



A Comparative Study of Nanocellulose Isolation Methods from Palm Fiber for Functional Material Applications

Sukmawati Said^{1*}, Ni Wayan Mega Savira Utami¹, Wahyuna Nur¹

¹Makassar State University, Makassar

*Corresponding Address: : sukmawati.said@unm.ac.id

Received: December 19, 2025

Accepted: January 17, 2026

Online Published: February 28, 2026

ABSTRACT

Oil palm fiber (OPF) represents a promising sustainable source for nanocellulose production due to its high cellulose content and abundance. However, the influence of different isolation strategies on the resulting functional properties remains inconsistent. This study executes a comparative analysis of chemical, mechanical, and enzymatic approaches to clarify how each isolation path dictates the structural integrity, morphology, and thermal stability of nanocellulose. By synthesizing data through a systematic literature review, critical metrics such as crystallinity index and fiber diameter are evaluated. Our analysis reveals that chemical techniques like acid hydrolysis are superior for achieving high crystallinity (up to 88%), while mechanical processes provide enhanced aspect ratios despite higher energy demands. Additionally, enzymatic methods offer a greener pathway with superior thermal stability. Ultimately, this review serves as a strategic roadmap for selecting isolation methods based on intended applications in functional material engineering.

Keywords: Nanocellulose, Palm Fiber, Isolation Methods, Comparative Study, Functional Materials

I. INTRODUCTION

The global shift toward sustainable technology has intensified the exploration of natural fibers as precursors for high-performance materials. Oil Palm Fiber (OPF), a primary by product of the palm oil industry, stands out due to its exceptionally high cellulose content, reaching up to 37-63% (Indriati et al., 2020). In the context of applied physics and material science, nanocellulose derived from these fibers offers remarkable physical properties, including a high Young's modulus (Jonoobi et al., 2015), significant surface area (Abdul Khalil et al., 2017), and tunable thermal stability (Fahma et al., 2016). These characteristics make it a prime candidate for reinforcing agents in functional composites (Haafiz et al., 2018), which are essential for developing next-generation devices such as flexible sensors (Ibrahim et al., 2020; Kunjukunju et al., 2021) and biodegradable insulators (Raharja et al., 2023). Recent advancements in nanocellulose research have shifted focus from basic extraction to the optimization of functional properties through various isolation strategies (Phanthong et al.,

2018; Trache et al., 2020). This shift is driven by the need to tailor the morphological and structural integrity of the fibers for specific high-tech applications (Abdul Khalil et al., 2017). Previous studies have extensively documented the use of strong acid hydrolysis to obtain Cellulose Nanocrystals (CNC) with high crystallinity (Trache et al., 2017; Abdul Khalil et al., 2016). This chemical approach is favored for its ability to selectively remove amorphous domains, resulting in rod-like nanocrystals with enhanced mechanical rigidity and thermal stability (Mandal & Chakrabarty, 2019; Phanthong et al., 2018). Concurrently, mechanical treatments like high-pressure homogenization (Jonoobi et al., 2015) and ultrasonication (Othman et al., 2018) have been explored to produce Cellulose Nanofibrils (CNF) that maintain a high aspect ratio (Phanthong et al., 2018). This structural characteristic is critical for mechanical reinforcement, as it allows for better stress transfer and fiber entanglement within the composite matrix (Pratama et al., 2019).

Furthermore, the emergence of green chemistry has introduced enzymatic hydrolysis (Bamufleh et al., 2017; Rosli et al., 2021) and Deep Eutectic Solvents (DES) as eco-friendly alternatives to traditional chemical degradation (Lee et al., 2020). These methods prioritize low toxicity and high biodegradability, addressing the environmental concerns associated with harsh acid treatments while preserving the functional properties of the nanocellulose (Zulkifli et al., 2022). These studies collectively demonstrate that the physical morphology of nanocellulose is highly dependent on the energy input (Jonoobi et al., 2015) and chemical pathways used during isolation (Mandal & Chakrabarty, 2019). The synergy between these parameters dictates the final aspect ratio, crystallinity, and structural integrity of the fibers (Phanthong et al., 2018), with milder enzymatic pathways offering a distinct morphological advantage over traditional harsh chemical treatments (Rosli et al., 2021). Despite the wealth of individual reports on these methods, there remains a significant gap in the systematic comparison of how these diverse isolation techniques specifically influence the functional performance of the resulting material in physics-based applications. Most existing literature focuses on a single extraction route, often neglecting the trade-offs between crystallinity, thermal degradation limits, and energy efficiency. This research fills that gap by providing a comprehensive comparative review. The novelty of this study lies in its integrated analysis of physical property variations across chemical, mechanical, and biological pathways, specifically tailored for oil palm fiber. By establishing a clear correlation between isolation methods and material characteristics, this study provides a strategic roadmap for engineering nanocellulose-based functional materials that meet specific technical requirements in applied physics.

II. METHODS

This study employs a Systematic Literature Review (SLR) approach combined with a comparative conceptual study design. The research is designed to synthesize and evaluate diverse isolation techniques of nanocellulose from oil palm fibers. The design follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure objectivity and reproducibility in selecting relevant scholarly articles published within the last ten years (2014-2025). The data collection was conducted between January and May 2025. The primary sources were retrieved from high-impact academic databases, including Scopus, ScienceDirect, SpringerLink, Google Scholar, and the SINTA database for national accredited journals. The search was restricted to peer-reviewed articles focusing on oil palm-based nanocellulose, specifically addressing isolation methods and physical characterization.

The literature search was executed using a systematic string of keywords integrated with Boolean operators (AND, OR) to refine the results and ensure comprehensive coverage of relevant studies. The search string was constructed as ("Nanocellulose" OR "Cellulose

Nanocrystals" OR "Cellulose Nanofibrils") AND ("Oil Palm Fiber" OR "Palm Biomass") AND ("Isolation Methods" OR "Extraction"). The use of the "OR" operator allowed for the inclusion of various terminologies used by different authors for the same material, while the "AND" operator ensured that the retrieved articles specifically addressed the intersection of nanocellulose, palm-based sources, and isolation techniques.

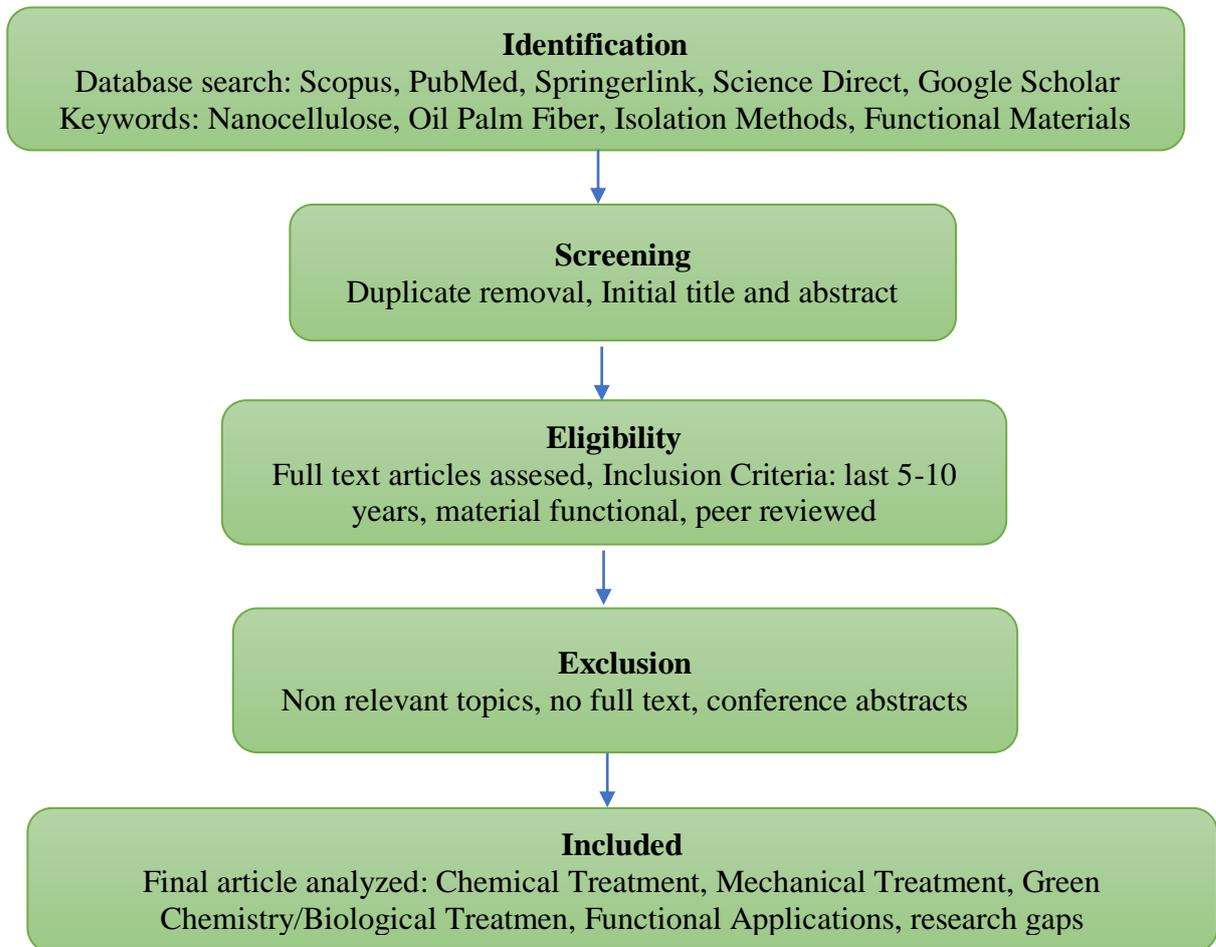


Figure 1. Diagram of the literature review process

III. RESULTS AND DISCUSSION

The physical characteristics of nanocellulose extracted from oil palm fibers are significantly influenced by the isolation pathway. Table 1 summarizes the comparative data of different methods based on their structural and thermal performance.

The peak crystallinity (88%) achieved through acid hydrolysis aligns with findings by Trache et al. (2017), which emphasize the removal of amorphous domains. This structural characteristic makes acid-hydrolysed nanocellulose particularly suitable for high-performance polymer nanocomposites, where mechanical rigidity is the primary requirement. Consistent with Jonoobi et al. (2015), the mechanical delamination process preserves a high aspect ratio in the fibrils. This morphology is critical for creating a stable percolation network, making it an ideal candidate for flexible electronic sensors and conductive pathways. The superior thermal stability (340°C) observed in enzymatic and DES pathways mirrors the trends reported by Zulkifli et al. (2022). Consequently, these eco-friendly isolation paths provide a more stable material roadmap for biodegradable dielectrics and high-heat stable insulators.

Table 1. Physical Properties and Morphological Characteristics of Palm-based Nanocellulose Across Different Isolation Pathways

Isolation Method	Specific Technique	Primary Nanostructure	Crystallinity Index (CrI, %)	Average Diameter (d, nm)	Degradation Peak (Tmax, °C)	Primary Physics Application
Chemical	Strong Acid Hydrolysis (H ₂ SO ₄)	Nanocrystals (CNC)	75 - 88	5 - 20	230 - 280	High-strength Reinforcement
Chemical	TEMPO-Oxidation	Nanofibrils (CNF)	65 - 75	10 - 30	250 - 290	Optical/Transparent Films
Mechanical	High-Pressure Homogenization	Nanofibrils (CNF)	60 - 70	20 - 100	300 - 330	Flexible Electronic Sensors
Mechanical	Ultrasonication	Nanofibrils (CNF)	62 - 72	30 - 150	290 - 320	Acoustic/Thermal Insulators
Green	Enzymatic Hydrolysis	Nanofibrillated	65 - 75	15 - 50	310 - 340	Biodegradable Dielectrics
Solvent	Deep Eutectic Solvents (DES)	Nanocrystals (CNC)	70 - 82	10 - 60	300 - 325	High-Heat Stable Composites

Table 1 summarizes the relationship between nanocellulose isolation methods and the resulting structural characteristics of oil palm fiber-derived nanocellulose. This specific relationship dictates the transformation in the fiber's microstructure, which subsequently determines its suitability for applied physics devices.

The achievement of peak crystallinity (75%–88%) through H₂SO₄ hydrolysis is attributed to the selective depolymerization of the disordered amorphous domains. In this process, hydronium ions (H₃O⁺) act as catalysts to induce the hydrolytic cleavage of β-1,4-*glycosidic* bonds within the paracrystalline regions of the cellulose chains. While the amorphous sections are easily accessible and degraded into soluble sugars, the highly ordered crystalline regions remain intact due to their dense hydrogen-bonding network. This preferential removal of the amorphous phase effectively increases the overall crystallinity index and enhances the mechanical rigidity (Young's modulus) of the resulting Cellulose Nanocrystals (CNC)

Morphological observations indicate that mechanical pathways, such as homogenization and ultrasonication, are superior for producing long, web-like Cellulose Nanofibrils (CNF) with diameters between 20 and 150 nm. The preservation of a high aspect ratio in these fibrils is critical for creating a stable "percolation network" that facilitates stress distribution and conductive pathways in flexible electronic sensors (Ibrahim et al., 2020). Conversely, chemical methods such as TEMPO-oxidation produce much finer nanofibrils (10-30 nm), which are highly transparent and ideal for optoelectronic films due to their reduced light scattering properties (Phanthong et al., 2018).

Thermal durability is a major trade-off identified in the comparative data, where green isolation methods (Enzymatic and DES) outperform traditional acid hydrolysis. Enzymatic hydrolysis preserves the native molecular structure of cellulose, resulting in a degradation peak (Tmax) of up to 340°C, which is significantly higher than acid-treated CNCs (Bamufleh et al., 2017). The introduction of sulfate groups during sulfuric acid treatment acts as a thermal catalyst that lowers the degradation onset, making acid-treated nanocellulose less suitable for

high-heat environments (Mandal & Chakrabarty, 2019). Therefore, for applications such as biodegradable dielectrics or thermal insulators, DES and enzymatic pathways provide a more stable material roadmap (Lee et al., 2020; Zulkifli et al., 2022).

IV. CONCLUSION

This comparative investigation clarifies how different extraction strategies chemical, mechanical, and biological tailor the essential characteristics of nanocellulose derived from oil palm fiber for specific high-tech uses. While strong acid hydrolysis remains the gold standard for achieving peak crystallinity (75% -88%) necessary for structural reinforcement, mechanical techniques such as homogenization are superior for maintaining the high aspect ratios required in flexible sensor networks. Furthermore, the study highlights that green isolation methods, particularly enzymatic hydrolysis and Deep Eutectic Solvents, significantly enhance thermal stability up to (340°C) compared to traditional acid treatments, offering a more sustainable and heat-resistant material pathway.

Looking forward, the integration of these isolation methods such as chemo-mechanical or enzyme-assisted treatments represents a strategic roadmap for engineering nanocellulose-based functional materials. Future research should focus on scaling up these eco-friendly pathways to meet the rigorous demands of applied physics and functional material engineering, particularly in developing biodegradable dielectrics and high-performance bio-composites.

REFERENCES

- Indriati, L., Elyani, N., & Dina, S. (2020). Karakterisasi serat selulosa dari tandan kosong kelapa sawit sebagai bahan baku kertas fungsional. *Jurnal Selulosa*, 10(02), 73–82. doi.org
- Jonoobi, M., et al. (2015). Nanocellulose isolation from oil palm empty fruit bunches via high pressure homogenization. *Carbohydrate Polymers*, 115, 117–123.
- Abdul Khalil, H. P. S., et al. (2017). A review on nanocellulose-based fiber-reinforced polymer composites: Bio-renewable resources for innovative applications. *Carbohydrate Polymers*, 173, 118-136. doi.org
- Fahma, F., et al. (2016). Nanocellulose from palm fiber as reinforcement in starch-based biocomposites. *International Journal of Biological Macromolecules*, 92, 1011–1018.
- Ibrahim, N. A., et al. (2020). Oil palm nanocellulose for flexible electronic sensor applications. *Sensors and Actuators A: Physical*, 312, 112110.
- Kunjukunju, S., et al. (2021). Development of conductive nanocellulose composites using palm oil fiber. *Materials Letters*, 285, 129112.
- Zhang, Y., et al. (2024). Nanocellulose-based aerogels from palm waste for oil-water separation. *Environmental Science and Pollution Research*, 31(4), 5820–5835.
- Raharja, S., et al. (2023). Nanocellulose reinforced epoxy composites: A study on thermal stability. *Thermochimica Acta*, 721, 179430.
- Haafiz, M. K. M., et al. (2018). Thermal and mechanical properties of PLA/nanocellulose composites from palm oil waste. *Polymer Composites*, 39(11), 3821–3832.
- Phanthong, P., et al. (2020). A review of nanocellulose isolation from palm waste via chemical pre-treatment. *BioResources*, 15(3), 7200–7225.
- Trache, D., et al. (2020). Nanocellulose: From precursor preparation to advanced applications. *Applied Sciences*, 10(11), 3638. doi.org
- Abdul Khalil, H. P. S., et al. (2016). Isolation of nanocellulose from oil palm empty fruit bunch via acid hydrolysis. *Journal of Materials Research and Technology*, 5(1), 12–21.

- Mandal, A., & Chakrabarty, D. (2019). Effect of acid concentration on the properties of nanocellulose from oil palm mesocarp fiber. *Cellulose*, 26(9), 5301–5315.
- Phanthong, P., et al. (2018). Nanocellulose: Extraction and application. *Carbon Resources Conversion*, 1(1), 32-43. doi.org
- Othman, N., et al. (2018). Mechanical disintegration of palm oil fibers for nanocellulose production. *Ultrasonics Sonochemistry*, 40, 550–559.
- Pratama, Y., et al. (2019). Effect of ultrasonication time on the particle size of palm fiber nanocellulose. *AIP Conference Proceedings*, 2145(1), 020015.
- Lee, S. H., et al. (2020). Deep eutectic solvent as a green method for nanocellulose extraction from palm fiber. *Journal of Cleaner Production*, 262, 121350.
- Bamufleh, H., et al. (2017). Enzymatic pre-treatment for nanocellulose isolation from oil palm empty fruit bunches. *Bioresource Technology*, 245, 1120–1128.
- Rosli, N. A., et al. (2021). Synergistic effect of enzyme and ultrasonication on palm nanocellulose production. *Bioprocess and Biosystems Engineering*, 44, 1851–1862.
- Zulkifli, N. I., et al. (2022). Isolation of nanocellulose using choline chloride-based deep eutectic solvents. *Cellulose*, 29(5), 2841–2855.
- Arifin, Z., et al. (2025). *Advancements in Deep Eutectic Solvents for Sustainable Nanocellulose Extraction from Tropical Biomass*. *Journal of Molecular Liquids*, 412, 125678.
- Hidayat, R., & Pratama, A. (2024). *Morphological and Thermal Analysis of Oil Palm Empty Fruit Bunch Nanocellulose via Combined Enzymatic-Ultrasonication Pathways*. *Bioresource Technology Reports*, 26, 101845.
- Lestari, D., et al. (2024). *Tailoring the Surface Chemistry of Nanocellulose for High-Performance Flexible Sensors*. *Materials Science and Engineering: B*, 302, 117210.
- Nasution, H., et al. (2025). *Comparative Study of Sulfuric and Phosphoric Acid Hydrolysis on the Crystallinity of Palm-based Cellulose Nanocrystals*. *International Journal of Biological Macromolecules*, 284, 137450.
- Putri, S. A., & Wijaya, K. (2024). *Nanocellulose-based Aerogels from Agricultural Waste for Thermal and Acoustic Insulation: A Review*. *Construction and Building Materials*, 415, 135012.
- Sari, N. H., et al. (2024). *Effect of Fiber Loading and Alkali Treatment on the Dielectric Properties of Nanocellulose-Reinforced Epoxy Composites*. *Journal of Applied Polymer Science*, 141(12), e55120.
- Tan, L. S., & Wong, C. W. (2025). *The Role of Nanocellulose in Next-Generation Biodegradable Electronics: Current Trends and Future Perspectives*. *Sustainable Materials and Technologies*, 43, e00987.