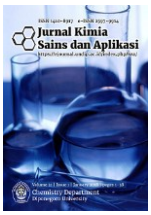
ISSN: 1410-8917
Jurnal Kimia Sains & Aplikasi
e-ISSN: 2597-9914

Jurnal Kimia Sains dan Aplikasi 28 (8) (2025): 426-435

Jurnal Kimia Sains dan Aplikasi
Journal of Scientific and Applied Chemistry

Journal homepage: http://ejournal.undip.ac.id/index.php/ksa



Development of Bioplastic Films from Cassava Peel Starch Reinforced with Banana Midrib Nanocellulose and the Effect of Sorbitol on Mechanical Strength

Anita Maharani Albarkah [1,*], Betty Marita Soebrata [1], Tetty Kemala [1]

[1] Department of Chemistry, Faculty of Mathematics and Science, IPB University, Bogor, Indonesia

* Corresponding author: anitamaharanialbarkah@gmail.com

https://doi.org/10.14710/jksa.28.8.426-435

Article Info

Article history:

Received: 24th June 2025
Revised: 19th August 2025
Accepted: 27th August 2025
Online: 31st October 2025

Keywords:
banana midrib; bioplastic; nanocellulose; sorbitol; starch

Abstract

Cassava peel and banana midrib, two abundant agricultural wastes, were utilized as sources of starch and cellulose to develop environmentally friendly bioplastic films. Cellulose was isolated through delignification and bleaching, followed by ultrasonication to produce nanocellulose. The obtained nanocellulose was characterized using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and a Particle Size Analyzer (PSA), which confirmed distinct cellulose functional groups, a crystallinity index of 58.7%, and an average particle size of 326.44 nm. Bioplastic films were prepared by blending cassava peel starch with banana midrib nanocellulose and varying concentrations of sorbitol as a plasticizer. The incorporation of nanocellulose increased thickness, density, and tensile strength, while reducing water absorption and water vapor transmission rate (WVTR), likely due to the reinforcing effect of nanocellulose within the polymer matrix. The addition of sorbitol at different concentrations influenced the mechanical properties of the bioplastics, with the composition containing 0.89 g sorbitol exhibiting favorable tensile strength and elongation. The optimal formulation consisted of 2.85 g cassava peel starch, 0.15 g nanocellulose, and 0.89 g sorbitol, yielding a tensile strength of 2.76 MPa and an elongation of 11.19%. These findings demonstrate that incorporating sorbitol and nanocellulose significantly enhances the performance of starch-based bioplastics, highlighting their potential application in sustainable packaging materials.

1. Introduction

Plastic is a material that is often used in everyday life, especially as packaging. Plastic is lightweight, waterproof, and easy to obtain because of its relatively cheap price. Synthetic plastics derived from petroleum are difficult to degrade, causing environmental pollution. Based on the Sistem Informasi Pengelolaan Sampah Nasional (SIPSN), it is recorded that waste generation in Indonesia reaches 26 million tons per year, with plastic waste ranked as the second largest waste [1]. Environmental pollution due to plastics that are difficult to decompose can be overcome by making bioplastics. Bioplastics are polymer compounds that have biodegradable and environmentally friendly plastic properties. Bioplastics can be derived from composite materials such as polymers with biodegradable properties, namely cellulose [2], polysaccharides [3], lipids [4], and proteins [5].

Bioplastics have various advantages, including easy degradation and easily available raw material sources, one of which comes from biomass. Agricultural biomass sources that can be utilized for bioplastics include cassava peels as a source of starch. Starch is a natural polysaccharide biomass product easily degraded by microorganisms [6]. The content in starch consists of amylose and amylopectin, which can produce bioplastics with good characteristics [7]. Starch can be obtained from corn, which contains *Lactococcus lactis* and has been utilized in film production [8], or from potatoes, which are widely used in the food industry and have therefore been extensively developed concerning pregelatinized starch [9]. Starch can also be derived from cassava peel,

which contains approximately 44–59% starch [10]. Cassava peel, on the other hand, is an agricultural by-product that is not typically used as a food source, thus providing added value to an underutilized waste product. Using cassava peel as a starch source also contributes to managing agricultural waste generated from the cassava-based food industry, such as fermented cassava (tapai) production.

Starch-based bioplastics typically exhibit poor mechanical properties; therefore, the addition of reinforcements such as cellulose is necessary. Cellulose is well utilized in bioplastics as a filler or reinforcement because it has good mechanical properties [11]. Cellulose can be derived from agricultural waste, including banana fronds. Cellulose contained in the banana midrib reaches more than 80% of the total, potentially making bioplastics [12]. In general, the content of banana midrib consists of 5% lignin, 63-64% cellulose, and 0.89 g hemicellulose [13]. The low lignin content of banana midrib makes it an attractive reinforcement material for bioplastics, while simultaneously helping to reduce agricultural waste accumulation. Cellulose contains hydroxyl groups that are stable and difficult to degrade. It is also hydrophilic, which leads to poor compatibility with hydrophobic polymer matrices [14]. A high cellulose content can be achieved using microwave heating at a maximum power of 800 W, which is more effective than conventional heating methods. Microwave-assisted extraction can yield cellulose with a purity of up to 86.43% [15]. This method accelerates the reaction rate and ensures uniform heating, producing high-purity cellulose [16].

The properties of cellulose can be optimized by reducing its particle size. A smaller filler increases the surface area, leading to stronger interactions between the matrix and the filler [17]. Therefore, nanocellulose has been widely developed as a filler for film matrices to strengthen their mechanical properties. The best film was obtained in the composition with corn starch, 5% nanocellulose, and sorbitol plasticizer. The composition produced a thickness of 0.256 mm, water vapor transmission rate (WVTR) of 2.259 g/m^{2}h, tensile strength of 4.69 MPa, and elongation of 56% [18]. A higher concentration of nanocellulose can enhance the tensile strength and water resistance of bioplastics. However, starch and nanocellulose-based bioplastics tend to be brittle and lack elasticity; therefore, plasticizers are required to improve their flexibility. Sorbitol is one of the most effective plasticizers, as it enhances the interaction between starch and nanocellulose, reduces the WVTR, and increases tensile strength compared to glycerol [18]. Additionally, sorbitol can weaken intermolecular hydrogen bonds and introduce void spaces within the bioplastic matrix [19].

The strength of bioplastics can be evaluated through tensile strength and elongation tests. Bioplastics reinforced with additional materials generally exhibit higher tensile strength, as the reinforcing agents help fill the voids within the bioplastic matrix, resulting in stronger intermolecular bonding [2]. Based on Indonesian National Standard No. 7188.7: 2016, the tensile strength of plastic ranges from 24.7-302 MPa, elongation of 21-200% and hydrophobicity of 99%. The mechanical properties of bioplastics are also influenced by density, which is the density of the materials that make up the bioplastic composite [20]. This research aims to make cassava peel starch-based bioplastics, utilize banana midrib waste as a source of nanocellulose, and determine the best composition of bioplastics.

2. Experimental

2.1. Materials

The materials used in this study included cassava peel waste obtained from a tapai-making factory in Tanah Sereal, Bogor, and klutuk banana midrib waste collected from the Cileungsi area, Bogor. Additional reagents included distilled water, a universal pH indicator, NaOH (Merck, 10% w/v), H_2O_2 (Merck, 10% v/v), H_2SO_4 (Merck, 25% v/v), sorbitol, and NaOCl (Merck, 5% v/v). The instruments used in this study were a sonicator, a microwave oven, a Fourier-transform infrared (FTIR) spectrometer (Shimadzu IRPrestige-21), an X-ray diffractometer (XRD; Bruker D8 Advance A25, Germany), a particle size analyzer (Horiba SZ-100Z), a tensile strength and elongation tester (Instron 3369), and standard laboratory glassware.

2.2. Cassava Peel Starch Preparation

Cassava peel waste was first cleaned by removing the brown outer skin. A total of 500 g of cassava peels were washed, cut into small pieces, and blended. The resulting pulp was mixed with one liter of water and filtered using a cloth to extract the juice. The filtrate was then left to settle for 24 hours to allow suspension formation. The resulting suspension was dried to obtain a powder, which was then weighed [6].

2.3. Isolation of Banana Midrib Cellulose

A total of 50 g of banana midrib waste was dried in an oven at 60°C. The dried material was then mixed with 600 mL of 10% (w/v) NaOH and heated in a microwave at 800 W for three minutes. The mixture was rinsed with distilled water until a neutral pH was achieved, followed by a bleaching process using 5% NaOCl and 10% (v/v) H_2O_2, also carried out in a microwave for four minutes. After cooling to room temperature, the mixture was washed with distilled water and filtered to obtain cellulose fibers [16].

2.4. Nanocellulose Synthesis via the Acid Hydrolysis Method

A total of 5 g of cellulose was placed in a 250 mL beaker, and 50 mL of 25% H_2SO_4 (1:10 v/v) was added. The mixture was stirred for one hour and then heated on a hot plate at 45°C while continuously stirred using a magnetic stirrer. After heating, the solution was allowed to cool, and 100 mL of distilled water (twice the volume of sulfuric acid) was added. The mixture was centrifuged at 5000 rpm for 30 minutes, and this process was repeated several times until the pH reached neutral. The resulting suspension was then subjected to ultrasonication for 30 minutes. The wet nanocellulose obtained was dried in an oven at 60°C [14].

2.5. Bioplastic Preparation

Bioplastics were prepared by dispersing nanocellulose in 10% (v/v) acetic acid for 30 minutes prior to blending with cassava peel starch. The use of acetic acid facilitates the dispersion of nanocellulose by reducing aggregation and provides an acidic medium that promotes starch gelatinization, thereby improving film homogeneity. Cassava starch was then mixed with 30 mL of distilled water and blended with nanocellulose and sorbitol according to the formulations listed in Table 1. The bioplastic solution was then molded using a Petri dish and a glass plate, then stored at room temperature for 24 hours until the bioplastic sheet could be removed from the molds [21].

Formulations D1–D3 represent the first set of films with a lower sorbitol concentration (0.89 g), whereas T1–T3 represent the second set with a higher sorbitol concentration (1.34 g). This variation was designed to evaluate the influence of plasticizer content on the flexibility and barrier properties of the films. Within each set, nanocellulose was varied to determine its reinforcement effect. The selected formulations were based on preliminary trials, where sorbitol levels of 0.89 g and 1.34 g provided films with sufficient integrity for further characterization.

2.6. Determination of Moisture Content

Moisture content determination was performed following the AOAC 2016 method [22]. A porcelain cup was cleaned and dried in an oven at 105°C for 30 minutes. After drying, the cup was cooled in a desiccator and weighed to obtain the empty weight. Samples of starch, banana midrib pulp, cellulose, and nanocellulose were weighed and placed into porcelain cups. The samples were then dried in an oven at 105°C for three hours. After drying, the porcelain cup was cooled in a desiccator until a constant weight was achieved.

2.7. Tensile Strength (MPa) and Elongation Testing

Bioplastic tensile strength testing was carried out based on ASTM D882 standards using an Instron tensile strength tool. The test was conducted by preparing a 2×10 cm bioplastic specimen, which was clamped on both sides with an initial gauge length of 50 mm. The crosshead speed was set at 10 mm/min, and all measurements were performed at a room temperature of 25°C, under 50% relative humidity. The tensile strength (σ) of the bioplastics was calculated using Equation 1, where σ represents tensile strength (MPa), F_{max} is the maximum tensile force (N), and A is the cross-sectional area (mm²).

$$\sigma = \frac{F_{max}}{A} \quad (1)$$

Each bioplastic composition was also measured for elongation to determine the composition with the best elongation. The elongation value was calculated using Equation 2, with ε (Elongation (%)), ΔL ((L–L₀) length increment (mm)), and L_0 (Initial length (mm)).

$$\varepsilon = \frac{\Delta L}{L_0} \times 100\% \quad (2)$$

Table 1. Composition of starch, nanocellulose, and sorbitol in bioplastic manufacturing

Composition	Starch (g)	Nanocellulose (g)	Sorbitol (g)
D1	3.00	0.00	0.89
D2	2.85	0.15	0.89
D3	2.70	0.30	0.89
T1	3.00	0.00	1.34
T2	2.85	0.15	1.34
T3	2.70	0.30	1.34

2.8. Water Vapor Transmission Rate Testing

WVTR testing of the bioplastics was conducted using a Petri dish filled with 15 mL of water and covered with aluminum foil. A 2 × 2 cm area was perforated at the center of the foil and sealed with the bioplastic film. The Petri dish was then placed in an oven at 40°C for 80 minutes [23]. The weight of the film was measured every 20 minutes, and the WVTR was calculated using Equation 3, where n is the weight change (g), t is the time, and A is the surface area (m²).

$$WVTR = \frac{n}{t \times A} \times 100\% \quad (3)$$

2.9. Water Absorbency Testing

The water absorption capacity (WAC) test was conducted using bioplastic samples measuring 2 × 2 cm, with their initial weights (W_0) recorded. The samples were immersed in a container containing 15 mL of distilled water and left to soak for 24 hours. After soaking, the bioplastics were removed, gently blotted to remove surface water, and weighed to obtain the final weight (W). The WAC was then calculated using Equation 4.

$$WAC = \frac{W - W_0}{W_0} \times 100\% \quad (4)$$

2.10. Density Testing

The density test was performed using a 10 mL pycnometer. The sample mass was measured using a digital scale. First, the empty pycnometer was weighed, followed by weighing the pycnometer filled with distilled water. Then, the pre-weighed sample was placed into the pycnometer containing distilled water, and the total weight was recorded [23]. The density of the bioplastic was calculated using Equation 5.

$$Ds = \frac{W_1 - W_0}{(W_3 - W_0) - (W_2 - W_1)} \times (D_1 - D_a) + D_a \quad (5)$$

Where, Ds represents the density in grams per cubic centimeter (g/cm³), W_0 is the empty weight of the pycnometer (g), W_1 is the weight of the pycnometer with the sample (g), W_2 is the weight of the pycnometer with the sample and water (g), W_3 is the weight of the pycnometer filled with water only (g), D_1 refers to the specific gravity of water (g/cm³), and D_a denotes the specific gravity of air at the experimental temperature (g/cm³).

2.11. Bioplastic Thickness Measurement

The thickness of the bioplastic was measured using a digital micrometer with an accuracy of 0.01 mm.

Measurements were taken at five different points on each sample, and the average value was calculated [24].

2.12. Characterization and Testing

Characterization was performed using Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and a Particle Size Analyzer (PSA). FTIR analysis was conducted to identify the functional groups present in the samples. Solid samples were mixed with KBr, placed on a sample holder, and analyzed over a wavenumber range of 4000–400 cm^{-1}. The resulting spectra, showing wavenumbers and percent transmittance, were interpreted to determine the functional groups.

XRD characterization was carried out to determine the crystallinity percentage of the samples. The samples were ground to a fine powder, placed evenly on a standard XRD sample holder, and analyzed using a Bruker D8 Advance A25 diffractometer (Germany).

PSA analysis was performed to determine the particle size distribution of the nanocellulose. Samples were dispersed in distilled water and sonicated for 45 minutes to ensure complete dispersion and prevent agglomeration. Particle size measurements were obtained using Dynamic Light Scattering (DLS) with a Horiba SZ-100Z Particle Size Analyzer.

2.13. Data Analysis

The research data were analyzed using ANOVA by determining statistical significance using analysis of variance with a 95% confidence level (p-value <0.05).

3. Results and Discussion

3.1. Cassava Peel Starch

Cassava peels contain starch ranging from 44% to 59%, making them a viable source of starch for bioplastic production [25]. In this study, the starch yield from 500 g of cassava peels was 44.35%. The resulting starch powder exhibited a white-brown color and was uniformly ground to ≤ 100 mesh, with a moisture content of 11.32% (Figure 1). These values comply with the SNI (3729:2008) standard, which sets a maximum moisture content of 13% for starch [26]. Moisture content testing serves as an important reference, as high moisture levels can promote mold growth during storage, leading to the degradation of starch components.

Figure 1. Cassava peel starch

3.2. Banana Midrib Nanocellulose

Cellulose isolation from banana midrib yielded 89.75% with an average moisture content of 7.66%, representing the highest yield obtained in this study. Cellulose was isolated through delignification and bleaching processes, which removed lignin and hemicellulose components, leaving only cellulose. This process produced a dark brown cellulose pulp, indicating partial lignin dissolution by alkali (Figure 2a). Residual lignin was further removed through oxidation and bleaching, resulting in white cellulose, which confirmed the effective elimination of most lignin and hemicellulose (Figure 2b).

Microwave heating during cellulose isolation accelerated the reaction and provided more uniform heating compared to conventional hot plate methods. The interaction of microwaves with molecules in the NaOH solution reduced the hemicellulose and lignin content that bound and hindered cellulose. Heating at 800 W was identified as the optimal power level to maximize cellulose yield during isolation [16].

The isolated cellulose was hydrolyzed to obtain white nanocellulose (Figure 3). The average yield of nanocellulose reached 69.98%, with a moisture content of 5.02%. Hydrolysis using 25% sulfuric acid effectively facilitated nanocellulose formation. However, excessively high acid concentrations may lead to a brownish coloration due to the overreaction of cellulose, resulting in hydrothermal carbonization and hydrocarbon formation [27]. The appearance of a blackish brown color indicates degradation and dissolution of cellulose components [28].

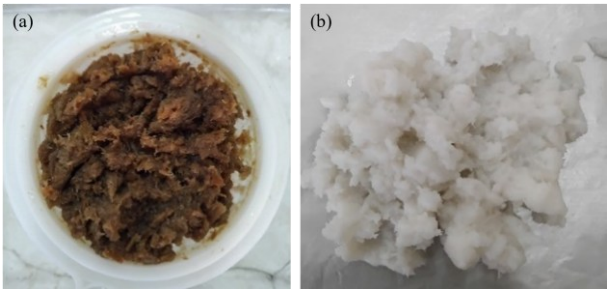


Figure 2. Banana midrib: (a) before delignification, and (b) after bleaching

Figure 3. Nanocellulose

Moreover, temperature also plays a critical role in nanocellulose production, as excessively high temperatures can induce carbonization of cellulose. In this study, heating at 45°C was applied to selectively degrade the amorphous regions of cellulose [29]. Subsequently, ultrasonication was employed to further disintegrate the cellulose fiber structure through ultrasonic waves, thereby reducing particle size and eliminating amorphous cellulose chains [30].

The resulting banana midrib cellulose was further characterized using a PSA, revealing an average particle size of 326.44 nm (Figure 4). Cellulose particles ranging from 10 to 350 nm are classified as nanocellulose [31], whereas cellulose nanocrystals typically have diameters between 1 and 100 nm [32]. Thus, the particle size obtained in this study falls within the nanocellulose range but does not meet the smaller size criteria of cellulose nanocrystals. This discrepancy is likely due to suboptimal mechanical treatment during ultrasonication, which may have limited the extent of cellulose chain breakage [29]. Increasing the sonication time has been shown to reduce particle size further [33]. The produced nanocellulose was subsequently used as a binder in a bioplastic formulation.

The crystalline structure of the nanocellulose was characterized using XRD to determine the degree of crystallinity (Figure 5). The diffraction pattern revealed the presence of both crystalline and amorphous phases. Distinct diffraction peaks with high intensity appeared at 2θ = 15.71°, 22.49°, and 34.51°, consistent with the Joint Committee on Powder Diffraction Standards (JCPDS) data No. 00-050-2241 (Table 2), confirming the cellulose structure. The crystallinity index of the nanocellulose, calculated from the XRD data, was 58.7%. This value is higher than that reported by Sangbara *et al.* [34], who found a crystallinity of 53.83%.

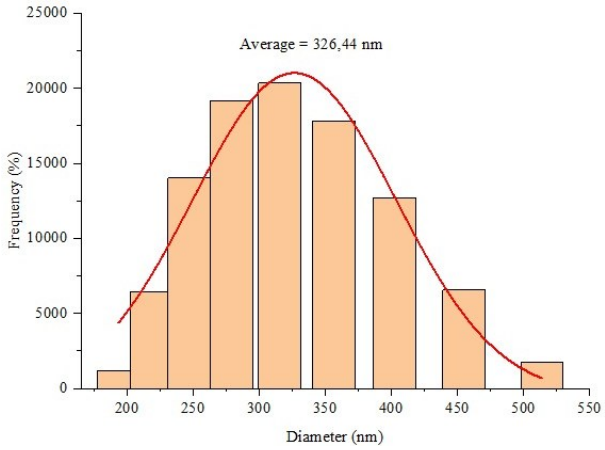


Figure 4. Mean particle size distribution of nanocellulose

Table 2. Comparison of XRD peak positions between the nanocellulose sample and standard JCPDS data

Sample	Sample 2θ peak (°)	JCPDS 2θ peak (°)	Intensity (%)
Nanocellulose	15.71	17.24	90
	22.49	20.64	100
	34.51	33.41	60

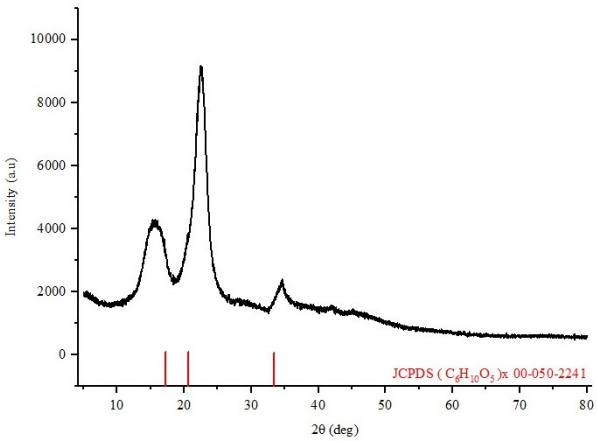


Figure 5. XRD diffractogram of nanocellulose

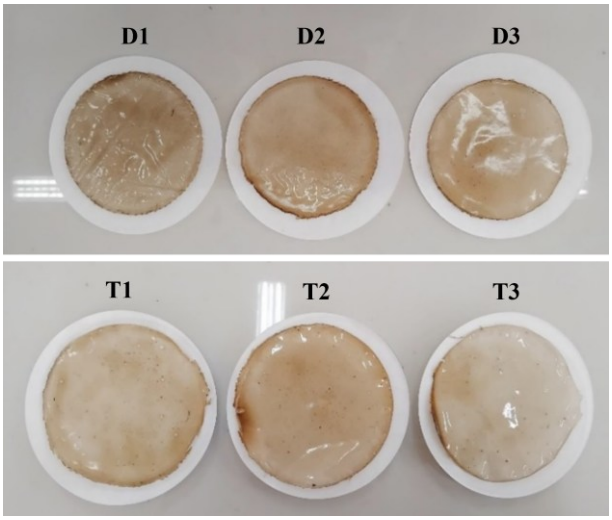


Figure 6. Bioplastics of various compositions

3.3. Starch-Nanocellulose Bioplastics

Bioplastics were fabricated using starch and nanocellulose. Starch was first dissolved in distilled water, while nanocellulose was dispersed in acetic acid. The two solutions were then combined and heated with the addition of sorbitol until the mixture thickened. Sorbitol was used to enhance the elasticity of the bioplastics while maintaining low water content. The resulting bioplastics were brown, transparent, and flexible (Figure 6). Variations in color and transparency among different compositions were primarily influenced by the thickness of the bioplastic, leading to minor color differences. Compositions D2, D3, T2, and T3 exhibited white spots attributed to the presence of nanocellulose.

3.4. Bioplastic Thickness

The thickness of each bioplastic composition was determined based on the average values, as presented in Figure 7. The thinnest film was obtained from composition T1 (0.0747 mm), which contained 3 g of starch and 1.34 g of sorbitol, while the thickest was recorded for composition T3 (0.0943 mm), consisting of 2.70 g of starch, 0.30 g of nanocellulose, and 1.34 g of sorbitol. According to the Japanese Industrial Standard (JIS) 2-1707 (1975), plastic films must not exceed a thickness of 0.25 mm [35]; hence, all bioplastic compositions comply with this specification. ANOVA

results revealed significant differences ($p < 0.05$) in thickness among the compositions. The increase in nanocellulose concentration was associated with greater bioplastic thickness, likely due to the higher total soluble solid content, which enhances solution viscosity and consequently increases the resulting film thickness [18].

Thickness is a critical physical parameter that significantly influences the properties of bioplastics, including transparency, density, tensile strength, and elongation. Generally, thicker bioplastics exhibit lower transparency but higher density, tensile strength, and elongation. Thickness can be affected by factors such as the volume of solution poured and the surface area of the mold. Additionally, thickness measurements can indicate the homogeneity of the bioplastic components; uneven thickness suggests suboptimal mixing, resulting in variable measurements across different points.

3.5. Bioplastic Density

Density measurements showed that composition T3, containing 2.70 g of starch, 0.3 g of nanocellulose, and 1.34 g of sorbitol, had the highest density value of 4.05 g/mL (Figure 8). According to SNI 7188-7 (2016), plastic materials must have a minimum density of 0.95 g/mL; thus, all bioplastic compositions meet this standard [36]. ANOVA analysis indicated no significant differences in density among the compositions ($p > 0.05$).

Nevertheless, density measurement is important as it influences properties such as the WVTR. Higher density typically correlates with improved mechanical properties and lower WVTR. The increased nanocellulose content tightens the bioplastic matrix, reducing pore spaces and making it more difficult for water vapor to penetrate. Consequently, samples with higher nanocellulose concentrations exhibited increased density.

Similar findings have been reported in previous studies, where denser film matrices achieved through additive incorporation resulted in enhanced compactness and reduced porosity, improving barrier properties. Although microstructural analysis was not performed in this study, the density data align well with these structural interpretations. Further microstructural characterization will be undertaken in future work [37].

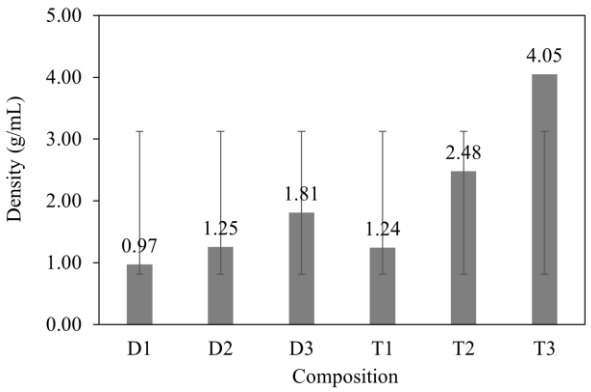


Figure 8. Density of bioplastics with various compositions (error bars represent standard deviation)

3.6. Water Absorbency of Bioplastics

The highest water absorption was observed in the bioplastic without nanocellulose addition, specifically in composition T1, which contained 3 g of starch and 1.34 g of sorbitol, reaching a value of 38.43%. In contrast, the lowest water absorption, 18.23%, was found in composition D3, which contained 2.70 g of starch, 0.3 g of nanocellulose, and 0.89 g of sorbitol (Figure 9). All results comply with the SNI 7188-7 (2016) standard, which sets a maximum water absorption of 21.5% [36]. ANOVA analysis revealed significant differences ($p < 0.05$) in water absorption among the bioplastic compositions. Bioplastics containing 1.34 g of sorbitol tended to absorb more water than those with 0.89 g, likely due to sorbitol's hydrophilic nature. Higher sorbitol content increases water absorption [38].

Water absorption capacity measures the bioplastic's ability to absorb water and reflects its resistance to moisture. Lower absorption values indicate better water resistance. The addition of nanocellulose reduced water absorption, as cellulose is less soluble in water, which decreases the overall hydrophilicity of the starch-based bioplastics. Strong hydrogen bonding between starch and nanocellulose fills the voids in the matrix, enhancing the material's durability. Water absorption also influences WVTR and tensile strength; lower absorption generally leads to reduced vapor transmission and improved tensile strength.

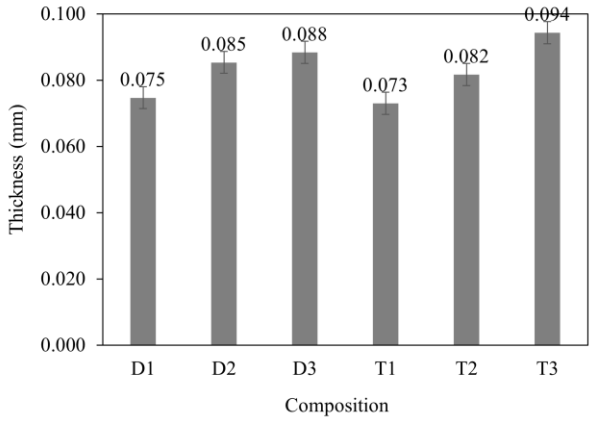


Figure 7. Thickness of bioplastics with various compositions

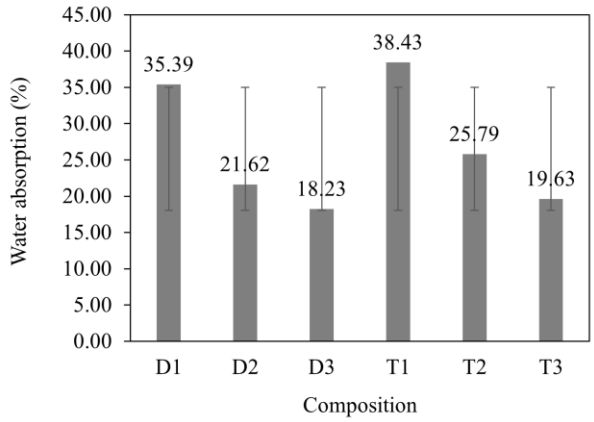


Figure 9. Water absorption of bioplastics with various compositions (error bars represent standard deviation)

3.7. Water Vapor Transmission Rate

WVTR measures the rate at which water vapor passes through the surface of bioplastics over time and per unit area [20]. This test evaluates the resistance of bioplastics to water vapor permeation. Figure 10 shows that the highest WVTR values were observed in compositions D1 and D2, both at 0.053 g/m²·s. ANOVA analysis indicated significant differences ($p < 0.05$) in WVTR among the bioplastic compositions. Higher nanocellulose content corresponded to lower WVTR values, indicating improved resistance to water vapor. This improvement is attributed to the reduction in pore size within the bioplastic matrix, caused by the formation of a hydrogen bonding network between nanocellulose and starch that limits pore formation and blocks water vapor pathways [18].

WVTR is also influenced by the density of the bioplastics; higher-density materials present greater resistance to water vapor permeation [23]. The WVTR results inversely correlate with density values shown in Figure 8, where composition T3 exhibited the highest density and lowest WVTR. Increasing nanocellulose concentration reduces WVTR because the nanoscale particles hinder water movement through the film matrix [18]. Additionally, sorbitol decreases WVTR by enhancing interactions between starch and nanocellulose, with higher sorbitol concentrations further reducing WVTR [39].

3.8. Tensile Strength and Elongation

The highest tensile strength was observed in composition D2, which contained 2.85 g of starch, 0.15 g of nanocellulose, and 0.89 g of sorbitol, with a value of 2.76 MPa (Figure 11). This tensile strength meets the Japanese Industrial Standard (JIS) 2-1707 (1975), which requires a minimum of 0.39 MPa [35]. ANOVA analysis showed no significant differences ($p > 0.05$) in tensile strength among the compositions. However, the addition of 0.15 g nanocellulose increased tensile strength, while 0.30 g nanocellulose reduced it. This can be caused by the thickness of bioplastics and low homogeneity. Nanocellulose added in large amounts can reduce homogeneity, which weakens the interaction between starch and nanocellulose.

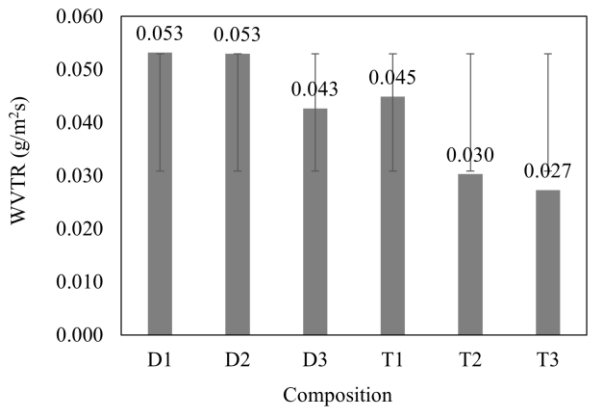


Figure 10. WVTR of bioplastics with various compositions (error bars represent standard deviation)

Another reason could be due to the interactions between starch, nanocellulose, and sorbitol. At a lower nanocellulose loading (0.15 g), nanocellulose may contribute to reinforcing the starch matrix through hydrogen bonding, thereby enhancing stress transfer. In contrast, at a higher nanocellulose loading (0.30 g), nanocellulose aggregation is likely to occur, which can compromise the structural integrity of the matrix. This effect is further modulated by sorbitol concentration, since sorbitol functions as a plasticizer. When combined with excessive nanocellulose, it may exert an antagonistic effect, leading to a reduction in tensile strength.

The tensile strength obtained in this study is lower than that reported by Arifin et al. [18], who achieved 4.69 MPa with 5% nanocellulose addition. Nevertheless, starch-based bioplastics generally exhibit medium tensile strength, which is suitable for lightweight packaging applications that require adequate protection and safety.

The highest percent elongation in bioplastics was observed in composition D2, which contained 2.70 g of starch, 0.15 g of nanocellulose, and 0.89 g of sorbitol, reaching 11.19%. This value meets the food packaging standard JIS 2-1707 (1975), which specifies an elongation range of 10–50% [35]. The lowest elongation was recorded in composition D1, which contained 0.89 g of sorbitol without nanocellulose, at 2.21% (Figure 12). ANOVA analysis revealed significant differences ($p < 0.05$) in elongation among the compositions. Increasing nanocellulose content generally resulted in lower elongation percentages, likely due to the rigid nature of nanocellulose, which makes bioplastics more prone to fracture under high tensile stress [18]. Additionally, the thickness of bioplastics influenced elongation, with thicker samples exhibiting higher percent elongation.

Based on the tensile strength and elongation results of samples D1-D3 and T1-T3, it is evident that increasing the sorbitol content from 0.89 g to 1.34 g generally reduces tensile strength but increases elongation. This indicates that higher plasticizer content improved flexibility at the expense of mechanical strength.

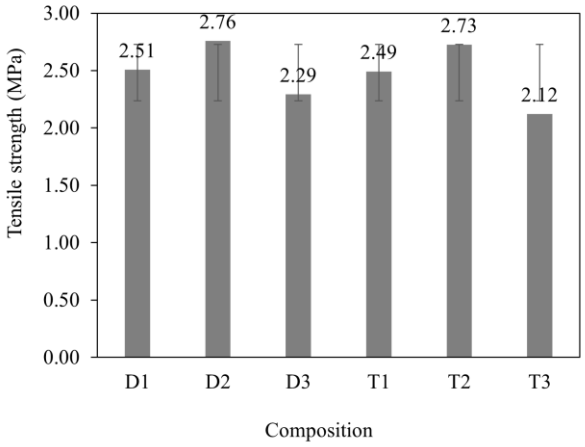


Figure 11. Tensile strength of bioplastic with various compositions (error bars represent standard deviation)

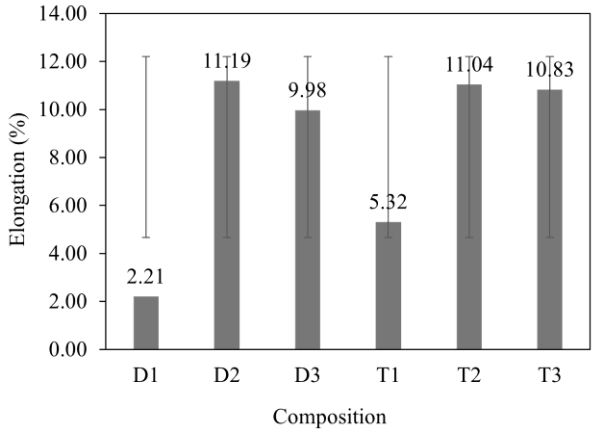


Figure 12. Percent elongation of bioplastics with various compositions (error bars represent standard deviation)

3.9. Fourier-transform Infrared Spectroscopy

Cellulose is a natural polymer made of glucose units $(C_6H_{10}O_5)n$, containing C–H, O–H, and C–O functional groups. The FTIR spectra of nanocellulose and starch samples show several characteristic peaks, as illustrated in Figure 13. The FTIR spectrum of starch-based bioplastics with nanocellulose addition closely resembles those of starch and nanocellulose. Key absorption peaks appear at 3284 cm^{-1} (O–H), 2928 cm^{-1} (C–H), 1637 cm^{-1} (C=C), and 1149 cm^{-1} (C–O) (Table 3). Compared with pure starch and nanocellulose, slight spectral shifts are observed, particularly in the O–H stretching region and the C–O or C–O–C stretching around 1000–1150 cm^{-1}. These shifts indicate possible hydrogen bonding and molecular interactions between starch, nanocellulose, and sorbitol within the bioplastic matrix. No new peaks were observed, indicating that the bioplastic's chemical properties are consistent with those of its constituent components [40].

Table 3. Wavenumbers of FTIR spectra of starch, nanocellulose, and bioplastic samples

Functional group	Wavenumber (cm^{-1})		
	Starch	Nanocellulose	Bioplastic
O–H stretching	3284	3281	3284
C–H stretching	2935	2988	2928
C=C stretching (lignin)	1656	1653	1637
O–H bending	1423, 1337	1429, 1324	1340
C–O stretching	1150	1157	1149
C–O–C stretching	1019	1031	1002
β-1,4 glycosidic bonds	931	899	930, 861

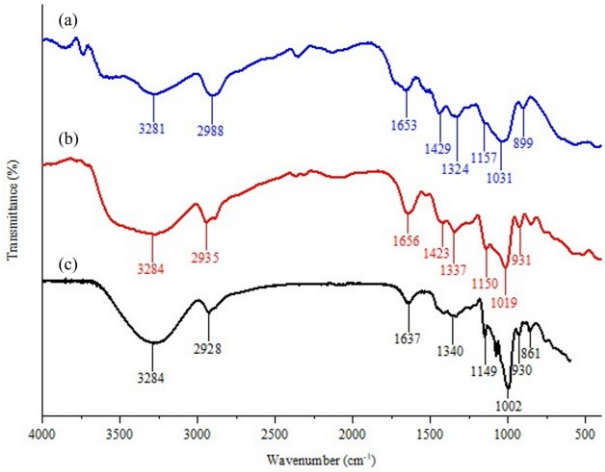


Figure 13. FTIR spectra of (a) nanocellulose, (b) starch, and (c) bioplastics with 0.15 g nanocellulose added

At lower nanocellulose loading, enhanced hydrogen bonding improves the compatibility between starch, nanocellulose, and sorbitol, contributing to increased tensile strength. However, at higher nanocellulose concentrations, possible aggregation may reduce the availability of hydroxyl groups for hydrogen bonding, thereby weakening the interfacial interactions and decreasing tensile strength. Thus, the FTIR results not only confirm the presence of functional groups but also provide evidence of molecular interactions that correlate with the mechanical behavior of the bioplastics.

4. Conclusion

The study successfully developed environmentally friendly bioplastics from cassava peel starch and banana midrib-derived nanocellulose. The addition of nanocellulose increased the thickness and density of the bioplastics while reducing water absorption and water vapor transmission rate (WVTR). The formulation with 2.85 g of starch, 0.15 g of nanocellulose, and 0.89 g of sorbitol exhibited the highest tensile strength and elongation, indicating superior mechanical performance. Furthermore, the use of sorbitol at an optimum concentration provided the best balance between rigidity and flexibility. Therefore, this study highlights the potential of cassava peel-based bioplastics as a sustainable alternative to petroleum-derived plastics, particularly for food packaging applications. However, the work is limited by the absence of structural and morphological characterizations, such as SEM or TEM, to fully establish the structure-property performance relationship. Future work should include microstructural evaluation, biodegradability testing, and optimization with alternative plasticizers to enhance performance and expand potential applications.

Acknowledgment

The authors gratefully acknowledge the Physical Chemistry Laboratory of the Department of Chemistry, Faculty of Mathematics and Natural Sciences, IPB University, for providing the facilities that supported this research. The authors also hope that this work will be of value to researchers and contribute to the advancement of scientific knowledge.

References

[1] Kementerian Lingkungan Hidup dan Kehutanan, *Sistem Informasi Pengelolaan Sampah Nasional (SIPSN)*, Kementerian Lingkungan Hidup dan Kehutanan, 2023

[2] Yuli Darni, Swarna Dharma Utama, Muhammad Haviz, Lia Lismeri, Herti Utami, Pengaruh Temperatur Gelatinisasi dan Penguat Selulosa Batang Sorgum Terhadap karakteristik Fisik dan Mekanik Bioplastik, *Jurnal Teknologi dan Inovasi Industri (JTII)*, 4, 2, (2023), https://doi.org/10.23960/jtii.v4i2.78

[3] Muhammad Dzaky, Laksmi Sulmartiwi, Dwi Yuli Pujiastuti, Application of Modified Starch on Bioplastic Spoon Based Carrageenan from *Eucheuma cottonii* on Biodegradability and Water Resistance, *Journal of Marine and Coastal Science*, 11, 2, (2022), 40-48 https://doi.org/10.20473/jmcs.v11i2.30488

[4] Dwi Fibriyani, Fera Arinta, Ratna Dewi Kusumaningtyas, Pengolahan Onggok Singkong sebagai Plastik *Biodegradable* Menggunakan *Plasticizer* Gliserin dari Minyak Jelantah, *Jurnal Aplikasi Teknologi Pangan*, 6, 2, (2017), 74-77

[5] Ariya Dwi Nugrahanto, Asih Kurniawati, Yuny Erwanto, Karakteristik fisis bioplastik yang dibuat dari kombinasi pati tapioka dan kasein susu apkir, *Majalah Kulit, Karet, dan Plastik*, 37, 2, (2021), 103-114

[6] Samsul Aripin, Bungaran Saing, Elvi Kustiyah, Studi Pembuatan Bahan Alternatif Plastik *Biodegradable* dari Pati Ubi Jalar dengan *Plasticizer* Gliserol dengan Metode *Melt Intercalation*, *Jurnal Teknik Mesin (Journal of Mechanical Engineering)*, 6, 2, (2017), 79-84 https://dx.doi.org/10.22441/jtm.v6i2.1185

[7] Azahra Rizka Amalia, Rian Fasya Kumara, Novy Pralisa Putri, Manufacturing of bioplastics from cellulose empty fruit bunches waste with addition of glycerol as plasticizer, *Konversi*, 8, 2, (2019), https://dx.doi.org/10.20527/k.v8i2.6839

[8] Wenting Lan, Rong Zhang, Tengteng Ji, Dur E. Sameen, Saeed Ahmed, Wen Qin, Jianwu Dai, Li He, Yaowen Liu, Improving nisin production by encapsulated *Lactococcus lactis* with starch/carboxymethyl cellulose edible films, *Carbohydrate Polymers*, 251, (2021), 117062 https://doi.org/10.1016/j.carbpol.2020.117062

[9] Barmi Hartesi, Lili Andriani, Lia Anggresani, Mahadma Bhima Whinata, Haflin Haflin, Modifikasi pati kentang secara pregelatinasi dengan perbandingan pati dan air (1: 1, 25), *Riset Informasi Kesehatan*, 9, 2, (2020), 177-187 https://doi.org/10.30644/rik.v9i2.431

[10] Indah Riwayati, Ahmad Choirul Anam, Farikha Maharani, Pengaruh suhu dan waktu proses modifikasi heat moisture treatment (HMT) pada tepung kulit singkong terhadap sifat kelarutan dan swelling power, *Jurnal Inovasi Teknik Kimia*, 5, 1, (2020), 50-55

[11] Tjahjono Herawan, Meta Rivani, Halimatudahliana, Suryo Irawan, Oil palm based cellulose esters as raw material for environmentally friendly bio-plastic, *Majalah Kulit, Karet, dan Plastik*, 34, 1, (2018), 33-40

[12] Syamsul Bahri, Pembuatan pulp dari batang pisang, *Jurnal Teknologi Kimia Unimal*, 4, 2, (2015), 36-50 https://doi.org/10.29103/jtku.v4i2.72

[13] Ani Melani, Atikah Atikah, Rafit Arjeni, Robiah Robiah, Pengaruh Volume Pelarut NaOH dan Temperatur Pemasakan *Pulp* dari Pelepah Pisang Klutuk, *Jurnal Distilasi*, 7, 1, (2022), 18-27

[14] Nina Hartati, Tetty Kemala, Komar Sutriah, Obie Farobie, Kompatibilitas Nanokristal Selulosa Termodifikasi Setrimonium Klorida (CTAC) dalam Matriks Poliasam Laktat sebagai Material Pengemas, *Jurnal Kimia Sains dan Aplikasi*, 22, 4, (2019), 157-163 https://doi.org/10.14710/jksa.22.4.157-163

[15] Inda Iliyin, Henny Purwaningsih, Tun Tedja Irawadi, Isolation and Characterization of Cellulose from Banana Stems using Microwave Heating, *Jurnal Kimia Valensi*, 6, 2, (2021), 169-176 https://doi.org/10.15408/jkv.v6i2.15962

[16] Nor Pana Yupa, Henny Purwaningsih, Tetty Kemala, Synthesis and Characterization of Corn Husk (*Zea Mays* L.) Cellulose Using Microwave-Assisted Extraction (MAE), *Jurnal Kimia Sains dan Aplikasi*, 26, 7, (2023), 268-275 https://doi.org/10.14710/jksa.26.7.268-275

[17] R. A. Ilyas, S. M. Sapuan, M. R. Ishak, E. S. Zainudin, Development and characterization of sugar palm nanocrystalline cellulose reinforced sugar palm starch bionanocomposites, *Carbohydrate Polymers*, 202, (2018), 186-202 https://doi.org/10.1016/j.carbpol.2018.09.002

[18] Heni Radiani Arifin, Mohamad Djali, Bambang Nurhadi, Shafrina Azlin Hasim, Amani Hilmi, Almira Vania Puspitasari, Improved properties of corn starch-based bio-nanocomposite film with different types of plasticizers reinforced by nanocrystalline cellulose, *International Journal of Food Properties*, 25, 1, (2022), 509-521 https://doi.org/10.1080/10942912.2022.2052085

[19] Ardimas Fauzan Huwaidi, Edy Supriyo, Pembuatan Plastik Biodegradable Pati Jagung Terplastisasi Sorbitol dengan Pengisi Selulosa dari Ampas Tebu, *Equilibrium Journal of Chemical Engineering*, 6, 1, (2022), 45-49 https://doi.org/10.20961/equilibrium.v6i1.62552

[20] Endang Warsiki, Iwan Setiawan, Hoerudin, Sintesa Komposit Bioplastik Pati Kulit Singkong-Partikel Nanosilika dan Karakterisasinya, *Jurnal Kimia dan Kemasan*, 42, 2, (2020), 37-45

[21] Jeya Jeevahan, M. Chandrasekaran, Akshay Sethu, Influence of nanocellulose addition on the film properties of the bionanocomposite edible films prepared from maize, rice, wheat, and potato starches, *AIP Conference Proceedings*, 2162, 1, (2019), 020073 https://doi.org/10.1063/1.5130283

[22] AOAC International, *Official Methods of Analysis*, 20th ed., AOAC Inc., Washington DC, 2016,

[23] Wouda Fiorendita Karim, Muslim Arfanshah Harahap, Mochamad Galih Prakoso, Muhammad Alhas Finaldin, Tetty Kemala, Characterization of Bioplastic Compostable PLA-Cellulose Based as Eco-friendly Packaging, *Indonesian Journal of Chemical Science*, 10, 3, (2021), 162-167

[24] Deivy Andhika Permata, Yoni Mellia Putri, Sahadi Didi Ismanto, Variasi penambahan gliserol pada pembuatan bioplastik limbah cair tahu, *Jurnal Teknologi Pertanian Andalas*, 28, 1, (2024), 46-53 https://doi.org/10.25077/jtpa.28.1.46-53.2024

[25] Yonia Avisha Harahap, Ayu Chandra Kartika Fitri, Yuni Eka Fajarwati, Analisis Kelarutan Bioplastik dari Pati Kulit Singkong dengan Penambahan Variasi Gliserol, Selulosa Jerami Padi, dan Kitosan, *Prosiding SENTIKUIN (Seminar Nasional Teknologi Industri, Lingkungan dan Infrastruktur)*, 2023

[26] Badan Standardisasi Nasional, *SNI 3729:2008: Syarat Mutu Tepung Sagu*, Badan Standardisasi Nasional, Indonesia, 2008,

[27] Viola Hoffmann, Dennis Jung, Joscha Zimmermann, Catalina Rodriguez Correa, Amal Elleuch, Kamel Halouani, Andrea Kruse, Conductive Carbon Materials from the Hydrothermal Carbonization of Vineyard Residues for the Application in Electrochemical Double-Layer Capacitors (EDLCs) and Direct Carbon Fuel Cells (DCFCs), *Materials*, 12, 10, (2019), 1703 https://doi.org/10.3390/ma12101703

[28] Srie Muljani, Adi Candra, Iklimatul Faiqoh, Sintesis dan Karakterisasi Selulosa Kristal dari Batang Tembakau, *Jurnal Teknik Kimia*, 17, 2, (2023), 46-51 https://doi.org/10.33005/jurnal_tekkim.v17i2.3780

[29] Endang Widiastuti, Ari Marlina, Optimasi Pembuatan Nanoselulosa dari Rumput Alang-Alang, *Fluida*, 13, 2, (2020), 59-64 https://doi.org/10.35313/fluida.v13i2.2249

[30] Halimatuddahliana Nasution, Ellsworth, Fenny Wijaya, Optimasi Suhu Hidrolisis dan Konsentrasi Asam Sulfat dalam Pembuatan Nanoselulosa Berbahan Dasar Serat Batang Pisang Kepok (*Musa acuminata* x *balbisiana*), *Jurnal Teknik Kimia USU*, 9, 1, (2020), 1-6 https://doi.org/10.32734/jtk.v9i1.3532

[31] Syed Farooq Adil, Vanita S. Bhat, Khalid Mujasam Batoo, Ahamad Imran, Mohamed E. Assal, Basavaraj Madhusudhan, Mujeeb Khan, Abdulrahman Al-Warthan, Isolation and characterization of nanocrystalline cellulose from flaxseed Hull: A future onco-drug delivery agent, *Journal of Saudi Chemical Society*, 24, 4, (2020), 374-379 https://doi.org/10.1016/j.jscs.2020.03.002

[32] Ufuoma Abigail Oyohwose, Victoria Ikpemhinoghena Omoko, Synthesis characterization and application of nanocrystalline cellulose: a review, *International Journal of Science and Research Archive*, 8, 2, (2023), 234-243 https://doi.org/10.30574/ijsra.2023.8.2.0217

[33] S. Silfia, F. Failisnur, S. Sofyan, Analisis gugus fungsi, distribusi, dan ukuran partikel tinta stempel dari ekstrak gambir (Uncaria gambir Roxb) dengan senyawa pengomplek NaOH dan $Al_2(SO_4)_3$, *Jurnal Litbang Industri*, 8, 1, (2018), 31-38

[34] Ervi Tandi Sangbara, Hotma Pretty Lestari Tampubolon, Fitriani Mandalurang, Marchelino Christofel Muaja, Regina Pairunan, Audy D. Wuntu, Isolasi Nanoselulosa Pelepah Aren (*Arenga pinnata* Merr.) untuk Menurunkan Kandungan Sianida dalam Limbah Tambang Emas Rakyat Sulawesi Utara, *CHEMISTRY PROGRESS*, 16, 2, (2023), 96-105 https://doi.org/10.35799/cp.16.2.2023.52459

[35] Japanese Standards Association, *JIS 21707.1975: General rules of plastic films for food packaging*, Japanese Standards Association Japan, 1975,

[36] Badan Standardisasi Nasional, *SNI 7188:2016: Kategori Produk Tas Belanja Plastik 20 dan Plastik Mudah Terurai*, Badan Standardisasi Nasional, Indonesia, 2016,

[37] Laras Putri Wigati, Ata Aditya Wardana, Francis Ngwane Nkede, Meng Fanze, Mohammad Hamayoon Wardak, M. A. Reshaka Kavindi, Tran Thi Van, Xirui Yan, Fumina Tanaka, Fumihiko Tanaka, Influence of cellulose nanocrystal formulations on the properties of pregelatinized cornstarch and cornmint essential oil films, *Scientific Reports*, 15, 1, (2025), 18997 https://doi.org/10.1038/s41598-025-03318-8

[38] Rega Desramadhani, Samuel Budi Wardhana Kusuma, The effect of sorbitol concentration on the characteristics of starch-based bioplastics, *Indonesian Journal of Chemical Science*, 12, 2, (2023), 130-142

[39] Desi Juliani, Nugraha Edhi Suyatma, Fahim Muchammad Taqi, Pengaruh Waktu Pemanasan, Jenis dan Konsentrasi *Plasticizer* Terhadap Karakteristik Termoplastik K -Karagenan, *Jurnal Keteknikan Pertanian*, 10, 1, (2022), 29-40 https://doi.org/10.19028/jtep.010.1.29-40

[40] Syifa Aulia Permata Sari, Ristika Oktavia Asriza, Adisyahputra, The Influence of Plasticizer Type on the Characteristics of Bioplastics Made from Taro Tuber Starch (*Colocasia esculenta* (L.) Schott) with the Addition of Cane Drague Cellulose, *SPIN Jurnal Kimia & Pendidikan Kimia*, 5, 2, (2023), 285-295 https://doi.org/10.20414/spin.v5i2.8211