 2 hours to perform delignification and bleaching. After that, the mixture is filtered, the residue is neutralized with distilled water to neutral pH, and the mixture is dried again in an oven at 60°C for 3 hours to obtain pure cellulose. The purified cellulose was hydrolyzed using a 50% H_2SO_4 solution at a solid-to-liquid ratio of 1:10 (w/v) at 45°C for 45 minutes. After that, the reaction was stopped by slowly adding ice water, and then the mixture was washed with distilled water until the pH was neutral. The MCC precipitate was separated by filtration using filter paper, then dried in an oven at 60°C for 5–6 hours [14].

2) Procedure for isolating cassava peel starch

2000 g of cassava peel was washed thoroughly and then drained. The cassava peel was cut into 2 cm^2 pieces and mixed with water at a 1:4 (w/v) ratio, then blended to obtain wet cassava peel pulp, which was then squeezed through a filter cloth. The resulting starch water was collected in a container and left to settle for 2 hours to obtain starch sediment. The precipitate obtained was added to water again and left to settle for another 12 hours. The solution was separated again, and the bottom layer (wet starch) was drained. The wet starch is oven-dried at 50°C for 6 hours to obtain cassava peel starch. Dried cassava peel will be gray in color; it will be ground with a mortar and pestle and sieved with a 100 mesh sieve [15].

3) Production of bioplastics with MCC fillers

A total of 10 g of cassava peel starch was dissolved in 100 mL of distilled water and heated at 60°C until a viscous starch solution was obtained. Microcrystalline cellulose (MCC) was added to the solution at concentrations of 0–15% (w/w), and the mixture was stirred until homogeneous. Subsequently, glycerol was incorporated at concentrations of 20–40% (v/w) relative to the starch content. The resulting mixture was heated at 70°C for 25 minutes under constant stirring. The solution was then cast into 21×22 cm acrylic molds and dried in an oven at 60°C for 8 hours [16].

2.3. Analysis of MCC

1) Organoleptic test

The organoleptic properties of the MCC samples were evaluated by placing them on a watch glass and visually assessing their color, odor, and physical appearance. Color identification was performed using an iodinated zinc chloride reagent. The reagent was prepared by dissolving 20 g of zinc chloride ($ZnCl_2$) and 6.5 g of potassium iodide (KI) in 10.5 mL of distilled water. Subsequently, 0.5 g of iodine (I_2) was added, and the mixture was stirred for 15 min. The MCC sample was then placed in a mortar, and the reagent was added dropwise until a color change was observed. The resulting color was confirmed using the CIELAB color system by measuring the a* and b* values with a chromameter. The hue angle (h°) was subsequently calculated using equation (1).

$$h^o = \tan^{-1}\left(\frac{b^*}{a^*}\right) + 360^o \quad (1)$$

2) Yield of MCC

The yield of MCC was calculated using equation (2).

$$\text{Yield of MCC (\%)} = \frac{\text{weight of MCC obtained}}{\text{weight of } \alpha\text{−cellulose after bleaching}} \text{ x } 100\% \quad (2)$$

3) Determination of pH

The pH of the sample was determined by dispersing 15 g of MCC in 100 mL of distilled water, then measuring it with a calibrated pH meter.

4) Particle size test of MCC

The particle size distribution of MCC was analyzed using a Particle Size Analyzer (PSA).

5) X-ray Diffraction (XRD) pattern of MCC

XRD was used to characterize the crystalline structure of MCC obtained from the pseudostem of kepok banana. The crystallinity index (CrI) was calculated using the Segal method, as described in equation (3).

$$\text{CrI} = \frac{\text{It}-\text{Ia}}{\text{It}} \text{ x } 100\% \quad (3)$$

Where I_t is the maximum intensity of the diffraction peak associated with the crystalline region, and I_a is the intensity at 2θ = 18°, representing the amorphous region.

2.4 Analysis of Bioplastics

1) Thickness

The bioplastic samples were cut into 2×2 cm pieces. The thickness was measured with a Vernier caliper at four points on each sample. The average thickness was calculated according to equation (4).

$$\text{Average thickness} = \frac{\text{point 1+point 2+point 3+point 4}}{4} \quad (4)$$

2) Density

After measuring the thickness, the volume of the samples was calculated using the formula (length × width × thickness). The samples were then weighed. The density was calculated according to equation (5).

$$\rho = \frac{m}{V} \quad (5)$$

Where ρ is the density (g/cm³), m is the mass of the bioplastic sample (g), and V is the volume of the bioplastic sample (cm³).

3) Water absorption capacity

The bioplastic samples were cut into 2×2 cm pieces and weighed to obtain the initial weight (W_o). The samples were then immersed in distilled water at room temperature for 20 min. After immersion, excess surface water was removed using tissue paper, and the samples were reweighed to obtain the wet weight (Wt). Water absorption was calculated according to equation (6).

$$\text{Water absorption capacity} = \frac{Wt - Wo}{Wo} \text{ x } 100\% \quad (6)$$

4) Tensile strength, elongation percent, Young's modulus

The bioplastic samples were cut into dimensions of 2×15 cm and tested using a Universal Testing Machine (UTM) (Tensilon RTF 1350). The samples were clamped at both ends and subjected to a vertical tensile load until failure. The tensile strength, elongation percent, and Young's modulus were automatically recorded by a computer connected to the instrument.

5) Functional groups and Morphological structure

Fourier Transform Infrared (FTIR) was used to identify the functional groups of the bioplastic samples, while Scanning Electron Microscopy (SEM) was employed to analyze their surface morphology. A total of three samples were selected to evaluate the effect of microcrystalline cellulose (MCC) on the properties of the bioplastics. These included samples containing 0% MCC (without MCC addition), 5% MCC (exhibiting the highest tensile strength), and 15% MCC (the highest MCC content).

6) Biodegradation

Biodegradation testing of the bioplastic was conducted under laboratory conditions at room temperature (28°C). Samples (5×2 cm) were prepared and their initial weight (W_o) recorded. In the soil burial method, samples were buried at a depth of 1 cm in soil within polybags, while in the open-air method, samples were directly exposed to ambient air for 15 days. Measurements were taken at 5, 10, and 15-day intervals. After each interval, the samples were retrieved and weighed to obtain the final weight (W_t). The biodegradation rate was then calculated using equation (7).

$$\%\text{Weight loss} = \frac{Wo - Wt}{Wo} \text{ x } 100\% \quad (7)$$

3. Result and Discussion

3.1. Characteristics and Testing of MCC from Kepok Banana Pseudostem

1) Organoleptic Testing

Characterization of physical properties through organoleptic testing, where the resulting MCC is powdery, odorless, and white in color. These results are consistent with previous findings reported by Akib *et al.* [17] who indicates a similar trend and supports the validity of the present study. In addition, an identification test was performed using an iodinated zinc chloride reagent. The results showed that the MCC turned dark purple upon addition of the reagent, indicating the presence of cellulose. To further confirm the color characteristics, color measurements were carried out using a chromameter based on the CIELAB color system (L*, a*, and b*).

2) MCC Yield

The average MCC yield was 21.45%. The MCC yield results of between 20-22% for all treatments indicate the consistency of the banana pseudostem extraction process [18].

3) Determination of pH

The pH value of MCC from kepok banana pseudostem is 6.4. This value is within the neutral pH range [19]. This pH indicates that the produced MCC is stable and safe for use as a reinforcing material in bioplastic production.

4) Particle Size Analysis (PSA)

The average particle size of MCC from kepok banana leaves is 0.07934 μm, or 79.34 nm. This value indicates that the MCC obtained has reached the nanometer scale, in accordance with the definition of nano-sized particles, which are in the range of 1-100 nm [20].

5) X-ray Diffraction

The crystal structure of MCC directly affects the physical and mechanical properties of the material, especially when applied as a filler or reinforcement in the manufacture of bioplastics [21]. The diffraction pattern of MCC from the pseudostem of kepok banana shows a main peak at 2θ = 22.6°, characteristic of type I cellulose. In addition, weak peaks are visible at approximately 15° and 34°, which are characteristic of type I cellulose. This pattern is consistent with that reported by Moon *et al*.[22] which states that type I cellulose has characteristic diffraction peaks at around 15°, 17°, 21°, 23°, and 34°. The MCC crystallinity index of kepok banana pseudostem can be calculated using the Segal method [23]. The MCC crystallinity index of kepok banana pseudostem was 81.02%. This indicates that the isolated cellulose structure has a high degree of crystal regularity.

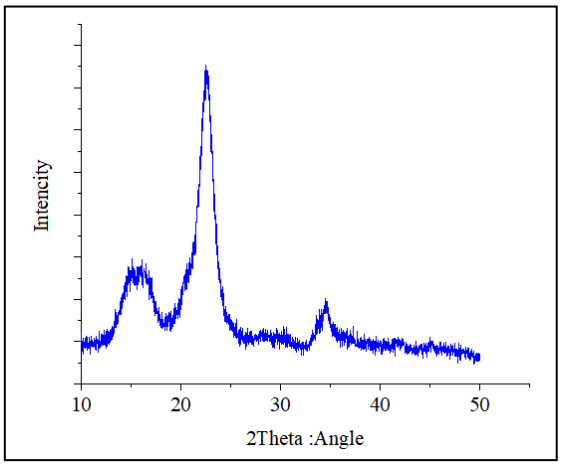

Fig. 1. Spectrum of MCC diffraction patterns from kepok banana pseudostem using XRD

3.2. Characteristics and Properties of Cassava Starch-Based Bioplastics

1) Thickness of Bioplastics

The thickness of bioplastic at each variation of MCC and glycerol concentration can be seen in Fig. 2. The thicker the bioplastic, the higher its water resistance and tensile strength. The results of the study show the thickness of bioplastic ≤ 0.25 mm, which complies with the Japanese Industrial Standard for bioplastics (JIS Z-1707:2019) [24].

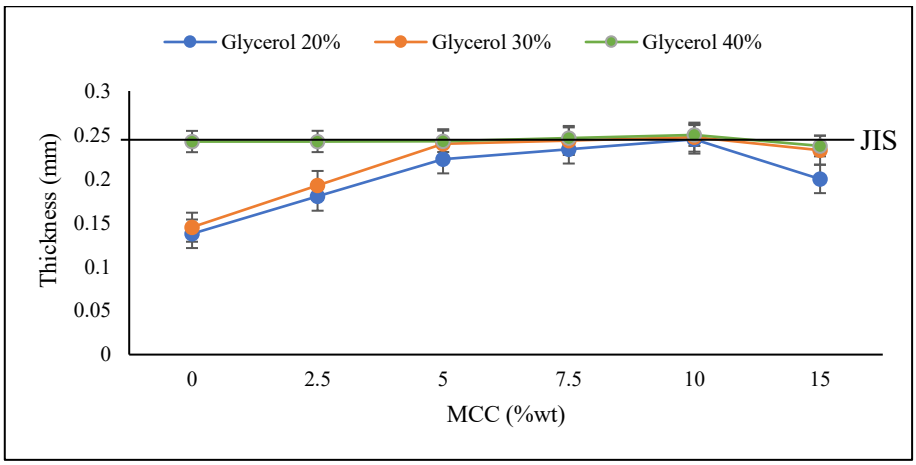

Fig. 2. Effect of MCC and glycerol concentration on bioplastic thickness

An increase in the concentration of MCC in the starch matrix increased the thickness of the bioplastic because the addition of fillers increased the dispersed solids in the starch solution [25] and glycerol affected the viscosity of the solution, which could increase the thickness of the bioplastic [26]. However, at an MCC addition of 15%, a decrease in thickness occurs due to agglomeration and uneven integration into the starch matrix [27].

2) Density of Bioplastics

Fig. 3 shows the effect of MCC and glycerol on the density value of bioplastics. The results showed that the density values for each experimental run ranged from 1.2 to 1.8 g/cm³. An increase in MCC concentration was associated with a corresponding increase in bioplastic density. The higher the MCC concentration, the higher the bioplastic density. This is because MCC has a dense and rigid crystalline structure, enabling it to fill the voids in the starch matrix and increase the density between polymer molecules [12], [28]. Increasing the concentration of glycerol as a plasticizer has the opposite effect. Glycerol is a hydrophilic compound that weakens the attractive forces between polymer chains, thereby increasing the flexibility of the film but also increasing the distance between molecules, resulting in a decrease in density [29].

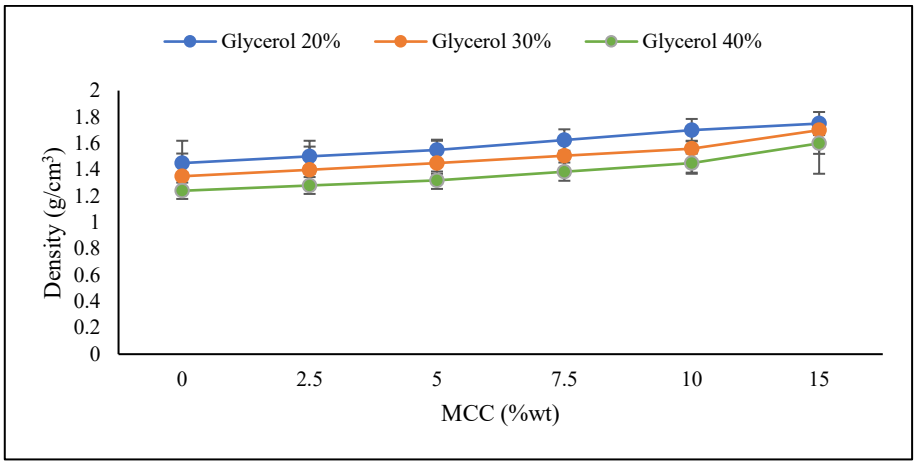

Fig. 3. Effect of MCC and glycerol concentration on bioplastics density

3) Water Absorption Capacity

Fig. 4 shows the effect of MCC and glycerol concentrations on the water absorption capacity of bioplastics. The decrease in water absorption with increasing MCC concentration indicates that MCC addition can improve the structure of the bioplastic matrix, owing to its high crystallinity and homogeneous particle distribution, thereby reducing the gaps through which water molecules can penetrate. The hydroxyl group (–OH) in MCC can also interact with the hydroxyl group in starch through hydrogen bonds and form a denser network [30].

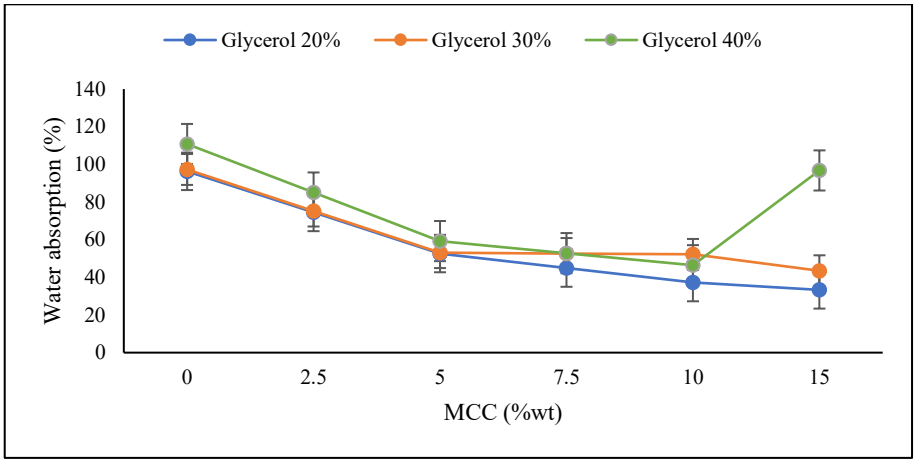

Fig. 4. Effect of MCC and glycerol concentration on the water absorption capacity

However, the addition of 7.5% and 10% MCC with 30% glycerol, as well as 15% MCC with 30% and 40% glycerol, resulted in increased water absorption. This phenomenon is attributed to excessive

incorporation of MCC, which leads to its nonuniform distribution within the polymer matrix and promotes the formation of amorphous regions that facilitate stretching of hydroxyl (–OH) groups, thereby enhancing water affinity [31]. The hydrophilic properties of starch and glycerol also contribute to increased water absorption. Starch molecules have hydroxyl groups that readily interact with water, and glycerol is hygroscopic, attracting water molecules [32].

4) Tensile Strength

Fig. 5 illustrates the effect of MCC and glycerol on the tensile strength of bioplastics. The highest tensile strength was obtained at a concentration of 5% MCC with 30% glycerol, at 2.5 ± 0.25 MPa. The tensile strength values of the bioplastic in this study met the requirements of SNI 7188-7:2022 and were higher than those reported by Olusanya *et al.* [33], who used corn starch with nanocrystalline cellulose as a reinforcing agent. Olusanya *et al.* reported a maximum tensile strength of 2.2 MPa with the addition of 1.5% (w/w) nanocrystalline cellulose, indicating relatively better mechanical performance. This shows that the addition of MCC in maximum amounts can improve the structure of the bioplastic matrix by increasing intermolecular bonds and strengthening the polymer network [34]. In contrast, adding more than 6% MCC will decrease tensile strength due to reduced homogeneity and adhesion between the filler and the starch matrix [35]. Increasing the glycerol concentration above 30% will decrease tensile strength because it increases the distance between polymer chains and reduces intermolecular forces, making the structure softer and less strong [36].

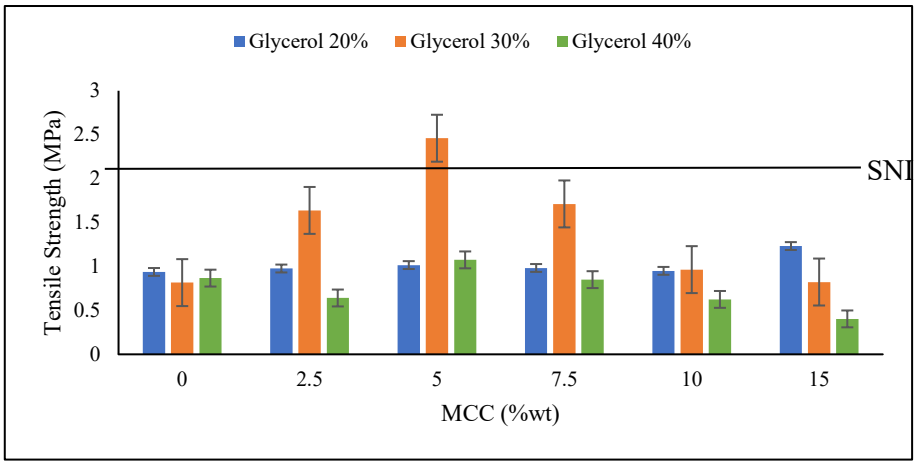

Fig. 5. Effect of MCC and glycerol concentration on the tensile strength of bioplastics

5) Percent Elongation and Young's Modulus

The elongation percentage and Young's modulus are shown in Fig. 6(a) and 6(b), respectively. The elongation percentage of the bioplastic in this study was found to be below the requirements specified in the SNI 7188-7:2022 standard [37]. Based on Fig. 6(a), at 20% glycerol, elongation decreased with MCC addition above 5%. This behavior is attributed to the rigid nature of MCC, which restricts the mobility of polymer chains, thereby reducing flexibility and elongation. At glycerol concentrations of 30% and 40%, elongation decreased in the presence of 5% MCC due to MCC agglomeration, resulting in a more brittle film. However, at MCC contents above 7.5%, the elongation increased, likely due to a more homogeneous distribution of MCC and improved interactions between MCC and starch, which enhanced the flexibility of the bioplastic matrix [38].

Young's modulus in bioplastics reflects the stiffness of the material and its ability to resist deformation under an applied force [38]. Bioplastics containing 20% glycerol exhibited a decrease in Young's modulus, but it increased again with the addition of 15% MCC because the bioplastics were still relatively stiff. Bioplastics with 30% and 40% glycerol showed a sharp increase at 5% MCC, followed by a decrease at 7.5-15% MCC. At 30% and 40% glycerol, the amount of plasticizer was sufficient to increase the flexibility and mobility of the polymer chains while still allowing good interaction with MCC. In contrast, at MCC 7.5-15%, the Young's modulus value decreased due to excess MCC forming particle agglomeration, causing uneven stress distribution and creating weak points in the composite structure [27]. These results indicate a direct relationship between tensile strength and Young's modulus, and an inverse relationship with elongation percent.

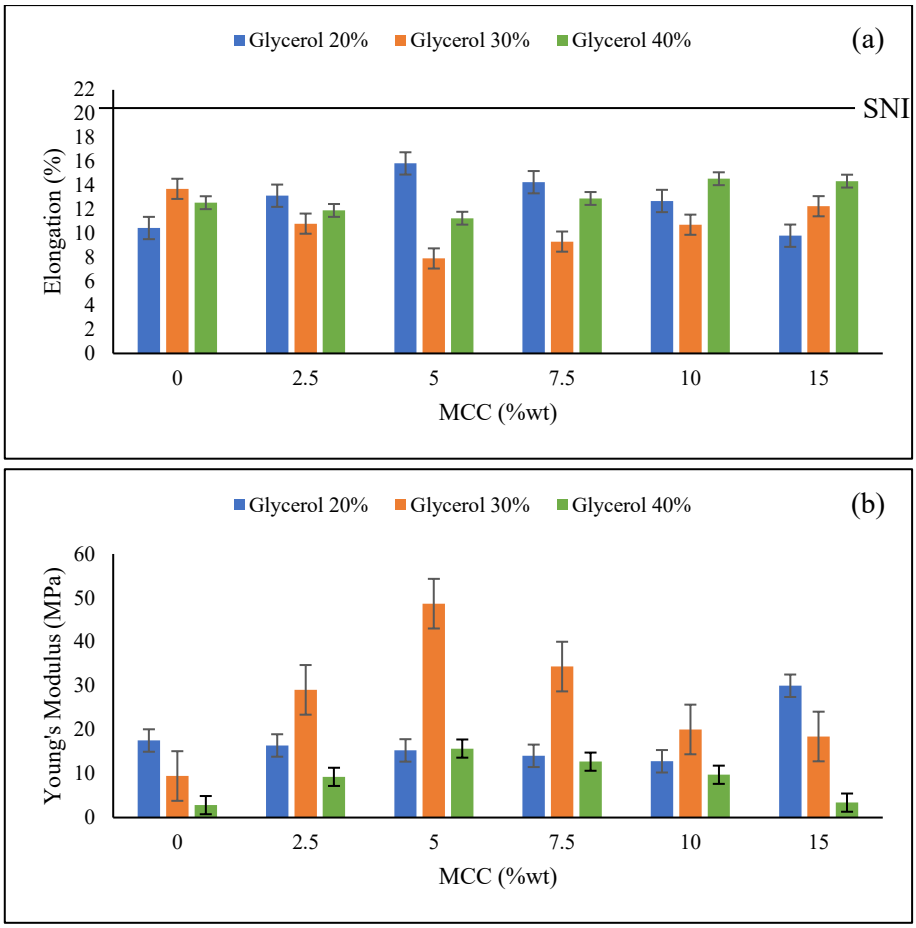

Fig. 6. Elongation percentage (a) and Young's modulus (b)

6) FTIR Analysis

Fig. 7 illustrates the FTIR spectra of bioplastics filled with 0%, 5%, and 15% MCC. In bioplastics without MCC filler, hydrogen bonds are visible at 3287.60 cm^{-1} with a transmittance of 56.24%. In a sample, hydrogen bonds are found in the absorption range between 3650-3250 cm^{-1}, either in the form of hydrate (H_2O), hydroxyl (-OH), ammonium, or amino [39]. In bioplastics with 5% and 15% fillers, hydrogen bonds were observed at absorption values of 3259.07 cm^{-1} and 3281.89 cm^{-1}. In contrast, the absorption transmittance for bioplastics with 5% and 15% fillers was lower, at 51.93% and 50.68%, respectively.

The decrease in transmittance indicates increased absorbance of functional groups due to greater interaction between starch molecules and MCC. In bioplastics with 5% and 15% fillers, hydrogen bonds are present at absorptions of 3259.07 cm^{-1} and 3281.89 cm^{-1}. In contrast, the absorption transmittance for bioplastics with 5% and 15% fillers is lower, at 51.93% and 50.68%. This indicates that adding MCC increases the density of hydrogen bonds in the film matrix. Absorption at 2935-2915 cm^{-1} indicates the presence of C-H functional groups, which are alkyl groups from the polysaccharide chain in the bioplastic film [40]. The addition of MCC filler shifts the peak to a slightly higher frequency. Bioplastic with 0% MCC showed an absorption at 2919.62 cm^{-1}; 5% MCC rose to 2928.17 cm^{-1}, and 2933.88 cm^{-1} at 15% MCC. The higher transmittance value in bioplastic with 5% MCC (80.32%) compared to without MCC (70.05%) indicates that the C-H groups in 5% MCC absorb less infrared radiation. This can be interpreted as the bioplastic structure in MCC 5% having good dispersion or interaction between the filler and the starch matrix, so that the C-H alkyl groups are locked or have strong intermolecular bonds. The decrease in transmittance in MCC 15% (79.69%) indicates that excess MCC filler causes aggregation [25]. Absorption at 1680- 1620 cm^{-1} indicates the presence of C=C groups from aromatic rings or double bonds [39]. Bioplastics without MCC filler show an absorption peak at 1644.51 cm^{-1} with a transmittance of 87.51%, while bioplastics with 5% and 15% MCC showed peaks at 1644.51 cm^{-1} (87.89%) and 1640.23 cm^{-1} (89.35%), respectively.

The increase in transmittance with the addition of MCC indicates that the C=C band absorbance decreases, indicating good interaction between the starch matrix and the MCC filler.

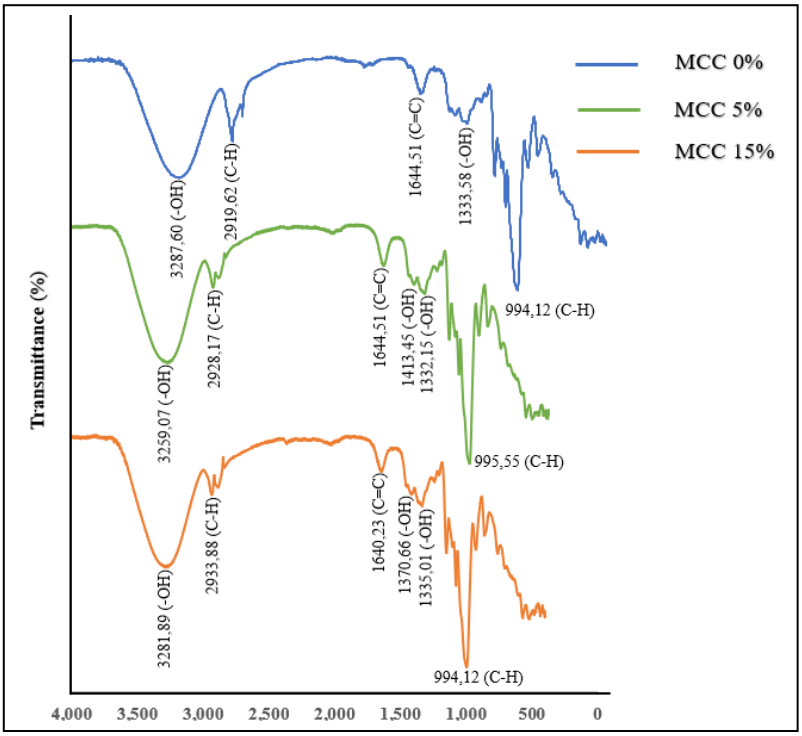

Fig. 7. FTIR spectrum of bioplastics filled with 0%, 5%, and 15% MCC

7) SEM Analysis

Fig. 8 illustrates the morphology of bioplastic from cassava peel starch using a Scanning Electron Microscope (SEM). Fig. 8(a) shows that the surface of the bioplastic without MCC addition appears relatively smooth, though some starch granules remain. This indicates that the starch gelatinization process is not yet completely homogeneous, so there are still insoluble starch parts that cause granules on the surface of the bioplastic film [12].

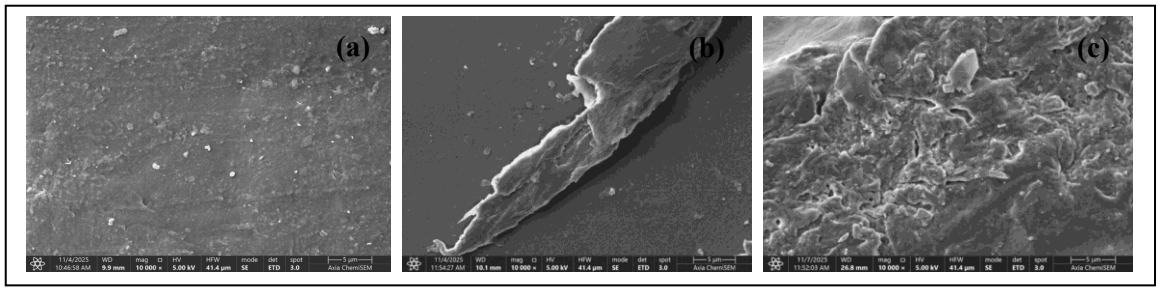

Fig. 8. SEM at 10,000x magnification with MCC filler 0% (a); 5% (b); 15% (c)

Fig. 8(b) illustrates that the addition of 5% MCC produces a denser, non-porous surface morphology and indicates the presence of MCC fibers dispersed in the starch matrix. This is because the addition of MCC to starch-based bioplastics increases the density of the film due to hydrogen interactions between the –OH groups in MCC and the –OH groups in starch [41]. In contrast, an excessive concentration of MCC may lead to agglomeration on the bioplastic surface, as depicted in Fig. 8 (c). This condition weakens the interfacial interactions between starch and MCC, as partial agglomeration of MCC particles limits their ability to form effective bonds with the starch polymer chains, thereby reducing the tensile strength of the bioplastic [42], [43].

8) Biodegradation Test

Fig. 9 illustrates the biodegradability of bioplastic using the soil burial test method (samples in direct contact with soil) and the open air test method (samples left in an open environment) at room temperature. The biodegradation results from both the soil burial and open-air tests showed negative

weight-loss percentages, indicating an apparent increase in the mass of several bioplastic samples. In the soil burial method, this phenomenon is primarily attributed to moisture absorption from the surrounding soil environment, facilitated by the hydrophilic nature of starch-based bioplastics and the presence of glycerol as a plasticizer, which enhances water uptake and induces swelling. In addition, the adhesion of soil particles and microbial biomass onto the sample surface may further contribute to the observed weight gain. A similar trend was observed in the open-air test, where negative % weight loss values were observed despite the absence of direct soil contact. This can be explained by moisture absorption from ambient humidity and by the deposition of airborne particles, such as dust and microorganisms, on the sample surface. Therefore, the negative % weight loss observed in both methods does not necessarily indicate the absence of biodegradation; rather, it reflects the predominance of moisture absorption and accumulation of external material over actual mass loss during the early stages of degradation.

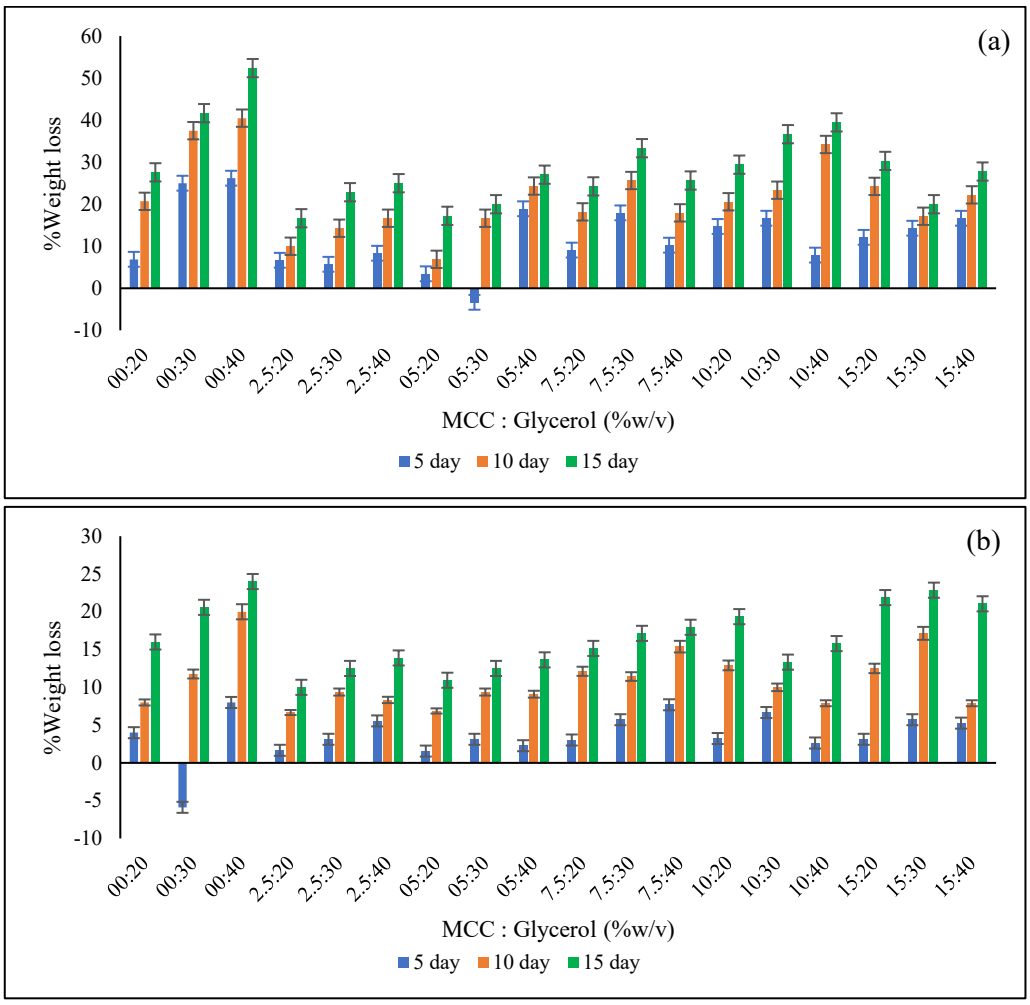

Fig. 9. Biodegradation test of bioplastics using the soil burial test (a); open air test (b)

Weight-loss analysis of bioplastics was conducted to assess their ability to degrade naturally and to determine the time required for proper decomposition. In the soil burial method, bioplastic material loses weight faster than in open air because soil contains more moisture and microorganisms that accelerate its breakdown; according to Folino *et al.* [44], starch-based bioplastics show 95% degradation in soil. The weight loss of bioplastics buried in soil was higher than that of bioplastics in an open environment. In the soil burial method, bioplastics containing 20% glycerol exhibited limited degradation, particularly at MCC 0–5%. However, when MCC was increased to 7.5–15%, mass loss increased because the higher cellulose fraction tended to agglomerate, forming areas that were more absorbent and more rapidly degraded by soil microbial cellulase enzymes [44]. At 30% and 40% glycerol, the increase in mass loss percentage was greater. This indicates that the higher the glycerol concentration, the more easily the bioplastic degrades [45]. In the open-air method, degradation

occurred much more slowly across all treatments because the process relied solely on oxidation, water evaporation, and surface microbial activity, which were much lower than in soil.

4. Conclusion

The bioplastic formulated with 5% filler and 30% glycerol exhibited the best overall performance among the tested samples, with a thickness of less than 0.24 mm, a density of 1.45 g/cm³, and a water absorption capacity of 53.13%. Its mechanical properties included a tensile strength of 2.4598 MPa, an elongation of 7.9274%, and a Young's modulus of 48.6875 MPa. In terms of biodegradability, the soil burial method showed a higher weight loss (20% within 15 days) than the open-air method (12.5%), indicating that soil conditions enhance degradation. Overall, these results highlight the significant influence of both material composition and environmental conditions on the performance of bioplastics, and contribute to the understanding of structure–property relationships in biopolymer composites, particularly the synergistic effects of MCC reinforcement and plasticizer content. Further studies are recommended to improve the mechanical properties of bioplastics by blending them with biodegradable polymers such as Polyvinyl Alcohol (PVA) or Polylactic Acid (PLA), thereby promoting the formation of a more compact, homogeneous matrix. In addition, careful control of environmental humidity is necessary during biodegradation testing, as moisture levels can significantly influence the degradation rate by enhancing water absorption and microbial activity.

Acknowledgment

The author gratefully acknowledges the Laboratory of Chemical Process Engineering, Universitas Sumatera Utara, for providing the laboratory facilities and technical support during the completion of this research. The author would also like to thank Professor Halimatuddahliana for her guidance on biopolymer research.

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