



Biopolimer Preparation of Cellulose Nanowhiskers from Oil Palm Empty Fruit Bunches (*Elaeis guineensis* Jacq.) as a Biopolymer Composite Material

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Abstract: This study aimed to develop cellulose nanowhiskers from oil palm empty fruit bunches (*Elaeis guineensis* Jacq.) as an environmentally friendly reinforcing material for biopolymer composites and to evaluate their characteristics using FTIR, TEM, XRD, and DSC analyses. This development was intended to produce composite materials with improved mechanical properties and thermal stability, thereby offering potential applications in eco-friendly products such as biodegradable packaging, lightweight automotive materials, and biopolymer-based construction materials. The fabrication process involved several sequential stages, including alkaline pretreatment using NaOH, bleaching with NaOCl, cellulose isolation, acid hydrolysis using H₂SO₄, and subsequent mechanical refinement using a ball mill. The yield calculation showed a value of 3.33% based on the initial raw material weight. TEM observations indicated that the cellulose nanowhiskers exhibited a varied particle size distribution, with particles in the range of 50–100 nm tending to be more uniform than larger particles. XRD analysis revealed a crystallinity index of 54.50% and a characteristic cellulose I pattern, indicating that most of the structure was present in crystalline form. DSC analysis further demonstrated that the cellulose nanowhiskers possessed good thermal stability. Based on these findings, cellulose nanowhiskers derived from oil palm empty fruit bunches show considerable potential as environmentally friendly reinforcing agents for biopolymer composites.

Keywords: Oil palm empty fruit bunches; cellulose nanowhiskers; biopolymer composites

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INTRODUCTION

Oil palm is one of the most strategic agricultural commodities in tropical countries such as Indonesia and Malaysia because of its substantial contribution to the food, cosmetics, and renewable energy industries (Gaffar et al., 2024). The continuous expansion of the palm oil industry has been accompanied by a significant increase in processing residues, particularly solid wastes generated from palm oil mills. According to Statistics Indonesia (BPS), the volume of oil palm waste continues to increase in line with industrial growth, creating considerable environmental and waste-management challenges.

Among the various solid wastes produced during palm oil processing, oil palm empty fruit bunches (OPEFB) are one of the most abundant and underutilized biomass residues. OPEFB are generated after the fruits are separated from the bunches and are often discarded, burned, or left to accumulate near processing facilities. These practices may contribute to environmental pollution, including smoke emissions, air-quality deterioration, and disruptions to surrounding communities. At the same time, such disposal methods indicate the limited valorization of a lignocellulosic biomass resource with considerable economic and industrial potential (Ritonga et al., 2023).

Oil palm solid waste generally consists of fronds, shells, and empty fruit bunches (Simatupang, 2020). Among these residues, OPEFB have attracted increasing attention because of their relatively high lignocellulosic content. OPEFB contain approximately 24.34% hemicellulose, 39.29% cellulose, and 13.42% lignin, indicating a strong fibrous structure and substantial potential as a cellulose-rich raw material. Although part of this biomass can be used as boiler fuel, OPEFB also have greater potential as reinforcing materials in polymer-based composites, particularly biopolymer composites (Idris et al., 2018).

Biopolymer composites have emerged as promising environmentally friendly materials because they are derived from renewable resources and can degrade more naturally than many synthetic plastics (Ramadhan et al., 2025). These materials are increasingly used in various industrial applications, including sustainable packaging, automotive interiors, and lightweight construction materials. In general, biopolymer composites consist of natural polymer matrices, such as cellulose, starch, or protein, combined with reinforcing materials to improve their mechanical strength, dimensional stability, and durability. Natural fillers obtained from agricultural residues, including cellulose-based nanomaterials, offer a sustainable strategy for enhancing composite performance while reducing dependence on fossil-based materials (Tarigan & Hasibuan, 2025).

Cellulose nanowhiskers are a type of nanocellulose characterized by a highly crystalline structure, nanoscale dimensions, lengths of approximately 500–2000 nm, and diameters of 1–100 nm. Compared with conventional cellulose, cellulose nanowhiskers exhibit superior mechanical, optical, and biological properties. These characteristics make them suitable as renewable reinforcing agents in various applications, including paper, plastics, composites, pharmaceuticals, automotive components, and electronic materials (Pasha et al., 2026). When incorporated into biopolymer matrices, cellulose nanowhiskers can improve the mechanical properties of composites while maintaining their environmentally friendly characteristics (Soykeabkaew et al., 2017).

Several studies have investigated the production of nanocellulose from OPEFB using different methods. Julianto et al. (2017) reported that acid hydrolysis using H_2SO_4 produced nanocellulose with an average size of approximately 290.4 nm and favorable physical properties, demonstrating the effectiveness of this method in breaking down lignocellulosic structures. Ningtyas et al. (2020) obtained nanocellulose with diameters of 1–100 nm and lengths of 500–2000 nm, indicating that processing conditions strongly influence particle size and morphology. Hendrawati et al. (2023) further emphasized that acid hydrolysis is one of the most widely used methods because it can remove amorphous regions and increase the crystalline fraction of cellulose. However, this method is often combined with mechanical treatments, such as ultrasonication or hydrothermal processing, to further reduce particle size and improve nanocellulose characteristics.

Despite the growing interest in OPEFB-derived nanocellulose, further development is still needed to optimize the utilization of this abundant agricultural residue as a reinforcing material for environmentally friendly biopolymer composites. The high cellulose content of OPEFB provides a strong basis for converting this waste into cellulose nanowhiskers with potential value-added applications. Therefore, this study aims to develop cellulose nanowhiskers from oil palm empty fruit bunches (*Elaeis guineensis* Jacq.) as an environmentally friendly reinforcing material for biopolymer composites.

METHOD

This study was conducted from February to March 2025 following a structured sequence of experimental stages. Raw material preparation, including washing, drying, and grinding of oil palm empty fruit bunches (OPEFB), was completed within 3–5 days. The chemical treatment stage, which comprised alkalization using NaOH and bleaching, required 5–7 days, including repeated washing until a neutral pH was achieved. Subsequently, acid hydrolysis using H_2SO_4 and purification through centrifugation and washing were carried out over 2–3 days. Mechanical disintegration using a ball mill and final drying were completed within 2 days. Overall, the effective synthesis time for cellulose nanowhiskers was approximately 2–3 weeks.

The synthesis of cellulose nanowhiskers from oil palm empty fruit bunches (*Elaeis guineensis* Jacq.) was performed at the Chemistry Laboratory, Universitas Islam Negeri Sumatera Utara (UINSU). The laboratory was equipped with standard chemical synthesis instruments, including a hot plate, magnetic stirrer, oven, and mechanical processing equipment, specifically a ball mill. These facilities supported the optimal implementation of both chemical and physical treatment processes.

Tools and Materials

The tools used in this study included scissors, knives, a blender, beakers, Petri dishes, measuring cylinders, glass stirring rods, an oven, hot plate, magnetic stirrer, analytical balance, pH meter, tissue paper, plastic wrap, aluminium foil, glass funnels, centrifuge, sample containers, and a ball mill. The characterization instruments used to evaluate the properties of the synthesized cellulose nanowhiskers included Fourier-transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), X-ray diffraction (XRD), and differential scanning calorimetry (DSC). The materials used in this study consisted of oil palm empty fruit bunches (*Elaeis guineensis* Jacq.), sodium hypochlorite (NaOCl), distilled water, sodium hydroxide (NaOH), sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), glacial acetic acid, and filter paper.

Research Procedure

- 1. Raw Material Preparation.** The OPEFB samples were cleaned to remove impurities, washed under running water, and then dried at approximately 60°C for 24 h. The dried samples were cut into small pieces and ground using a blender to obtain a more homogeneous particle size.
- 2. Alkali Treatment: Initial Delignification.** The OPEFB powder was immersed in 2–5% (w/v) NaOH solution at 80–90°C for 2–4 h under continuous stirring using a magnetic stirrer. This step was performed to remove lignin and hemicellulose from the biomass matrix. After the reaction was completed, the samples were washed with distilled water until a neutral pH was reached and then filtered.
- 3. Bleaching Process.** The alkali-treated samples were subsequently bleached using NaOCl or H_2O_2 solution at 60–80°C for 1–2 h. This process was repeated 2–3 times, if necessary, until the sample became visibly lighter in color. The bleached samples were then washed until neutral pH was achieved and dried.
- 4. Acid Hydrolysis: Formation of Cellulose Nanowhiskers.** The bleached cellulose was hydrolyzed using 45–65% (v/v) H_2SO_4 solution at 40–50°C for 30–60 min under constant stirring. This stage aimed to remove the amorphous regions of cellulose and produce crystalline nanowhisker structures.
- 5. Neutralization and Purification.** The hydrolysis reaction was terminated by adding cold distilled water. The resulting suspension was then centrifuged at 8,000–10,000 rpm for 10–15 min. The washing process was repeated until the pH approached

neutrality. The suspension could subsequently be dialyzed, when applicable, to remove residual acid.

6. Mechanical Disintegration. The cellulose suspension was processed using ultrasonication or a ball mill for 30–60 min to obtain a more homogeneous cellulose nanowhisiker dispersion.

7. Drying. The final product was dried in an oven at a low temperature of approximately 50°C or by freeze-drying to preserve the nanoscale structure.

RESULTS AND DISCUSSION

This study successfully synthesized cellulose nanowhiskers from oil palm empty fruit bunches (OPEFB) through sequential alkaline pretreatment using NaOH, bleaching using NaOCl, cellulose isolation, acid hydrolysis using sulfuric acid (H_2SO_4), and mechanical refinement using ball milling to obtain cellulose nanowhisiker powder. During the synthesis process, the material underwent several physical and chemical changes, which were evaluated through color observation, functional group analysis using FTIR, crystallinity analysis using XRD, thermal stability analysis using DSC, and particle morphology observation using TEM.

Color Changes

The synthesis of cellulose nanowhiskers from oil palm empty fruit bunches (OPEFB) resulted in a marked color change, from dark brown to light brown and finally to grayish white. This change was directly associated with the chemical treatment stages applied during the process. In the initial stage, alkaline treatment using NaOH removed part of the lignin and hemicellulose through saponification reactions and the cleavage of ester bonds, resulting in a brighter material color. Higher NaOH concentrations and increased reaction temperatures may accelerate delignification; however, these conditions must be carefully controlled to prevent cellulose degradation.

The bleaching process further removed residual lignin and chromophoric compounds responsible for the dark color of the raw material. The subsequent hydrolysis step using sulfuric acid (H_2SO_4) contributed to the removal of amorphous cellulose regions and residual organic impurities, producing a more crystalline structure with a whiter appearance. The concentration of H_2SO_4 and reaction temperature strongly influence hydrolysis efficiency. Under optimal conditions, this process can produce cellulose nanowhiskers with high purity while preserving their crystalline structure.

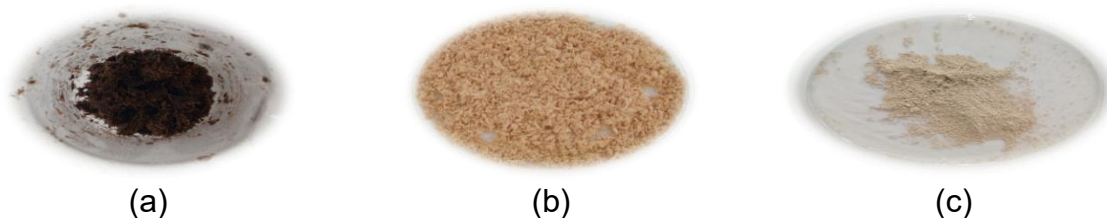


Figure 1. (a) OPEFB powder, (b) bleached cellulose, and (c) ball-milled cellulose nanowhiskers

Figure 1(a) shows the dark brown OPEFB fibers with a coarse texture, indicating the presence of high lignin and hemicellulose contents as well as natural pigments. Figure 1(b) shows a color change to light brown after alkalization and bleaching, indicating the partial removal of non-cellulosic components. Figure 1(c) shows grayish-

white and more homogeneous cellulose nanowhiskers, indicating successful purification and the formation of nanoscale particles. The fine and homogeneous powder texture indicates a uniform particle distribution with minimal agglomeration, suggesting the successful formation of cellulose nanowhiskers. This characteristic contributes to improved mechanical properties and thermal stability of the material (Rashid et al., 2022).

Characterization of Cellulose Nanowhiskers from Oil Palm Empty Fruit Bunches (*Elaeis guineensis* Jacq.)

After synthesis, characterization tests were conducted to determine the properties of the cellulose nanowhiskers and to confirm the successful formation of nanoscale structures. The analyses included yield determination, FTIR for functional group identification, XRD for crystallinity evaluation, TEM for morphological observation, and DSC for thermal property analysis.

1. Yield Analysis Based on SNI 14-0444-1989 and 0444-2009

The yield of cellulose nanowhiskers was calculated based on the ratio of product weight to the initial cellulose isolate weight:

$$\text{Yield} = \frac{3.94}{5} \times 100 = 78.8\%$$

The calculation showed a yield of 3.33% from 150 g of dried OPEFB, which produced 5 g of cellulose nanowhiskers. This value is commonly observed in acid hydrolysis methods because most non-cellulosic components are eliminated during processing. A relatively low overall yield indicates successful purification and the formation of crystalline cellulose. Factors affecting yield include raw material condition, chemical concentration, temperature, reaction time, filtration, and washing processes (Nafisah et al., 2022).

2. FTIR Analysis

FTIR analysis was conducted to identify the chemical functional groups present in OPEFB powder, isolated cellulose, and cellulose nanowhiskers. The spectra showed characteristic functional groups of cellulose, confirming the successful isolation process. The functional group assignments are presented in Table 1.

Table 1. FTIR functional group interpretation of OPEFB cellulose nanowhiskers

Functional Group	Absorption Wavenumber (cm ⁻¹)	OPEFB Powder	Cellulose	Cellulose Nanowhiskers
O–H stretching	3334	3334	3334	3353
C–H aliphatic	2927	2927	2887	2919
O–H bending	1638	1638	1638	1645
C–O	1017	1017	1023	1030

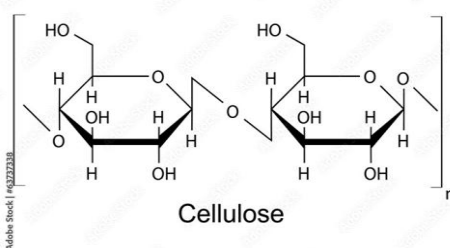


Figure 2. Cellulose structure

Cellulose consists of linear chains of glucose units linked by β -1,4-glycosidic bonds, forming a rigid and ordered structure. Hydrogen bonding between chains provides high strength and stability, which serves as the structural basis for cellulose nanowhisker formation.

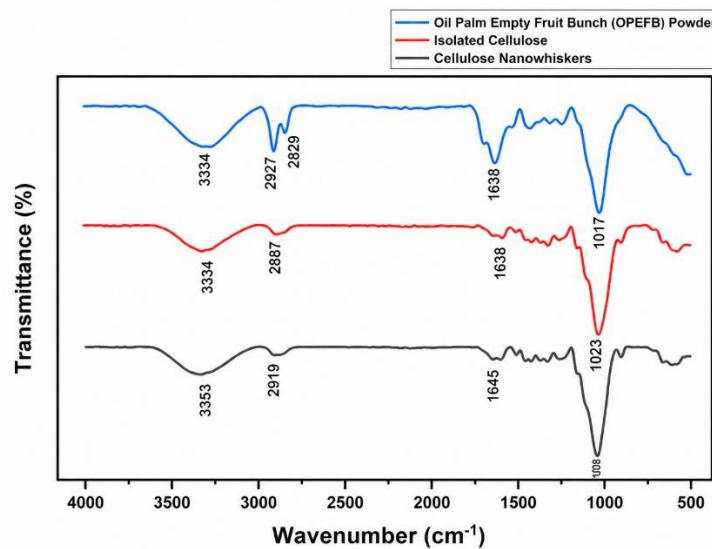


Figure 3. FTIR spectrum

The FTIR spectra showed that OPEFB powder, isolated cellulose, and cellulose nanowhiskers contained the same major functional groups, namely O–H, C–H, O–H bending, and C–O groups. However, the key observation was not only the presence of these groups but also the shifts in peak position and changes in absorption intensity, which reflect chemical transformations during the synthesis process (Du et al., 2017). The absorption band at 3334–3353 cm^{-1} , corresponding to O–H stretching, appeared in all samples. This indicates that the fundamental cellulose structure was not degraded during processing. However, the shift of this band to a higher wavenumber in the cellulose nanowhisker sample indicates changes in hydrogen-bonding interactions among cellulose chains. This shift suggests that after lignin and hemicellulose removal, the cellulose structure became more ordered and intermolecular interactions became stronger, indicating increased crystallinity (Rahmawati et al., 2025).

The absorption band at 2927–2919 cm^{-1} , associated with aliphatic C–H groups, showed a slight shift and decrease in intensity. This change indicates a reduction in lignin and hemicellulose components that previously formed the complex lignocellulosic matrix. Therefore, the observed spectral changes confirm that alkalization and bleaching were effective in removing non-cellulosic components. The band at 1638–1645 cm^{-1} , related to O–H bending, indicates the presence of bound water within the cellulose structure. The slight shift in this band suggests changes in the molecular environment caused by the removal of amorphous regions, allowing cellulose hydroxyl groups to become more exposed. This feature is important because it enhances the surface reactivity of cellulose nanowhiskers, particularly for their application as reinforcing agents in composite materials.

3. TEM Analysis

TEM analysis was performed to observe the morphology and particle size of OPEFB-derived cellulose nanowhiskers. The analysis was conducted on four samples with different size ranges, as shown in Figure 4.

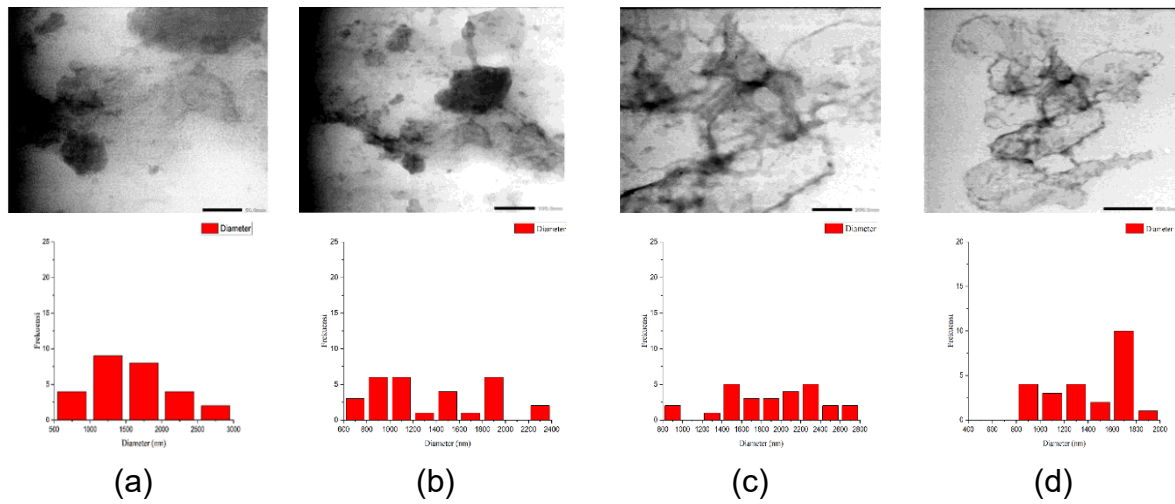


Figure 4. TEM analysis results

Based on the TEM results shown in Figure 4, the cellulose nanowhiskers were successfully characterized by determining the average particle diameter, as presented in Table 2.

Table 2. Average diameter of OPEFB cellulose nanowhiskers based on TEM analysis

Sample name	Diameter range (nm)	Frequency	Total diameter	Average diameter (nm)
50 nm	500–3000	27	42,750	1583.33
100 nm	600–2400	29	39,100	1348.28
200 nm	800–2800	27	51,700	1914.81
500 nm	800–2000	24	34,000	1416.67

The TEM analysis showed that the particle size of cellulose nanowhiskers influenced their distribution. At the 50 nm scale, the particles tended to be relatively uniform and monodisperse, with a narrow distribution, indicating good synthesis quality. At the 100 nm scale, the distribution became broader, suggesting increased size variation. In contrast, the 200 nm and 500 nm samples showed wider particle distributions and visible aggregation, which may be attributed to stronger interparticle interactions (Qureshi et al., 2024).

This phenomenon is consistent with previous studies reporting that smaller particles, particularly those in the range of 50–100 nm, exhibit better stability and homogeneity than larger particles, which are more prone to aggregation (Sun et al., 2021). Therefore, smaller particle sizes are considered more advantageous because they provide a more uniform distribution and enhance application potential, especially in fields requiring optimal interfacial interactions, such as functional materials and biomedical applications (Aprilia et al., 2020).

4. XRD Analysis

XRD analysis was conducted to determine the crystallinity of cellulose nanowhiskers derived from OPEFB. The results shown in Figure 5 indicate that the sample was successfully characterized by determining the crystallinity index, as presented in Table 3.

Table 3. Crystallinity index of OPEFB cellulose nanowhiskers based on XRD analysis

Sample name	Crystallinity index (%)
Cellulose nanowhiskers from oil palm empty fruit bunches	54.50

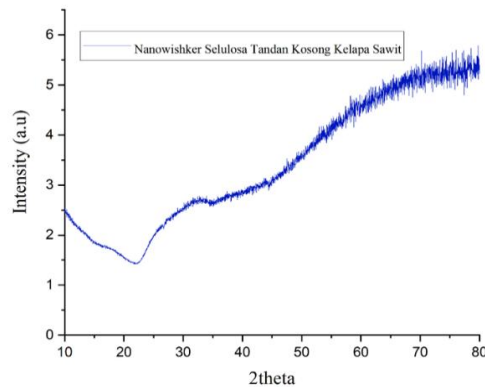


Figure 5. XRD analysis results

The XRD results showed that the cellulose nanowhiskers exhibited a typical cellulose I diffraction pattern, with a main peak at approximately $2\theta = 22^\circ$, indicating an ordered crystalline structure. In addition, a broad region observed at around $2\theta = 15^\circ\text{--}18^\circ$ indicates the presence of amorphous phases in the sample.

The crystallinity index obtained was 54.50%, indicating that the cellulose structure became more ordered after chemical treatment. Compared with previous studies, this value is within the typical crystallinity range of cellulose nanowhiskers derived from lignocellulosic biomass, which generally falls between 50% and 70%, depending on the hydrolysis method and raw material source. This result suggests that alkalization, bleaching, and acid hydrolysis were sufficiently effective in increasing the crystalline fraction by removing amorphous components such as lignin and hemicellulose (Nugraha et al., 2021).

The formation of a crystalline structure confirms that delignification, bleaching, and acid hydrolysis successfully removed amorphous non-cellulosic components, including lignin and hemicellulose. This differs from untreated OPEFB, which generally exhibits less distinct diffraction patterns with broadened peaks, indicating a predominantly amorphous structure (Tarigan et al., 2021).

The crystallinity index of 54.50% is considered acceptable for cellulose-based materials. This value indicates the dominance of crystalline regions, which contribute to improved mechanical properties and thermal stability. The increase in crystallinity also confirms the effectiveness of acid hydrolysis in removing amorphous regions and enriching the crystalline structure of cellulose (Gan et al., 2020).

Furthermore, no structural transformation from cellulose I to cellulose II was observed, indicating that the native cellulose structure was preserved. Overall, these results demonstrate that the synthesized cellulose nanowhiskers possess good crystallinity and have potential as reinforcing agents in environmentally friendly biopolymer composites.

To clarify the differences between the amorphous and crystalline structures in the samples, a comparison is presented in Table 4.

Table 4. Comparison between amorphous and crystalline structures

Aspect	OPEFB (amorphous)	Cellulose nanowhiskers (crystalline)
XRD pattern	Broad peaks with low sharpness	Sharp and ordered peaks
Crystallinity	Low (<40%)	Moderately high (50–70%)
Structure	Irregular structure with high lignin content	Ordered structure composed of cellulose chains
2θ peak	Approximately $18^\circ\text{--}22^\circ$, but broad	Approximately $15^\circ\text{--}16^\circ$ and $22^\circ\text{--}23^\circ$
Material properties	Weak and less stable	Strong and stable

5. DSC Analysis

DSC analysis was conducted to evaluate the thermal stability and phase transitions of OPEFB-derived cellulose nanowhiskers. This analysis produced a thermogram showing changes in energy as a function of temperature. The test was conducted on one sample, and the results are presented in Table 5.

Table 5. DSC data of OPEFB nanocellulose

Sample name	Enthalpy (J/g)	Tg (°C)	Td (°C)	Tm (°C)
Nanocellulose from oil palm empty fruit bunches	-114.17	154.99	158.28	155.83

The DSC results showed that the cellulose nanowhiskers had relatively good thermal stability. The sample underwent a thermal transition at $T_g = 154.99^\circ\text{C}$, reached a peak at $T_m = 155.83^\circ\text{C}$, and ended at $T_d = 158.28^\circ\text{C}$, indicating melting or thermal transition within the crystalline region. The enthalpy value of -114.17 J/g indicates an endothermic process, in which the sample absorbed heat energy during the phase transition. Overall, these results suggest that the nanocellulose exhibited good thermal stability at temperatures above 150°C .

The endothermic peak at 155.83°C indicates that the sample absorbed heat during the heating process. In cellulose-based materials, an endothermic event in this temperature region is generally associated with the evaporation or desorption of bound water and the disruption of hydrogen-bonding interactions within the cellulose structure. Cellulose contains abundant hydroxyl groups that promote intra- and intermolecular hydrogen bonding, as well as interactions with water molecules. Therefore, the observed endothermic transition may be attributed to the release of bound moisture and rearrangement of hydrogen bonds within the cellulose nanowhiskers (Paajanen et al., 2017; Adel et al., 2023).

The enthalpy value of -114.17 J/g further confirms that the thermal event was endothermic. This value indicates that the material required heat energy before undergoing structural changes. The ability to absorb heat is related to the ordered arrangement of cellulose chains and the presence of crystalline regions. This interpretation is consistent with the XRD results, which showed a crystallinity index of 54.50%. Crystalline cellulose domains generally require more energy to disrupt than amorphous regions; therefore, the semi-crystalline structure of the synthesized cellulose nanowhiskers contributes to their thermal stability (Huq et al., 2025).

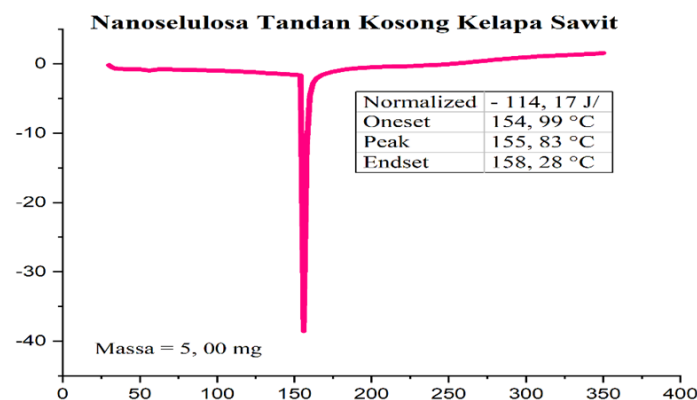


Figure 6. DSC thermogram

Based on Figure 6, the DSC thermogram showed a distinct endothermic peak at 155.83°C within a narrow temperature range of $154.99\text{--}158.28^\circ\text{C}$. This narrow peak

suggests that the sample had relatively homogeneous thermal properties. The absence of a pronounced exothermic peak indicates that no significant oxidative degradation, recrystallization, or secondary thermal reaction occurred within the tested temperature range. In addition, the absence of a clearly defined glass transition suggests that the thermal response was dominated by moisture release and hydrogen-bond rearrangement rather than extensive polymer chain mobility.

Overall, the DSC results indicate that cellulose nanowhiskers synthesized from OPEFB possess good thermal stability at temperatures above 150°C. This thermal behavior supports the FTIR results, which confirmed the presence of cellulose hydroxyl groups, and the XRD results, which demonstrated the formation of a semi-crystalline cellulose structure. Therefore, OPEFB-derived cellulose nanowhiskers have strong potential as sustainable reinforcing agents in biopolymer composite applications.

CONCLUSION

This study successfully synthesized cellulose nanowhiskers from oil palm empty fruit bunches through alkalization, bleaching, and acid hydrolysis, which effectively removed lignin and hemicellulose, although the process resulted in a relatively low yield. Characterization confirmed the formation of cellulose nanowhiskers with characteristic cellulose functional groups, as identified by FTIR; relatively uniform nanoscale particle dimensions, as observed by TEM; a crystallinity index of 54.50%, as determined by XRD; and good thermal stability, as indicated by DSC analysis. These findings demonstrate that the obtained cellulose nanowhiskers possess an adequate crystalline structure and thermal stability for potential use as reinforcing agents in biopolymer composites. Owing to these characteristics, this material has the potential to improve the mechanical properties and thermal resistance of composites, making it a promising environmentally friendly reinforcing material derived from biomass waste.

RECOMMENDATION

Further studies are recommended to evaluate the mechanical properties of biopolymer composites reinforced with cellulose nanowhiskers, including tensile strength and elasticity tests, to determine their practical material performance. In addition, direct application development should be conducted, particularly in the field of environmentally friendly packaging, such as biodegradable packaging, to assess the potential of cellulose nanowhiskers in enhancing the strength, durability, and stability of packaging materials.

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REFERENCES

Adel, A. M., El-Shafei, A. M., Ibrahim, A. A., & Al-Shemy, M. T. (2023). Morphological, spectroscopic and thermal analysis of cellulose-based materials. *Polymers*, 15(6), 1530.

- Aprilia, S., Koryanti, E., & Royani, I. (2020). Optimasi ukuran dan jumlah pori yang terbentuk pada molecularly imprinted polymer (MIP) nano karbaril (C₁₂H₁₁NO₂). *Positron*, 10(2), 93–98. <https://doi.org/10.26418/positron.v10i2.40104>
- Du, L., Wang, J., Zhang, Y., Qi, C., Wolcott, M. P., & Yu, Z. (2017). Preparation and characterization of cellulose nanocrystals from the bio-ethanol residuals. *Nanomaterials*, 7(51), 1–12. <https://doi.org/10.3390/nano7030051>
- Gaffar, U. H., Husen, O. O., Alam, R. A. C., Harwanto, F., Jayadisastira, Y., Pramulya, R., & Anam, K. (2024). *Minyak kelapa dan minyak sawit: Dampak kesehatan, lingkungan, ekonomi dan sosial di balik produksi*. Tohar Media.
- Gan, P. G., Sam, S. T., Abdullah, M. F. bin, & Omar, M. F. (2020). Thermal properties of nanocellulose-reinforced composites: A review. *Journal of Applied Polymer Science*, 137, Article 48544. <https://doi.org/10.1002/app.48544>
- Hendrawati, T. Y., Umar, E., Ramadhan, A. I., Sari, A. M., Salsabila, M., Suryani, R., & Rahardja, I. B. (2023). Sintesis dan karakterisasi nanoselulosa serbuk dari tandan kosong kelapa sawit menggunakan ultrasonifikasi. *Jurnal Teknologi*, 15(1), 160–166. <https://doi.org/10.24853/jurtek.15.1.159-166>
- Huq, T., Salmieri, S., Khan, A., Khan, R. A., & Lacroix, M. (2025). Effect of acid hydrolysis conditions on the extraction of cellulose nanofibers: Crystallinity, morphology, and thermal stability. *Polymers*, 17(10), 1313.
- Idris, N. A., Loh, S. K., Lau, H. L. N., Yau, T. C., Mustafa, E. M., Vello, V., & Moi, P. S. (2018). Palm oil mill effluent as algae cultivation medium for biodiesel production. *Journal of Oil Palm Research*, 30(1), 141–149. <https://doi.org/10.21894/jopr.2018.0011>
- Julianto, H., Farid, M., & Rasyida, A. (2017). Ekstraksi nanoselulosa dengan metode hidrolisis asam sebagai penguat komposit absorpsi suara. *Jurnal Teknik ITS*, 6(2), 242–245. <https://doi.org/10.12962/j23373539.v6i2.24259>
- Mishra, R. K., Sabu, A., & Tiwari, S. K. (2025). Comprehensive review of cellulose nanocrystals: Preparation, properties, and applications. *Bulletin of the National Research Centre*, 49, Article 13.
- Nafisah, A. R., Rahmawati, D., & Tarmidzi, F. M. (2022). Synthesis of cellulose nanofiber from palm oil empty fruit bunches using acid hydrolysis method. *Indonesian Journal of Chemical Science*, 11(3), 233–240.
- Ningtyas, K. R., Muslihudin, M., & Sari, I. N. (2020). Sintesis nanoselulosa dari limbah hasil pertanian dengan menggunakan variasi konsentrasi asam. *Jurnal Penelitian Pertanian Terapan*, 20(2), 142–147.
- Nugraha, A. B., Nuruddin, A., & Sunendar, B. (2021). Isolasi nanoselulosa terkarboksilasi dari limbah kulit pisang ambon lumut dengan metode oksidasi. *Journal of Science and Applicative Technology*, 5(1), 236–244. <https://doi.org/10.35472/jsat.v5i1.413>
- Paajanen, A., Ceccherini, S., Maloney, T., & Ketoja, J. A. (2017). Dynamics of water bound to crystalline cellulose. *Scientific Reports*, 7, Article 12131.
- Pasha, M. F., Ramadhan, A., & Prasetya, S. T. R. (2026). *Cellulose nanocrystal dalam rekayasa material: Potensi, aplikasi, dan tantangan masa depan*. Media Nusa Creative.
- Qureshi, S. S., Nizamuddin, S., Xu, J., Vancov, T., & Chen, C. (2024). Cellulose nanocrystals from agriculture and forestry biomass: Synthesis methods, characterization and industrial applications. *Environmental Science and Pollution Research*, 31. <https://doi.org/10.1007/s11356-024-35127-3>

- Rahmawati, A., Faidah, L., & Yogaswara, R. R. (2025). Sintesis dan karakterisasi nanokristalin selulosa dari limbah pelepah pisang dengan variasi suhu bleaching dan konsentrasi asam sulfat. *Jurnal Fisika Unand*, 14(4), 332–338.
- Ramadhan, M. M., Hidayat, R., Utomo, T. Y. R., & Silalahi, N. H. M. (2025). Pemanfaatan kitin dan kitosan untuk pembuatan polimer yang lebih ramah lingkungan dengan mempertimbangkan potensi dan aplikasi material. *Jurnal Teknik Silitek*, 5(03), 1617–1627.
- Rashid, S., Shahi, A. K., Dutta, H., & Sahu, J. K. (2022). Extraction and characterization of cellulose and cellulose nanowhiskers from almond shell biomass, metal removal and toxicity analysis. *Biointerface Research in Applied Chemistry*, 12(2), 1705–1720. <https://doi.org/10.33263/BRIAC122.17051720>
- Ritonga, P. C., Putri, S. A. E., Setiawan, E., Pramaysella, A. D., & Puyanggana, C. K. B. (2023). Efektivitas ekstraksi selulosa tandan kosong kelapa sawit sebagai absorben menggunakan metode delignifikasi dan bleaching. *Jurnal Teknologi Pertanian*, 24(3), 149–156.
- Simatupang, T. H. (2020). *Aplikasi limbah cair kelapa sawit dan pupuk urea pada pertumbuhan bibit kelapa sawit (Elaeis guineensis Jacq) di main nursery* [Undergraduate thesis, Universitas Islam Riau].
- Soykeabkaew, N., Tawichai, N., Thanomsilp, C., & Suwanton, O. (2017). Nanocellulose-reinforced “green” composite materials. *Walailak Journal*, 14(5), 353–368.
- Sun, H., Jiao, R., An, G., Xu, H., & Wang, D. (2021). Influence of particle size on the aggregation behavior of nanoparticles: Role of structural hydration layer. *Journal of Environmental Sciences*, 103, 33–42.
- Tarigan, A. S., & Hasibuan, A. Y. P. (2025). Eksplorasi nanokristal selulosa dari sumber ramah lingkungan untuk inovasi berkelanjutan. *Nexus: Jurnal Sains dan Teknologi*, 1(1), 23–42. <https://doi.org/10.51510/nst.v1i1.2358>
- Tarigan, A. S., Wirjosentono, B., Zuhra, C. F., & Zulfazri. (2021). Isolasi nanoselulosa dari tandan kosong sawit menggunakan hidrolisis asam sebagai material biomedis. *KLOROFIL: Jurnal Ilmu Biologi dan Terapan*, 5(1), 1–3. <https://doi.org/10.30821/kfl:jibt.v5i1.9273>
- Vikman, M., Vuorinen, T., & Koivula, H. (2007). Glass transition temperature and thermal decomposition of cellulose. *Cellulose*, 14, 417–424.