

ORIGINAL ARTICLE

Biodegradable Pickering Emulsions Stabilized by Cellulose Nanocrystals Derived from *Pongamia pinnata* Fruit Peel Waste

I. P. Siahloho¹, V. Purwandari^{2*}, N. Masruchin³, C. Masyitah¹ and L. Zai²¹Faculty of Pharmacy and Health Sciences, University of Sari Mutiara Indonesia, Jalan Kapten Muslim no. 79 Medan, Indonesia²Faculty of Science, Technology, and Information, University of Sari Mutiara Indonesia, Jalan Kapten Muslim no. 79 Medan, Indonesia³The Center for Research on Biomass and Bioproducts, National Research and Innovation Agency of Republic Indonesia, Indonesia

ABSTRACT – Agricultural residues can be used as alternative sources of cellulose for the preparation of functional nanomaterials. In this study, *Pongamia pinnata* fruit peel was investigated as a cellulose source for the production of cellulose nanocrystals (CNCs) and their application in oil-in-water (O/W) Pickering emulsions. The fruit peel was subjected to alkaline treatment, two-step bleaching, and sulfuric acid hydrolysis. The sequential treatment yielded 63% purified cellulose. Fourier transform infra-red (FTIR) analysis showed the removal of bands associated with non-cellulosic components, while X-ray diffraction (XRD) analysis indicated a cellulose I structure and an increase in crystallinity index from approximately 63% for purified cellulose to 77% for the CNCs. Thermogravimetric analysis-derivative thermogravimetry (TGA/DTG) analysis showed changes in the thermal decomposition behavior after acid hydrolysis. Transmission electron microscopy (TEM) analysis revealed rod-like CNCs with lengths of approximately 200–400 nm, with mean diameters of 9.8 ± 7.6 nm for the hydrogen peroxide–citric acid (HPCA)-derived CNCs and 10.9 ± 6.7 nm for the alkaline hydrogen peroxide–peracetic (AHP–PAA)-derived CNCs. The CNCs were modified with cetyltrimethylammonium bromide (CTAB) and evaluated at concentrations of 0.4%, 0.5%, and 0.6% (w/v) in O/W Pickering emulsions. Among the tested formulations, the 0.6% CNC–CTAB emulsion showed the lowest visible phase separation during seven days of storage. These results indicate that *P. pinnata* fruit peel can be used as a cellulose feedstock for CNC production and that CTAB-modified CNCs can contribute to Pickering emulsion stabilization.

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INTRODUCTION

The use of renewable resources in materials research has increased interest in bio-based polymers and nanomaterials as alternatives to materials derived from non-renewable sources [1], [2]. Cellulose nanocrystals (CNCs) are one of the nanocellulose materials that have been studied for applications in biomedical systems, composites, and other functional materials because of their nanoscale dimensions, stiffness, and surface functionality [3]. CNCs are generally obtained by hydrolyzing the less ordered, amorphous regions of cellulose, leaving crystalline domains that form nanoscale particles with distinct mechanical and interfacial properties [4].

Pickering emulsions are stabilized by solid particles that adsorb at the oil–water interface, instead of relying on conventional molecular surfactants [5], [6]. Once adsorbed at the interface, these particles can form a barrier around the oil droplets and reduce droplet coalescence and aggregation, which contributes to emulsion stability [7], [8]. CNCs are of interest for this application because their nanoscale dimensions, surface characteristics, and relatively high aspect ratio can support their adsorption and arrangement at the oil–water interface [9]. Previous studies have therefore examined nanocellulose-based particles as stabilizers for Pickering emulsions in applications including food, pharmaceutical, and related formulation systems [10].

Many studies on CNCs have used relatively well-established cellulose sources, including wood pulp and cotton. The use of agricultural residues as alternative feedstocks can provide access to cellulose-rich biomass that is otherwise discarded after agricultural or food-processing activities. In this context, *Pongamia pinnata* is of interest because its fruit peels are generated as a by-product of fruit processing, while the seeds are primarily used for oil production. Previous studies on *P. pinnata* have mainly examined its seeds for biodiesel production and its biomass for other utilization routes [11]–[13].

However, the fruit peel has received much less attention as a source of cellulose for nanocellulose production. In particular, the use of *P. pinnata* fruit peel for CNC production and the characterization of the resulting CNCs for Pickering emulsion stabilization remain insufficiently investigated. This gap provides the basis for the present study, which uses *P. pinnata* fruit peel as a cellulose source and evaluates the resulting CNCs for Pickering emulsion stabilization.

This study investigates the isolation of CNCs from *P. pinnata* fruit peels and their use in oil-in-water (O/W) Pickering emulsions. The changes in the chemical structure, crystallinity, thermal properties, and morphology of the cellulose during CNC preparation were characterized using Fourier transform infra-red (FTIR), X-ray diffraction (XRD), thermogravimetric analysis (TGA), and transmission electron microscopy (TEM), respectively. The CNCs were then modified with cetyltrimethylammonium bromide (CTAB) and evaluated at different concentrations as stabilizing particles in Pickering emulsions. Emulsion stability was assessed during seven days of storage to compare the performance of the different CNC–CTAB formulations.

EXPERIMENTAL METHOD

Materials

Fruit peels of *Pongamia pinnata* were collected from Medan, Indonesia. Sodium hydroxide, hydrogen peroxide, citric acid, sulfuric acid (40%), cetyltrimethylammonium bromide (CTAB), and olive oil were purchased from Merck.

Method and Procedure

Extraction of Cellulose from *Pongamia pinnata* Fruit Peels

Two cellulose extraction routes were evaluated, namely the hydrogen peroxide–citric acid (HPCA) route and the alkaline hydrogen peroxide–peracetic acid (AHP–PAA) route, as illustrated in Figure 1 and Figure 2.

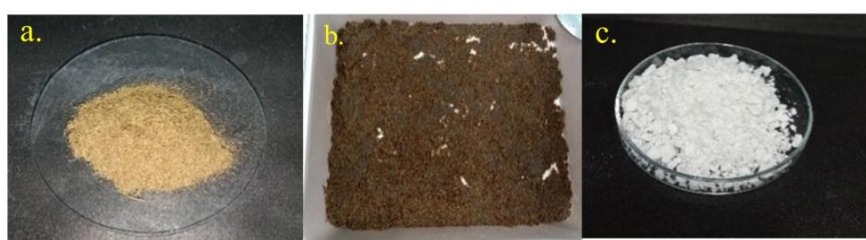


Figure 1. Stages of cellulose extraction from *Pongamia pinnata* fruit peels using the HPCA method: (a) raw peel powder, (b) delignified material after alkaline treatment, and (c) purified cellulose obtained after HPCA bleaching



Figure 2. Stages of cellulose purification using the AHP-PAA bleaching sequence: (a) raw peel material, (b) delignified fibers, (c) intermediate AHP-treated cellulose, and (d) final PAA-Bleached cellulose

HPCA Route

Dried *Pongamia pinnata* fruit peels (100 g) were mixed with 1000 mL of 5% (w/v) sodium hydroxide (NaOH) solution at a solid-to-liquid ratio of 1:10. The mixture was heated and stirred at 65 °C for 2 h for delignification. After treatment, the material was washed with running water until a neutral pH (approximately 7) was reached. The resulting delignified pulp was dried before the subsequent bleaching treatment.

A total of 610 mL of HPCA bleaching solution was prepared by mixing 305 mL of 30% hydrogen peroxide (H₂O₂) with 305 mL of citric acid at a 1:1 volume ratio. The bleaching solution was divided into two portions. The first portion (300 mL) was added to 61 g of delignified pulp, and the mixture was heated and stirred at 90 °C for 1 h. The remaining 310 mL of the bleaching solution was then added, and the mixture was heated and stirred at 90 °C for a further 2 h. After bleaching, the mixture was filtered, and the residue was washed with running water until a neutral pH (approximately 7) was reached. The resulting cellulose was dried at room temperature for 2 days.

AHP–PAA Route

Dried *P. pinnata* fruit peels (200 g) were mixed with 2000 mL of 5% (w/v) NaOH solution at a solid-to-liquid ratio of 1:10. The mixture was heated and stirred at 75 °C for 30 min for delignification. After treatment, the material was washed with water until a neutral pH (approximately 7) was reached and then dried at room temperature for 3 days.

The dried residue was subjected to alkaline hydrogen peroxide (AHP) treatment using 800 mL of 5% (w/v) NaOH solution and 800 mL of 10% H₂O₂ solution. The mixture was heated and stirred at 75 °C for 1 h. After treatment, the material was washed and filtered until a neutral pH was reached.

The resulting residue was subsequently subjected to peracetic acid (PAA) bleaching. The PAA solution was prepared by mixing 300 mL of glacial acetic acid, 300 mL of 30% H₂O₂, and 300 mL of distilled water. The mixture was heated and stirred at 90 °C for 1 h. After treatment, the material was washed and filtered until a neutral pH was reached to obtain purified cellulose.

Isolation of Cellulose Nanocrystals (CNC)

The dried purified cellulose was hydrolyzed using 40% sulfuric acid (H_2SO_4) at a cellulose-to-acid solution ratio of 1:20 (g/mL). The hydrolysis was conducted at 45–50 °C for 90 min. After hydrolysis, the resulting cellulose nanocrystal (CNC) suspension was centrifuged three times and neutralized with distilled water until a neutral pH was reached. The suspension was subsequently sonicated at 15% amplitude for 15 min. (Figure 3).

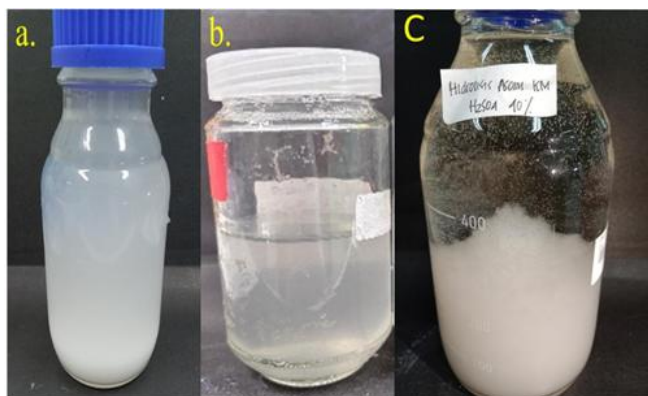


Figure 3. Acid hydrolysis and sonication stages during CNC production: (a) hydrolyzed sample derived from HPCA-based cellulose, (b) CNC suspension after sonication (HPCA), (c) hydrolyzed sample derived from AHP-PAA-based cellulose, and (d) CNC suspension after sonication (AHP-PAA).

CTAB Modification of CNCs

CNCs were modified with cetyltrimethylammonium bromide (CTAB) to alter their surface characteristics. An aqueous CNC suspension (0.5% w/v) was mixed with 0.05 M CTAB solution at a 1:1 mass ratio of CNC to CTAB. The mixture was stirred at 500 rpm and 60 °C for 2 h. After treatment, the CNC-CTAB complex was recovered by centrifugation at 10,000 rpm for 10 min. The collected material was washed three times by redispersion and centrifugation using a water/ethanol mixture (1:1, v/v) to remove unreacted CTAB. The washed CNC-CTAB complex was then freeze-dried before use in Pickering emulsion preparation.

Preparation of Pickering Emulsion

CNC-CTAB dispersions at concentrations of 0.4%, 0.5%, and 0.6% (w/v) were prepared in distilled water. Olive oil was gradually added to each dispersion to obtain a final oil concentration of 10% (v/v). The mixtures were homogenized using an Ultra-Turrax homogenizer at 10,000 rpm for 5 min. The resulting oil-in-water (O/W) emulsions were stored for seven days, and their stability was evaluated by visual and microscopic observations during the storage period. The overall preparation procedure for the CNC-CTAB-stabilized Pickering emulsions is summarized in Figure 4, including CNC isolation, CTAB modification, emulsion preparation, and subsequent stability evaluation.

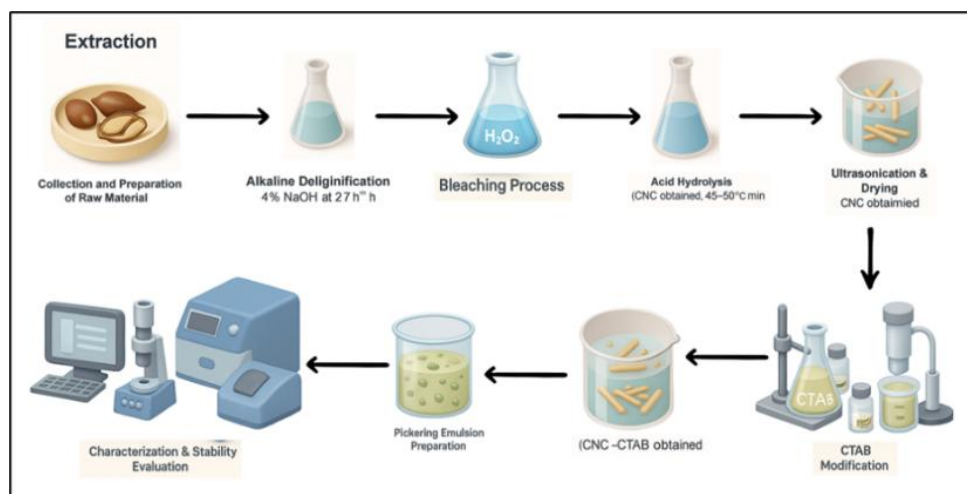


Figure 4. Process flow diagram illustrating the preparation of Pickering emulsions stabilized by CTAB-modified cellulose nanocrystals (CNC-CTAB)

Characterization

Fourier transform infra-red (FTIR) spectroscopy was used to examine changes in the chemical structure of the samples during the treatment process. X-ray diffraction (XRD) was used to evaluate changes in the crystallinity of the cellulose, while thermogravimetric analysis (TGA) was used to characterize the thermal behavior of the samples. The morphology and dimensions of the CNCs were analyzed using transmission electron microscopy (TEM). Individual, well-dispersed CNC particles observed in multiple TEM fields were measured using ImageJ (BRIN, Indonesia). A total of 112 particles for the HPCA-derived CNCs and 24 particles for the AHP–PAA-derived CNCs were analyzed. Particle lengths were reported as the observed minimum–maximum range, while diameters were expressed as mean $\pm$ standard deviation.

The crystallinity index (CrI) of purified cellulose and CNCs was determined from the X-ray diffraction profiles using the empirical Segal equation (Equation 1):

$$CrI(\%) = \left(\frac{I_{200} - I_{am}}{I_{200}} \right) \times 100 \quad (1)$$

where I_{200} is the maximum intensity of the crystalline peak assigned to the (200) lattice plane at approximately $2\theta = 22.1$ – 22.6° , and I_{am} is the minimum intensity corresponding to the amorphous phase at approximately $2\theta = 18.0$ – 18.5° .

RESULT AND DISCUSSION

Characterization of Cellulose and Cellulose Nanocrystals (CNCs)

The hydrogen peroxide–citric acid (HPCA) treatment produced 63.0 g of purified cellulose from 100.0 g of dried *P. pinnata* fruit peel, corresponding to a cellulose yield of 63.0% on a dry-weight basis. The yield was calculated according to Equation (2), using the initial dry mass of fruit peel as the reference mass. This value is within the range reported for cellulose recovery from several agricultural residues and is higher than the values reported for sugarcane bagasse and rice straw under the conditions reported in the corresponding study [14]. However, differences in biomass composition and pretreatment conditions should be considered when comparing cellulose yields among different feedstocks. The cellulose yield was calculated using the equation given below (Equation 2):

$$\text{Yield (\%)} = \left(\frac{W_{\text{purified cellulose}}}{W_{\text{raw peel powder}}} \right) \times 100 = \left(\frac{63.0 \text{ g}}{100.0 \text{ g}} \right) \times 100 = 63.0\% \quad (2)$$

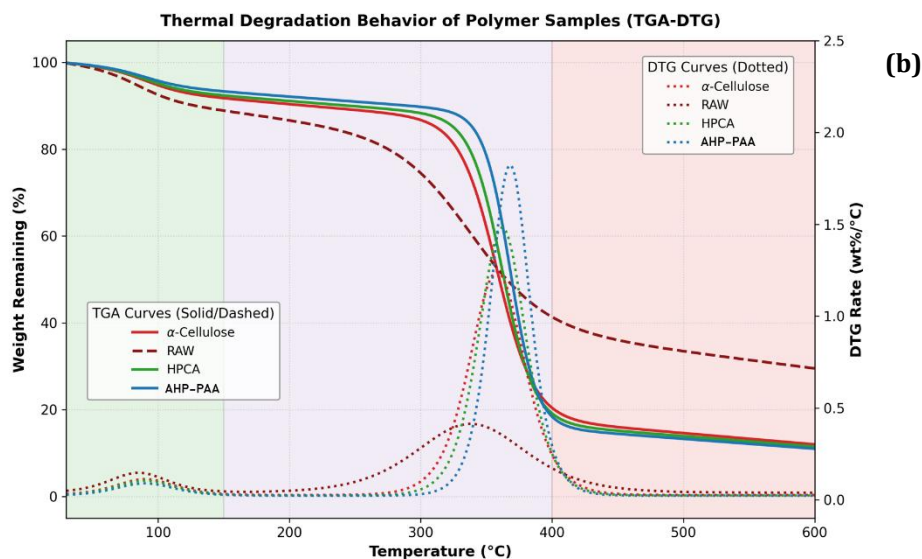
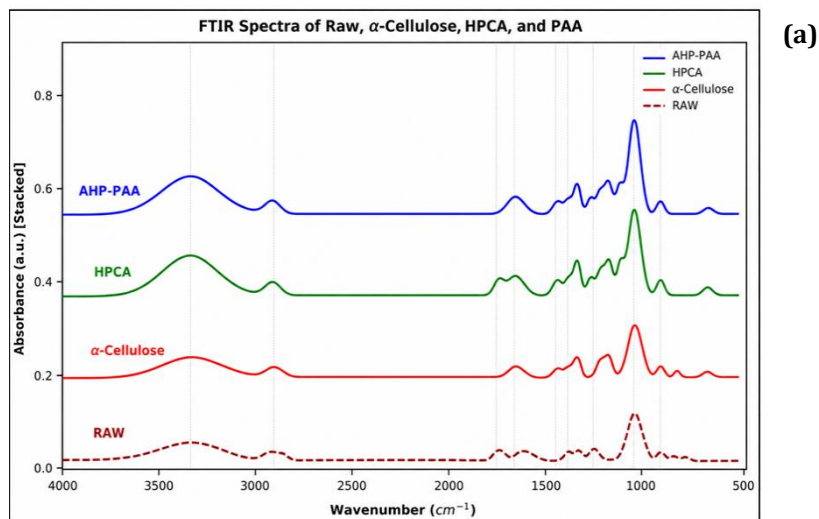
The obtained yield was higher than the values reported for several agricultural residues, including sugarcane bagasse (approximately 40–45%) and rice straw (35–42%) [14]. This result indicates that the bleaching sequence used in this study provided a relatively high cellulose recovery from *P. pinnata* fruit peel. The recovered cellulose was subsequently used as the starting material for sulfuric acid hydrolysis to produce CNCs.

The Fourier transform infra-red (FTIR) spectra of raw *P. pinnata* fruit peel, purified cellulose, and CNCs obtained through the hydrogen peroxide–citric acid (HPCA) and alkaline hydrogen peroxide–peracetic (AHP–PAA) routes showed several characteristic absorption bands associated with cellulose and other components of the biomass. The broad band at approximately 3330 – 3380 cm^{-1} was assigned to O–H stretching, while the band at approximately 2895 – 2917 cm^{-1} was associated with C–H stretching. In the raw fruit peel, absorption bands around 1734 , 1510 , and 1240 cm^{-1} were observed and were no longer detected after the chemical treatments, consistent with changes in non-cellulosic components [15], [16]. The bands at approximately 1638 , 1427 – 1431 , 1369 – 1370 , 1314 – 1317 , 1160 – 1161 , and 1025 – 1030 cm^{-1} correspond to characteristic vibrational modes of the cellulose structure. After acid hydrolysis, the O–H band around 3300 cm^{-1} showed a change in band shape, which may reflect changes in hydrogen bonding within the cellulose structure [17]. A weak shoulder around 805 – 810 cm^{-1} was also observed in the CNC spectra and may be associated with sulfate-containing groups introduced during sulfuric acid hydrolysis.

The thermal behavior of raw *P. pinnata* fruit peel, purified cellulose, and CNCs obtained through the HPCA and AHP–PAA routes was evaluated using thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) thermograms (Figure 5 (b)). The TGA/DTG curves showed an initial mass loss of approximately 4–6% for the samples, corresponding mainly to moisture evaporation. The principal thermal decomposition of the cellulose-based samples occurred in the approximately 350 – 380°C region. After sulfuric acid hydrolysis, the CNC samples exhibited a shift in the main degradation region toward lower temperatures compared with purified cellulose. This shift may be associated with sulfate-containing groups introduced during acid hydrolysis, as reported in previous studies [18], [19]. At approximately 400°C , the CNC samples retained about 21.5–23% of their initial mass, while the raw *P. pinnata* fruit peel retained approximately 46%. The higher residual mass of the CNC samples compared with the raw biomass is consistent with differences in their thermal decomposition and carbonization behavior. Overall, the TGA/DTG profiles indicate that sulfuric acid hydrolysis altered the thermal decomposition behavior of the cellulose, with the CNC samples showing a shift in the main degradation region toward lower temperatures.

Furthermore, the X-ray diffraction (XRD) patterns of raw *P. pinnata* fruit peel, purified cellulose (α -cell), and CNCs obtained through the HPCA and AHP–PAA routes are shown in Figure 5. The purified cellulose and CNC samples exhibited the characteristic diffraction pattern of cellulose I, with three main peaks centered at 15.63° , 22.07° , and 34.63° , corresponding to the (110), (200), and (004) crystallographic planes, respectively [20]. The crystallinity index (CrI) was calculated using the empirical Segal method according to Equation (1). For purified cellulose, the measured intensities of the crystalline peak and the amorphous contribution yielded a CrI of approximately 63.0%. Following sulfuric acid hydrolysis, the CrI increased to approximately 77.0% in the CNC samples. The CrI increased from approximately 63%

for purified cellulose to 77% for the CNCs. This increase is consistent with the preferential hydrolysis of less ordered cellulose regions during acid hydrolysis, as reported in previous studies [3], [4]. However, the increase in CrI alone does not directly demonstrate selective degradation of the amorphous regions. The XRD results are also consistent with the FTIR observations, which showed characteristic cellulose bands and changes in the O–H stretching region after hydrolysis [17], [20]. In addition, the transmission electron microscopy (TEM) images showed predominantly rod-like CNC particles with lengths of approximately 200–400 nm. ImageJ analysis gave mean diameters of 9.8 ± 7.6 nm for the HPCA-derived CNCs and 10.9 ± 6.7 nm for the AHP–PAA-derived CNCs. The relatively large standard deviations indicate a broad distribution of particle diameters [21]. Together, these results support the structural changes associated with CNC formation, although the increase in CrI primarily reflects the relative enrichment of crystalline cellulose following removal of less ordered regions.



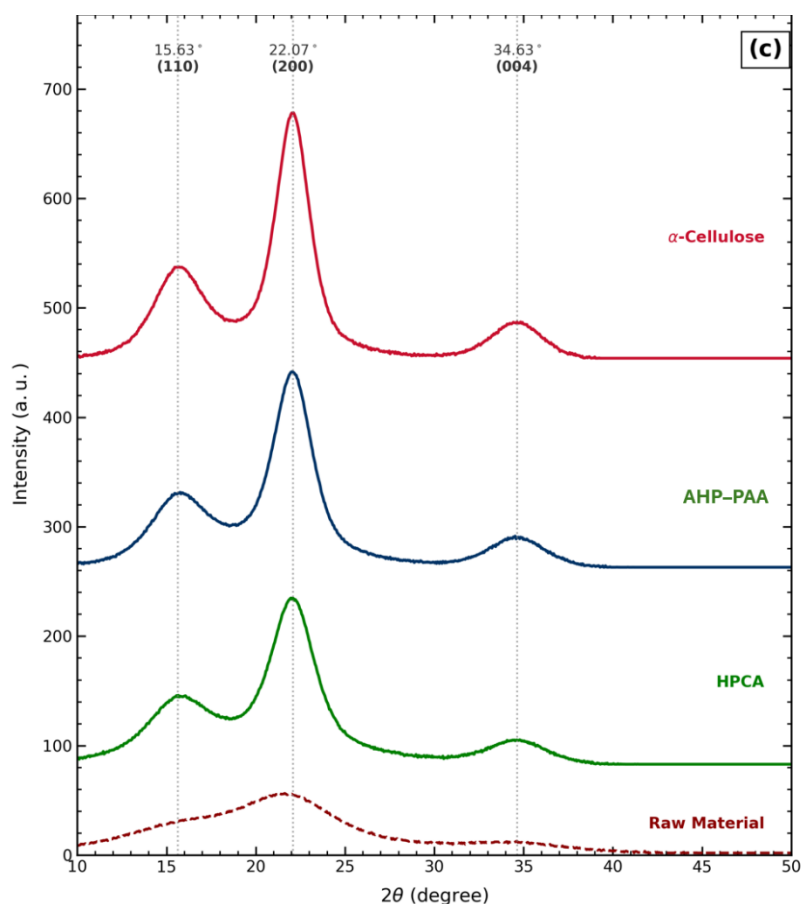


Figure 5. Characterization of raw biomass, purified cellulose, and derived CNC samples: (a) FTIR spectra showing the progressive removal of non-cellulosic functional groups, (b) TGA/DTG curves demonstrating thermal degradation behavior, and (c) XRD patterns of raw *P. pinnata* fruit peel, purified cellulose (α -cell), and CNCs obtained through the HPCA and AHP-PAA hydrolysis routes.

Morphology of CNCs and Pickering Emulsion Stability

Transmission electron microscopy (TEM) was used to examine the morphology and dimensions of the isolated CNCs. As shown in Figure 6, both HPCA-derived and AHP-PAA-derived CNCs exhibited predominantly rod-like morphologies. Quantitative image analysis using ImageJ was performed on 112 particles for the HPCA-derived sample and 24 particles for the AHP-PAA-derived sample. The particle lengths ranged from approximately 200 to 400 nm. The mean particle diameters were 9.8 ± 7.6 nm for the HPCA-derived CNCs and 10.9 ± 6.7 nm for the AHP-PAA-derived CNCs, with median diameters of 7.6 and 9.3 nm, respectively. The relatively large standard deviations indicate a broad distribution of particle diameters. The observed rod-like morphology and nanoscale dimensions are consistent with reported characteristics of CNCs derived from lignocellulosic materials [22].

The nanoscale dimensions and rod-like morphology of the CNCs may influence their behavior at the oil–water interface. After surface modification with cetyltrimethylammonium bromide (CTAB), the CNC–CTAB particles exhibited altered surface characteristics that can facilitate their interaction with both aqueous and oil phases [13]. The resulting emulsions showed dispersed oil droplets, with differences in phase separation observed among the CNC–CTAB concentrations. Among the formulations tested, the emulsion containing 0.6% (w/v) CNC–CTAB showed the lowest visible phase separation during seven days of storage compared with the 0.4% and 0.5% formulations (Figure 7). The higher stability observed for the 0.6% CNC–CTAB emulsion may be related to increased availability of modified CNC particles for stabilization of the oil–water interface and changes in the continuous phase. CTAB modification may alter the surface properties and interparticle interactions of CNCs, which can influence their behavior at the oil–water interface [13], [23]. Based on previous studies, electrostatic repulsion and steric effects may contribute to reducing droplet contact and aggregation [6], [7], [13], [23]. However, these mechanisms are proposed explanations in the present study because zeta potential, interfacial tension, contact angle, and interfacial rheological properties were not directly measured. Therefore, the individual contributions of electrostatic and steric stabilization cannot be determined from the present experimental data.

At the lower CNC–CTAB concentrations of 0.4% and 0.5% (w/v), the emulsions showed greater phase separation during storage than the 0.6% formulation. One possible explanation is that the lower particle concentration provided less CNC–CTAB material for stabilization of the oil–water interface. As the CNC–CTAB concentration increased to 0.6% (w/v), the greater number of particles may have provided more extensive coverage of the oil droplets and contributed to the lower degree of visible phase separation observed after seven days. Excess particles in the continuous phase may also

influence the physical properties of the aqueous phase and thereby reduce droplet movement. These effects are consistent with proposed stabilization mechanisms for particle-stabilized emulsions, in which particle adsorption at the oil–water interface and interactions among particles in the continuous phase can contribute to emulsion stability [13], [23]. However, because interfacial coverage, viscosity, and electrostatic properties were not directly measured in this study, the relative contribution of these mechanisms cannot be determined from the present data. The higher stability observed for the 0.6% (w/v) formulation may be explained by a combination of particle-mediated interfacial stabilization and changes in the continuous phase. CNC–CTAB particles can contribute to stabilization through their presence at the oil–water interface, while CTAB modification may alter the surface properties and interparticle interactions of the CNCs [13], [23]. These effects could reduce droplet contact and aggregation and thereby contribute to the lower phase separation observed at the higher CNC–CTAB concentration. This interpretation is consistent with reported stabilization mechanisms for Pickering emulsions containing surface-modified particles and nanocellulose [6], [7], [13], [23]. However, direct measurements of contact angle, interfacial tension, zeta potential, and rheological properties were not performed in the present study. Therefore, the relative contributions of steric and electrostatic effects cannot be separated from the current experimental data.

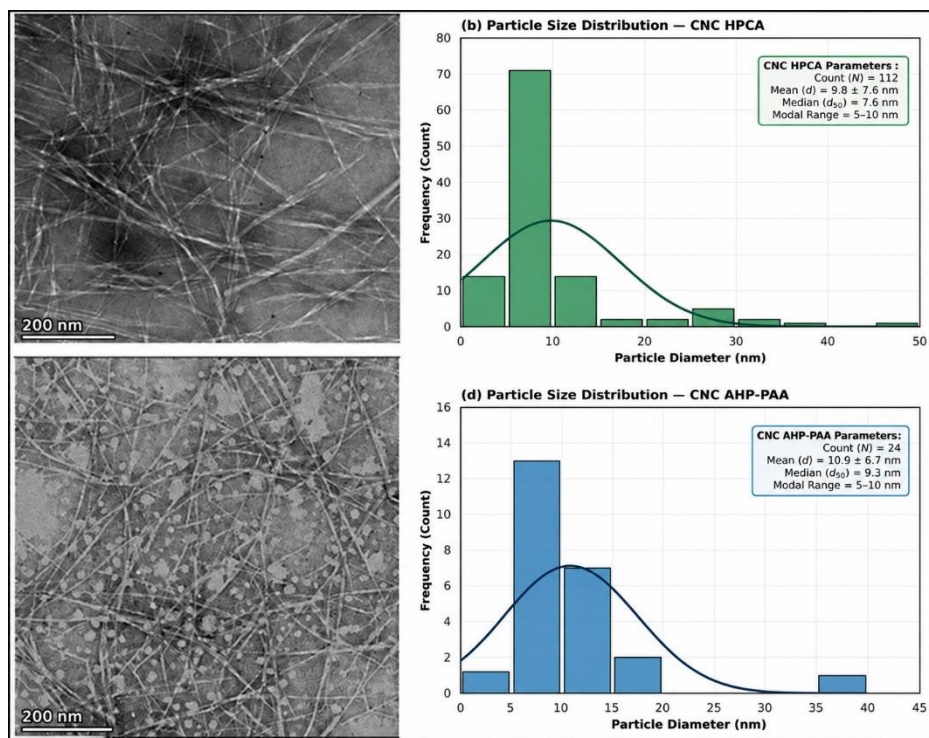


Figure 6. TEM micrographs and particle size distributions of CNCs obtained from the HPCA and AHP–PAA routes, showing predominantly rod-like morphology and nanoscale dimensions

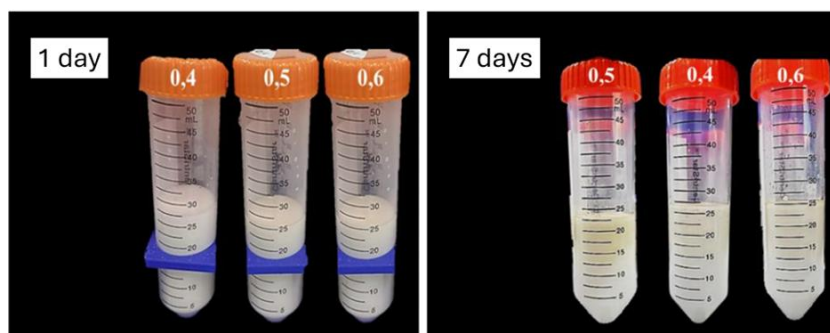


Figure 7. Stability assessment of oil-in-water Pickering emulsions stabilized by CNC–CTAB at 0.4%, 0.5%, and 0.6% (w/v) during seven days of storage

CONCLUSION

This study investigated the use of *Pongamia pinnata* fruit peel as a cellulose source for cellulose nanocrystal (CNC) production and evaluated the resulting cellulose nanocrystal–cetyltrimethylammonium bromide (CNC–CTAB) particles as stabilizers for oil-in-water Pickering emulsions. The hydrogen peroxide–citric acid (HPCA) treatment produced purified cellulose with a yield of 63%. Sulfuric acid hydrolysis produced rod-like CNCs with lengths of approximately 200–400 nm, mean diameters of 9.8 ± 7.6 nm for the HPCA-derived CNCs and 10.9 ± 6.7 nm for the alkaline hydrogen

peroxide–peracetic (AHP–PAA)-derived CNCs, and a crystallinity index of approximately 77%. The CNCs were subsequently modified with CTAB and evaluated at concentrations of 0.4%, 0.5%, and 0.6% (w/v) in oil-in-water (O/W) Pickering emulsions. Among the tested formulations, the 0.6% CNC–CTAB emulsion showed the lowest visible phase separation during seven days of storage. These results indicate that *P. pinnata* fruit peel can serve as a cellulose feedstock for CNC production and that CTAB-modified CNCs can contribute to the stabilization of Pickering emulsions. The observed stability may involve particle-mediated interfacial stabilization and changes in the continuous phase, although the individual contributions of steric and electrostatic effects could not be determined because interfacial and rheological properties were not directly measured.

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REFERENCES

- [1] J.-Y. Lee, S.-E. Lee, and D.-W. Lee. “Current Status and Future Prospects of Biological Routes to Bio-Based Products Using Raw Materials, Wastes, and Residues as Renewable Resources.” *Crit. Rev. Environ. Sci. Technol.*, vol. 52, no. 14, pp. 2453–2509, 2022.
- [2] S. Ahmed. *Biobased nanomaterials*. Singapore: Springer Nature, 2024.
- [3] A. B. Rashid, M. E. Hoque, N. Kabir, F. F. Rifat, H. Ishrak, A. Alqahtani, and M. E. H. Chowdury. “Synthesis, Properties, Applications, and Future Prospective of Cellulose Nanocrystals.” *Polymers (Basel)*, vol. 15, no. 20, p. 4070, 2023.
- [4] M. Raza and B. Abu-Jdayil. “Cellulose Nanocrystals From Lignocellulosic Feedstock: A Review of Production Technology and Surface Chemistry Modification.” *Cellulose*, vol. 29, no. 2, pp. 685–722, 2022.
- [5] F. B. de Carvalho-Guimarães, K. L. Correa, T. P. de Souza, J. R. Rodriguez Amado, R. M. Ribeiro-Costa, and J. O. C Silva-Júnior. “A Review of Pickering Emulsions: Perspectives and Applications.” *Pharmaceuticals*, vol. 15, no. 11, p. 1413, 2022.
- [6] F. Heidari-Dalfard, S. Tavasoli, E. Assadpour, R. Miller, and S. M. Jafari. “Surface Modification of Particles/Nanoparticles to Improve the Stability of Pickering Emulsions: A Critical Review.” *Adv. Colloid Interface Sci.*, vol. 336, p. 103378, 2025.
- [7] S. H. Teo, C. Y. Chee, M. Z. Fahmi, S. C. Wibawa Sakti, and H. V. Lee. “Review of Functional Aspects of Nanocellulose-Based Pickering Emulsifier for Non-Toxic Application and Its Colloid Stabilization Mechanism.” *Molecules*, vol. 27, no. 21, 2022.
- [8] J. P. S. Morais, M. D. F. Rosa, E. S. D. Brito, H. M. C. D. Azeredo, and M. C. B. D. Figueirêdo. “Sustainable Pickering Emulsions With Nanocellulose: Innovations and Challenges.” *Foods*, vol. 12, no. 19, p. 3599, 2023.
- [9] Z. Li, S. Anankanbil, J. N. Pedersen, M. Nadzieja, and Z. Guo. “Nanocellulose Fractionated From TEMPO-Mediated Oxidation of Cellulose as an Energy-Free Ingredient for Stabilizing Pickering Emulsion.” *Biochem. Eng. J.*, vol. 191, p. 108795, 2023.
- [10] P. M. Reque and A. Brandelli. “Encapsulation of Probiotics and Nutraceuticals: Applications in Functional Food Industry.” *Trends Food Sci. Technol.*, vol. 114, pp. 1–10.
- [11] A. Ahmad, H. P. S. Abdul Khalil, R. D. Bairwan, M. I. Ahmad, A. A. A. Abdullah, C. K. Abdullah, E. B. Yahya, M. S. C. Zain, and S. A. Hamid. “Sustainable Cellulose Extraction: Unlocking the Potential of Tropical Fruit Peels for Advanced Materials.” *Clean Technol. Environ. Policy*, vol. 27, no. 2, pp. 919–951, 2025.
- [12] S. Prabhakaran, D. Pandey, J. K. Nayak, and R. Chauhan. “Plant Breeding, Genetics and Biotechnology on Pierre (*Pongamia pinnata* L.).” *Breed. Biotechnol. Grass Bast Fiber Crop.*, pp. 721–753, 2025.
- [13] X. Gong, M. F. Ismail, and Y. Boluk. “Interactions Between Cetyltrimethylammonium Bromide Modified Cellulose Nanocrystals and Surfaces: An Ellipsometric Study.” *Surfaces*, vol. 7, no. 2, pp. 428–441, 2024.
- [14] W. Thongsomboon, Y. Baimark, and P. Srihanam. “Valorization of Cellulose-Based Materials From Agricultural Waste: Comparison Between Sugarcane Bagasse and Rice Straw.” *Polymers (Basel)*, vol. 15, no. 15, p. 3190, 2023.
- [15] R. Md Salim, J. Asik, and M. S. Sarjadi. “Chemical Functional Groups of Extractives, Cellulose and Lignin Extracted From Native *Leucaena leucocephala* Bark.” *Wood Sci. Technol.*, vol. 55, no. 2, pp. 295–313, 2021.
- [16] R. Vârban, I. Crişan, D. Vârban, A. Ona, L. Olar, A. Stoie, and R. Ştefan. “Comparative FT-IR Prospecting for Cellulose in Stems of Some Fiber Plants: Flax, Velvet Leaf, Hemp and Jute.” *Appl. Sci.*, vol. 11, no. 18, p. 8570, 2021.
- [17] B. Shao, Z. Han, R. Pang, D. Wu, B. Xie, and Y. Su. “The Crystalline Structure Transition and Hydrogen Bonds Shift Determining Enhanced Enzymatic Digestibility of Cellulose Treated by Ultrasonication.” *Sci. Total Environ.*,

vol. 876, p. 162631, 2023.

- [18] E. Apaydin Varol, and U. Mutlu. "TGA-FTIR Analysis of Biomass Samples Based on the Thermal Decomposition Behavior of Hemicellulose, Cellulose, and Lignin." *Energies*, vol. 16, no. 9, p. 3674, 2023.
- [19] J. Wang, X. Zhao, A. Wu, Z. Tang, L. Niu, F. Wu, F. Wang, T. Zhao, and Z. Fu. "Aggregation and Stability of Sulfate-Modified Polystyrene Nanoplastics in Synthetic and Natural Waters." *Environ. Pollut.*, vol. 268, p. 114240, 2021.
- [20] C. Huang, H. Yu, S. Y. H. Abdalkarim, Y. Li, X. Chen, X. Yang, Y. Zhou, and L. Zhang. "A Comprehensive Investigation on Cellulose Nanocrystals With Different Crystal Structures From Cotton via an Efficient Route." *Carbohydr. Polym.*, vol. 276, p. 118766, 2022.
- [21] G. Peng and D. Wu. "Insight Into Different Roles of Chitin Nanocrystals and Cellulose Nanocrystals Towards Stabilizing Pickering Emulsions." *Hydrocolloids*, vol. 131, p. 107808, 2022.
- [22] C. Miao, M. N. Mirvakili, and W. Y. Hamad. "A Rheological Investigation of Oil-in-Water Pickering Emulsions Stabilized by Cellulose Nanocrystals." *J. Colloid Interface Sci.*, vol. 608, pp. 2820–2829, 2022.
- [23] A. Ghaffarkhah, S. A. Hashemi, A. A. Isari, M. Panahi-Sarmad, F. Jiang, T. P. Russell, ... and M. Arjmand. "Chemistry, Applications, and Future Prospects of Structured Liquids." *Chem. Soc. Rev.*, 2024.