

Characterization of Optical and Mechanical Properties of Nanocellulose from Oil Palm Empty Fruit Bunch Biomass Using Acid Hydrolysis

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Abstract:

This study aims to investigate the optical and mechanical properties of nanocrystalline cellulose (NCC) derived from oil palm empty fruit bunch (OPEFB) as a renewable lignocellulosic biomass for sustainable functional materials. NCC was synthesized through sequential delignification, bleaching, and sulfuric acid hydrolysis at concentrations of 30 wt% and 40 wt%. The resulting NCC was characterized using UV–Vis spectroscopy and tensile testing. UV–Vis analysis showed absorption peaks at 292, 291, and 289 nm for commercial NCC, OPEFB-derived NCC hydrolyzed with 30 wt% H₂SO₄, and OPEFB-derived NCC hydrolyzed with 40 wt% H₂SO₄, respectively. Tauc plot analysis yielded estimated optical band gap energies of 4.25, 4.26, and 4.29 eV, respectively. Tensile testing showed that the commercial NCC exhibited the highest tensile strength and Young's modulus, whereas the OPEFB-derived NCC showed lower mechanical performance. The NCC hydrolyzed with 30 wt% H₂SO₄ exhibited a tensile strength of 9.65 MPa and a Young's modulus of 0.330 GPa, while the 40 wt% H₂SO₄ sample exhibited values of 3.99 MPa and 0.176 GPa, respectively. Increasing the sulfuric acid concentration resulted in a slight increase in the estimated optical band gap but a decrease in tensile strength and Young's modulus. Among the hydrolysis conditions investigated, 30 wt% H₂SO₄ provided a more balanced combination of optical and mechanical properties. These findings indicate that OPEFB can serve as a renewable precursor for the development of cellulose-based functional materials and provide a basis for further investigation of their structural and functional properties.

1. Introduction

The increasing production of oil palm in Indonesia has made a significant contribution to the national economy; however, it also generates a large amount of biomass waste, one of which is oil palm empty fruit bunches (OPEFB). Approximately 25–26% of the total fresh fruit bunches processed into palm oil are converted into OPEFB waste, most of which remains underutilized. In fact, OPEFB contains a relatively high cellulose content, approximately 55.75%, along with 28.93% hemicellulose and 15.32% lignin, making it highly potential as a raw material for high-value-added products such as nanocellulose (Mohammad Padzil et al., 2020; Hidayah & Wusko, 2020).

Cellulose is the most abundant natural biopolymer on Earth, characterized by its biodegradable, renewable, non-toxic nature, and excellent mechanical stability (Yuni Hendrawati et al., 2023). At the nanoscale, cellulose exhibits superior properties compared to bulk cellulose, including a high specific surface area, high crystallinity, greater elastic modulus, and the ability to form strong hydrogen bonds. Nanocellulose generally consists of cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF) (Farooq

et al., 2020), which have been widely applied in various fields such as composites, biosensors, photodetectors, and environmentally friendly electronic devices (Poulose et al., 2022; Hartati et al., 2023).

Acid hydrolysis is one of the most commonly used methods for producing nanocellulose due to its effectiveness in removing the amorphous regions of cellulose fibers, thereby increasing the crystallinity of the material (Ismail et al., 2023). Sulfuric acid (H_2SO_4) is the most widely used reagent because it can produce stable nanocellulose particles in suspension form as a result of sulfate ester group formation on the surface. Previous studies have reported that nanocellulose derived from OPEFB through 45% sulfuric acid hydrolysis achieved a particle size of approximately 79 nm, indicating successful isolation at the nanoscale (Aulia et al., 2013; Dyah Kencana Wulan et al., 2024).

In addition to the synthesis process, the characterization of nanocellulose is an essential step to evaluate its potential applications. Optical characterization using UV–Vis spectroscopy can be employed to determine the absorbance and band gap energy of the material, which are closely related to its potential as a semiconductor or light-sensing material (Orelma et al., 2020). Recent studies have reported optical band gap values for OPEFB-derived cellulose-based composites (Moon et al., 2011), with a value of approximately 2.769 eV reported for an OPEFB alkali cellulose/PVA composite (Adiati et al., 2024). However, this value was obtained from a composite material and therefore cannot be directly compared with the band gap of the NCC obtained in the present study. In the present study, NCC derived from OPEFB through sulfuric acid hydrolysis exhibited band gap energies in the range of 4.25–4.29 eV. The difference may be associated with differences in material composition, sample preparation, and optical analysis conditions between the cellulose-based composite reported in the literature and the NCC investigated in this study.

On the other hand, the characterization of mechanical properties, such as tensile strength testing, is also crucial to evaluate the strength, flexibility, and stability of nanocellulose materials (Maghfirah et al., 2022). The mechanical properties of nanocellulose are influenced by particle size, crystallinity, fiber distribution, and intermolecular interactions through hydrogen bonding. Nanocellulose is known to possess a high Young's modulus of up to approximately 130 GPa, making it a highly promising reinforcing material for the development of flexible sensor films and smart composite materials (Kamel & Khattab, 2020).

Although numerous studies have discussed the synthesis of nanocellulose from OPEFB, studies integrating both optical and mechanical characterizations simultaneously remain relatively limited, particularly those employing variations in acid hydrolysis concentration as the main parameter. In fact, these two characteristics play a crucial role in determining the performance of nanocellulose for biomaterial-based sensor applications.

Based on these considerations, this study aims to synthesize nanocrystalline cellulose (NCC) from oil palm empty fruit bunch (OPEFB) biomass using sulfuric acid hydrolysis at different concentrations and to investigate the optical and mechanical properties of the resulting NCC. The optical properties were evaluated using UV–Vis spectroscopy and Tauc plot analysis, while the mechanical properties were evaluated through tensile testing. The findings are expected to contribute to the development of sustainable and environmentally friendly biomass-based functional materials with potential applications in optical sensing and green electronic materials.

2. Theoretical Framework

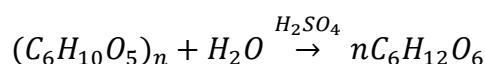
2.1. Acid Hydrolysis Method

Oil palm empty fruit bunches (OPEFB) are lignocellulosic waste materials with a high α -cellulose content and considerable potential as precursors for nanocellulose production. The main structure of OPEFB consists of three major components, namely cellulose, hemicellulose, and lignin. The cellulose component serves as the primary crystalline phase, which can be isolated through delignification and bleaching processes prior to nanosizing. Its high cellulose content makes OPEFB an economical and sustainable raw material for nanocellulose production (Asmoro et al., 2025) (Dyah Kencana Wulan et al., 2024). Chemically, cellulose is a linear polysaccharide composed of β -1,4-D-glucopyranose units with the general formula $(C_6H_{10}O_5)_n$. This structure contains hydroxyl groups that enable the formation of intra and intermolecular hydrogen bonds, resulting in both crystalline and amorphous regions (Indarti et al., 2019).

Nanocellulose is a cellulose derivative with nanometer-scale dimensions that exhibits superior properties, such as high surface area, high crystallinity, excellent mechanical strength, and good biocompatibility. Based on its morphology, nanocellulose is generally classified into Cellulose Nanocrystals (CNC), which possess a rod-like structure, and Cellulose Nanofibrils (CNF), which consist of long fibrillar structures. CNC is produced through the removal of amorphous regions, leaving only the crystalline domains. Cellulose nanocrystals possess high intrinsic mechanical properties due to their crystalline structure and strong intermolecular interactions. However, the mechanical properties of NCC films may differ substantially from those of individual nanocrystals because film formation introduces additional structural factors (Gupta et al., 2022).

The acid hydrolysis method is the most commonly used technique for the production of cellulose nanocrystals (CNC). The main principle of this method is the cleavage of β -1,4-glycosidic bonds in the amorphous regions of cellulose using strong acids such as H_2SO_4 . Theoretically, the amorphous regions are more susceptible to hydrolysis due to their less ordered structure, looser molecular packing, and lower bond energy compared to the crystalline regions.

General reaction:



However, under controlled conditions, the hydrolysis process does not proceed completely to glucose formation, but only cleaves the amorphous regions, resulting in the isolation of nanocrystalline cellulose. The following are the main stages of acid hydrolysis (Shanmugarajah et al., 2015) (Ismail et al., 2023) :

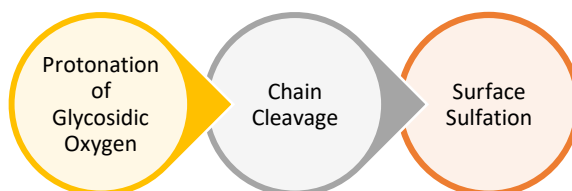


Figure 1. Stages of Acid Hydrolysis Reaction

2.2. Optical Properties

Optical properties are material characteristics related to the interaction between light and matter, including absorption, transmission, reflection, and light scattering. In nanocellulose, optical properties are important parameters because they are directly associated with its potential applications in optical sensors, photodetectors, and biomass-based semiconductor materials. Nanocellulose possesses nanoscale dimensions, high surface area, excellent optical transparency, and the ability to form three-dimensional networks, all of which influence its absorption and light transmission behavior (Adiati et al., 2024).

Fundamentally, the interaction of light with nanocellulose follows the principle of electronic transitions, in which electrons are excited from the valence band to the conduction band when the energy of the incident photon is equal to or greater than the band gap energy. The magnitude of this energy determines the ability of the material to absorb light at a specific wavelength.

The relationship between photon energy and wavelength is expressed by the following equation:

$$E = h\nu = \frac{hc}{\lambda} \quad (1)$$

where E is photon energy (eV), h is Planck's constant (6.626×10^{-34} Js), c is speed of light (3×10^8 m/s) and λ is wavelength (m).

This equation shows that the shorter the wavelength, the greater the energy carried by the photon. Absorbance is the ability of a material to absorb light energy at a specific wavelength. Absorbance measurements of nanocellulose are generally performed using UV-Vis spectroscopy within the 200–900 nm range. The absorbance of the sample can be described by the Beer–Lambert law, which is expressed as :

$$A = \log \frac{I_0}{I} \quad (2)$$

where A is absorbance, I_0 is initial light intensity, and I is light intensity after passing through the sample. Smaller particle sizes enhance interaction with light due to the larger surface area. In the study by Adiati et al., the highest absorbance occurred at a wavelength of 400–425 nm, indicating a strong response in the visible light region (Adiati et al., 2024).

The optical band gap was estimated using the Tauc relation, which is expressed as:

$$(\alpha h\nu)^n = A (h\nu - E_g) \quad (3)$$

where α is the absorption coefficient, $h\nu$ is the photon energy, E_g is the optical band gap energy, and A is a proportionality constant.

2.3. Mechanical Properties

Mechanical properties refer to a material's ability to withstand external forces or loads without undergoing permanent damage. For nanocellulose, mechanical properties are a key characteristic determining its potential in advanced material applications, such as structural composites, flexible sensors, eco-friendly electronics, and biomaterials. Nanocellulose exhibits exceptional mechanical properties due to its composition of crystalline cellulose domains featuring strong hydrogen bonding between polymer chains (Gupta et al., 2022). In general, the key mechanical property parameters of nanocellulose include tensile strength, modulus of elasticity (Young's modulus), elongation at break, and toughness.

Tensile Strength

Tensile strength is the ability of a material to withstand maximum stress before fracturing, It is calculated using the following equation:

$$\sigma = \frac{F}{A} \quad (4)$$

Where σ is tensile stress (MPa), F is maximum applied force (N) and A is cross-sectional area (m^2). In nanocellulose, high tensile strength is attributed to strong β -1,4-glycosidic bonds, networks of intra- and intermolecular hydrogen bonds, and a dense crystalline structure. According to Gupta et al., cellulose nanocrystals (CNCs) possess a theoretical tensile strength of up to 9.2 GPa and a strain at break of approximately 8.5%, demonstrating superior mechanical performance compared to many synthetic polymers (Gupta et al., 2022). Meanwhile, in the literature review by Chen et al., CNCs obtained via acid hydrolysis were reported to have a tensile strength of approximately 10 GPa (Chen et al., 2020).

Young's Modulus

Young's modulus indicates the stiffness of a material against elastic deformation, It is calculated using the following equation:

$$E = \frac{\sigma}{\varepsilon} \quad (5)$$

Where E is modulus of elasticity (GPa), σ is stress and ε is strain. The higher the modulus of elasticity, the stiffer the material. Cellulose I β has a theoretical modulus of elasticity of approximately 206 GPa (along the axial direction of the cellulose chain), whereas experimental results for CNCs yield values of 120–220 GPa; meanwhile, cellulose nanofibrils (CNF) have a Young's modulus of approximately 80 GPa. These values indicate that nanocellulose possesses a stiffness comparable to that of Kevlar and higher than that of many other biopolymers (Gupta et al., 2022).

3. Method

3.1. Tools and Materials

The primary material used in this study was oil palm empty fruit bunch (OPEFB) powder—sieved to 80 mesh and obtained from a local oil palm plantation—serving as the cellulose source. Delignification was performed using 5% sodium hydroxide (NaOH), while bleaching employed a mixture of 30 wt% hydrogen peroxide (H_2O_2) and citric acid. Nanocellulose synthesis was carried out via acid hydrolysis using sulfuric acid (H_2SO_4) at concentrations of 30 wt% and 40 wt%. The pH was raised using distilled water over a period of three days; distilled water also served as the washing medium and solvent throughout the synthesis process. Key equipment included a hot plate magnetic stirrer (with temperature and stirring speed controls) for the delignification, bleaching, and acid hydrolysis stages; a drying oven for sample drying; an analytical balance for mass measurement; and beakers, volumetric flasks, volumetric pipettes, and spatulas for solution preparation. Nanocellulose separation was achieved using a centrifuge at 8,000 rpm, while suspension homogenization was performed using an ultrasonicator. A rotary evaporator was used to obtain the gel phase, followed by final drying at room temperature for seven days.

3.2. Synthesis of Nanocrystalline Cellulose

100 g of 80-mesh oil palm empty fruit bunch (OPEFB) powder was used as the starting material. The sample was then delignified using a 5% NaOH solution at 75°C for 2 hours with constant stirring at 700

rpm; this step aimed to remove lignin and a portion of the hemicellulose, thereby increasing cellulose purity. Following delignification, the residue was washed with distilled water until neutral pH was reached and then oven-dried at room temperature for 48 hours. This process yielded crude cellulose with a recovery rate of approximately 45% of the initial OPEFB mass. The delignified cellulose was subsequently purified through a bleaching process using a mixture of 30 wt% H_2O_2 and citric acid in a total volume of 500 mL. The process was conducted at 90°C with a stirring speed of 750 rpm for 75 minutes until a white color was obtained, indicating a reduction in residual lignin and chromophores. After bleaching, the sample was washed until neutral and dried at room temperature to obtain α -cellulose.

The obtained α -cellulose was subsequently hydrolyzed using sulfuric acid (H_2SO_4) solutions at concentrations of 30 wt% and 40 wt% at 70°C for 90 minutes, with a stirring speed of 700 rpm. This step aimed to remove the amorphous regions of the cellulose and yield crystalline domains at the nanoscale. Upon completion of the hydrolysis process, the suspension was centrifuged at 4000 rpm for 20 minutes to separate the NCC particles from the acid solution. The supernatant was discarded, and the precipitate was washed repeatedly with distilled water. Finally, the pH of the suspension was raised using an NaOH solution until it approached neutrality.

The suspension resulting from neutralization was then homogenized using ultrasonication to break up particle agglomerations and enhance the homogeneity of the dispersion. Subsequently, a second centrifugation step was performed to separate the nanocellulose fraction from the remaining long, incompletely hydrolyzed cellulose fibers.

The obtained supernatant fraction was collected as an NCC suspension, while the precipitate was separated. To obtain NCC in gel form, the suspension could be concentrated using a rotary evaporator; meanwhile, to obtain NCC in powder form, the suspension was dried at room temperature for 5 days.

3.3. Optical Characterization

The optical properties of the nanocrystalline cellulose (NCC) samples were characterized using a Biobase BK-UV1900PC UV–Vis spectrophotometer. The measurements were performed to investigate the ultraviolet–visible absorption characteristics of commercial NCC and NCC derived from oil palm empty fruit bunches (OPEFB) through sulfuric acid hydrolysis at concentrations of 30 wt% and 40 wt%. The optical measurements were conducted using laboratory facilities at the Spectroscopy Laboratory, IPB University, Indonesia. Access to the instrument was obtained through the laboratory's external testing service by submitting an online application via a Google Form. Following submission, the laboratory staff provided technical guidance on sample dimensions, solvent selection, and the appropriate wavelength range for the measurements, and subsequently issued a cost quotation. Upon completion of payment, the laboratory conducted the measurements and delivered the results to the email address registered in the application form.

Before measurement, each NCC sample was prepared as a gel dispersion in 5 mL of distilled water. The resulting dispersions were analyzed using the UV–Vis spectrophotometer to obtain their absorbance spectra over the measured wavelength range of 200 – 800 nm. The instrument was used to record wavelength-dependent absorbance, identify the absorption maxima, and evaluate differences in the optical responses of the samples. The resulting absorbance data were subsequently used to estimate the optical band gap energy using the Tauc plot method. Commercial NCC, produced from microcrystalline cellulose through sulfuric acid hydrolysis, was included as a reference for comparison with the OPEFB-derived NCC samples.

The UV–Vis measurements provided the experimental optical data required to compare the effects of sulfuric acid concentration on the absorption characteristics and estimated optical band gap of the synthesized NCC. The spectrophotometer was used specifically for optical characterization and band gap estimation, rather than for direct measurement of the electrical conductivity or device-level sensing performance of the samples.

3.4. Mechanical Characterization

Mechanical tensile testing was conducted using a Fila Utama Universal Tensile Machine, with reference to ASTM D882 for thin polymer films. The NCC thin-film specimens measured 10 mm in width, 100 mm in length, and 200 μm in thickness. Tensile strength, Young's modulus, and elongation at break were determined from the stress–strain response.

4. Result

4.1. Synthesis of OPEFB-Derived NCC

The synthesis of NCC from OPEFB was carried out through sequential delignification, bleaching, and sulfuric acid hydrolysis. The delignification step using 5% NaOH at 75°C for 2 hours resulted in crude cellulose with a recovery of approximately 45% of the initial OPEFB mass. The cellulose was then subjected to bleaching using H_2O_2 and citric acid to obtain α -cellulose. Subsequently, the α -cellulose was hydrolyzed using 30 wt% and 40 wt% H_2SO_4 at 70°C for 90 minutes. After hydrolysis, the suspensions were centrifuged, washed, neutralized, and ultrasonicated before a second centrifugation step was performed. The resulting NCC suspensions were then used for optical and mechanical characterization.

4.2. UV-Vis Test Results

UV-Vis spectrophotometry was conducted to assess the response to visible light and determine the energy band gap, thereby characterizing NCCs produced via 30 wt% and 40 wt% acid hydrolysis and comparing them with commercial NCC. The energy band gap was calculated using the Tauc plot method, yielding the following results:

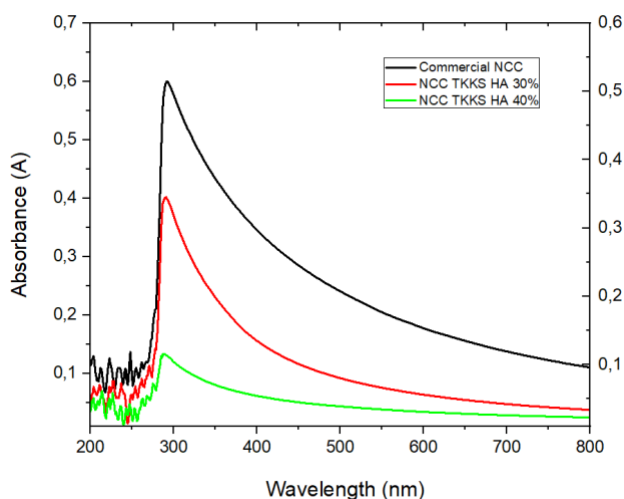


Figure 2. UV–Vis absorption spectra of commercial NCC and OPEFB-derived NCC hydrolyzed with 30 wt% and 40 wt% H_2SO_4 .

The absorption peaks observed at 289–292 nm indicate that all NCC samples exhibit a similar optical response in the near-UV region. The small shift in the absorption maximum from 292 nm for commercial

NCC to 291 nm and 289 nm for the 30 wt% and 40 wt% H₂SO₄-treated OPEFB-derived NCC, respectively, corresponds to a slight increase in photon energy. From a physical perspective, the shift toward shorter wavelengths indicates that the absorption occurs at slightly higher photon energies for the NCC samples treated with higher sulfuric acid concentrations. Nevertheless, the small magnitude of the wavelength shift suggests that the fundamental optical response of the cellulose-based materials remains relatively similar among the samples.

The commercial NCC exhibited a higher absorbance intensity than the OPEFB-derived NCC samples. This difference may be related to differences in the origin and processing history of the materials. The commercial NCC used in this study was produced from microcrystalline cellulose (MCC) through sulfuric acid hydrolysis, whereas the OPEFB-derived NCC underwent additional delignification and bleaching steps before acid hydrolysis. Differences in the resulting material composition and surface characteristics may contribute to the different optical responses observed in the UV–Vis spectra. However, the UV–Vis data alone do not allow the higher absorbance of commercial NCC to be directly attributed to higher crystallinity or purity.

Among the OPEFB-derived NCC samples, the sample hydrolyzed with 30 wt% H₂SO₄ exhibited a higher absorbance intensity than the sample hydrolyzed with 40 wt% H₂SO₄. This difference may be associated with differences in the chemical and physical characteristics of the NCC obtained under the two hydrolysis conditions. Increasing the sulfuric acid concentration changes the hydrolysis environment and may affect the extent of cellulose chain cleavage and the surface characteristics of the resulting NCC. These changes can influence the interaction of the material with incident UV–Vis radiation and consequently affect the measured absorbance. However, since particle size, morphology, and crystallinity were not directly characterized in this study, the observed difference in absorbance cannot be specifically attributed to changes in these structural parameters.

The observed optical behavior is further reflected in the Tauc analysis. Based on a 1 cm path length and Tauc plot analysis, the optical parameters, including wavelength, absorbance, absorption coefficient, photon energy, and band gap energy, were determined for each sample, as summarized in Table 1. The estimated band gap values show a gradual increase for the OPEFB-derived NCC samples with increasing sulfuric acid concentration.

Table 1. Optical parameters and band gap energy of commercial NCC and OPEFB-derived NCC under different sulfuric acid hydrolysis concentrations

Sample NCC	λ (nm)	A	α (cm ⁻¹)	h ν (eV)	($\alpha h\nu$) ²	E _g (eV)
Commercial	292	0.600	1.3818	4.247	34.43	4.25
OPEFB HA 30%	291	0.345	0.7945	4.261	11.46	4.26
OPEFB HA 40 wt%	289	0.134	0.3086	4.276	1.74	4.29

UV–Vis characterization results show that commercial NCC has a band gap energy of 4.25 eV, whereas NCC produced via hydrolysis with 30 wt% and 40 wt% H₂SO₄ exhibits band gap energies of 4.26 eV and 4.29 eV. The increase in band gap energy with rising acid concentration indicates a blue shift in the absorbance spectrum. The band gap energy increased slightly with increasing sulfuric acid concentration, from 4.25 eV for commercial NCC to 4.26 eV and 4.29 eV for NCC hydrolyzed with 30 wt% and 40 wt% H₂SO₄. This result indicates a change in the optical response of the NCC samples with increasing acid concentration. However, changes in crystallinity and particle size cannot be directly confirmed from the UV–Vis results alone because structural and morphological characterizations were not performed in the present study.

The band gap values obtained in this study (4.25–4.29 eV) are higher than the approximately 2.769 eV reported by Adiati et al. (2024) for an OPEFB alkali cellulose/PVA composite. This difference should be interpreted with consideration of the differences in material composition. The value reported by Adiati et al. was obtained from a cellulose-based composite containing PVA, whereas the present study investigated NCC derived from OPEFB through sulfuric acid hydrolysis without the addition of a polymer matrix. The presence of PVA and the interaction between cellulose and the polymer matrix can influence the optical response and the apparent band gap obtained from UV–Vis analysis. Differences in sample preparation and the calculation or fitting procedure used for the Tauc analysis may also contribute to variations in the obtained band gap values. Therefore, the band gap value of 2.769 eV should not be considered a direct reference value for pure NCC derived from OPEFB.

4.3. Tensile Strength Result

The mechanical properties of nanocrystalline cellulose (NCC) were characterized using a Universal Tensile Machine (UTM) to evaluate tensile strength, Young's modulus, and elongation at break (Mohamad Haafiz et al., 2016). The stress–strain curves of the three samples are presented in Figure 3, while the main mechanical parameters are summarized in Table 2. As shown in Figure 3, the three samples exhibit significantly different mechanical behaviors. The commercial NCC demonstrated the highest mechanical performance, with a tensile strength of 10.97 MPa, a Young's modulus of 0.368 GPa, and an elongation at break of 44.6%. The relatively high elongation indicates a more ductile behavior, allowing the material to undergo greater plastic deformation before fracture.

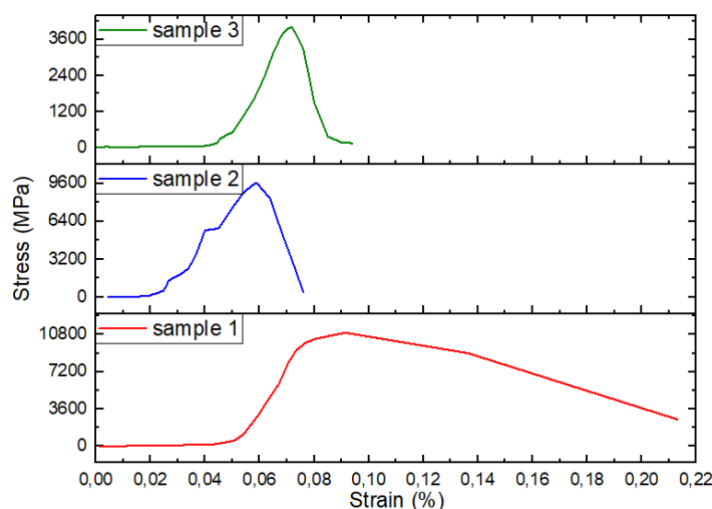


Figure 3. Comparative stress–strain behavior of commercial NCC and OPEFB-derived NCC under different sulfuric acid hydrolysis concentrations

In comparison, the NCC produced by 30 wt% H_2SO_4 hydrolysis showed a slightly lower tensile strength of 9.65 MPa, with a Young's modulus of 0.330 GPa and an elongation at break of 7.60%. The significant decrease in elongation suggests that the material became more brittle than the commercial NCC. This behavior can be attributed to the acid hydrolysis process, which partially removes the amorphous regions of cellulose, increasing crystallinity but reducing structural flexibility. Meanwhile, the NCC produced by 40 wt% H_2SO_4 hydrolysis exhibited the lowest tensile strength, measuring only 3.99 MPa, with a Young's modulus of 0.176 GPa and an elongation at break of 9.40 wt%. Although its elongation at break was slightly higher than that of the 30 wt% hydrolyzed sample, both tensile strength and modulus decreased substantially. This phenomenon indicates the occurrence of over-hydrolysis, where the higher acid

concentration caused excessive degradation of cellulose chains, reducing the structural integrity of the material.

Table 2. *Mechanical properties of commercial nanocrystalline cellulose and OPEFB-derived nanocrystalline cellulose obtained by sulfuric acid hydrolysis at different concentrations*

Sample NCC	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Commercial	10.97	0.368	44.6
H ₂ SO ₄ 30%	9.65	0.330	7.60
H ₂ SO ₄ 40 wt%	3.99	0.176	9.40

These results indicate that increasing sulfuric acid concentration during hydrolysis does not necessarily improve the mechanical properties of NCC. Although the UV–Vis analysis showed an increase in band gap energy from 4.25 eV (commercial NCC) to 4.28 eV (40 wt% H₂SO₄ hydrolysis), suggesting increased crystallinity and smaller particle size, the mechanical properties deteriorated. This demonstrates a clear trade-off between enhanced optical properties and reduced mechanical strength.

Overall, the 30 wt% H₂SO₄-hydrolyzed NCC retained mechanical properties relatively close to those of commercial NCC, while the 40 wt% H₂SO₄-hydrolyzed NCC underwent more significant structural changes, making it more suitable for applications emphasizing optical performance rather than mechanical strength.

5. Discussion

5.1. Mechanical Properties and Effect of Acid Hydrolysis

The mechanical behavior of the NCC films varied with the hydrolysis condition. The commercial NCC showed higher tensile strength and stiffness than the OPEFB-derived NCC, which may be related to differences in material origin, processing history, and film formation characteristics. The commercial NCC used in this study was prepared from microcrystalline cellulose through sulfuric acid hydrolysis, whereas the OPEFB-derived NCC underwent additional delignification and bleaching steps before hydrolysis. These differences in processing history may influence the composition, surface characteristics, and interparticle interactions within the resulting films.

The NCC obtained using 30 wt% H₂SO₄ exhibited mechanical properties relatively close to those of the commercial NCC. This behavior suggests that, under the conditions investigated, the hydrolysis treatment was able to modify the cellulose structure while maintaining sufficient structural integrity for film formation. Acid hydrolysis is generally expected to preferentially affect the less ordered regions of cellulose. However, because crystallinity was not directly characterized in the present study, the mechanical response cannot be used as direct evidence of an increase in crystallinity. The relatively high stiffness of the 30 wt% sample may instead be discussed in terms of the combined effects of cellulose chain interactions, hydrogen bonding, and the organization of the NCC film network.

A different mechanical response was observed for the sample treated with 40 wt% H₂SO₄. The substantial reduction in tensile strength and Young's modulus suggests that the higher acid concentration may have resulted in more extensive cellulose chain degradation. Prolonged or more intensive acid hydrolysis can promote cleavage of glycosidic bonds, which may reduce molecular chain length and weaken interactions within the film network. Consequently, the resulting film may have lower resistance to tensile loading. This interpretation is consistent with the observed reduction in mechanical performance, although direct evidence of molecular degradation or structural changes would require additional characterization.

The mechanical properties obtained in this study are also considerably different from those reported for individual cellulose nanocrystals. Gupta et al. (2022) reported Young's modulus values of approximately 120–220 GPa and a theoretical tensile strength of about 9.2 GPa for cellulose nanocrystals. The difference is primarily related to the scale and configuration of the materials being evaluated. The literature values refer to individual cellulose nanocrystals or intrinsic/theoretical nanoscale properties, whereas the present study evaluates macroscopic NCC films with a thickness of 200 μm . Film-level properties can be affected by particle packing, voids, particle distribution, interparticle interactions, and the film formation and drying processes. Therefore, the mechanical properties obtained in this study should be interpreted as the macroscopic behavior of NCC films rather than the intrinsic mechanical properties of individual nanocrystals.

The slightly higher elongation observed for the 40 wt% sample compared with the 30 wt% sample may indicate a change in the deformation behavior of the film. One possible explanation is that more extensive hydrolysis altered the interactions and organization of cellulose chains within the film, allowing somewhat greater deformation before fracture. Nevertheless, this interpretation remains tentative because molecular structure, morphology, and particle size were not directly characterized. The result is therefore better interpreted as a difference in macroscopic deformation behavior rather than as direct evidence of a particular structural mechanism.

5.2. Optical Properties and Band Gap

The UV–Vis results indicate that the NCC samples have similar absorption characteristics in the near-UV region, with only a small shift in the absorption maximum among the samples. The shift toward shorter wavelength with increasing sulfuric acid concentration corresponds to a slightly higher photon energy. This observation is consistent with the Tauc analysis, which showed a small increase in the estimated optical band gap for the OPEFB-derived NCC samples.

The difference in optical response between the commercial and OPEFB-derived NCC can be considered in relation to their different material origins and processing histories. The commercial NCC was derived from microcrystalline cellulose, while the OPEFB-derived NCC was obtained from a lignocellulosic biomass through sequential delignification, bleaching, and sulfuric acid hydrolysis. Such differences in processing may influence the chemical composition and surface characteristics of the resulting materials and consequently affect their interaction with incident UV–Vis radiation. However, the UV–Vis results alone do not provide sufficient evidence to attribute the differences in absorbance or band gap directly to crystallinity, particle size, or morphology.

The optical band gap obtained in the present study is higher than the value of approximately 2.769 eV reported by Adiati et al. (2024) for an OPEFB alkali cellulose/PVA composite. This difference should be interpreted in terms of the different material systems. The study by Adiati et al. investigated a composite consisting of OPEFB-derived alkali cellulose and PVA, whereas the present study investigated NCC derived from OPEFB without a PVA matrix. The presence of a polymer matrix and the interactions between cellulose and PVA can influence the optical response and the apparent band gap obtained from UV–Vis analysis. Differences in sample preparation and Tauc plot analysis may also contribute to the variation. Therefore, the reported band gap of the OPEFB cellulose/PVA composite should not be treated as a direct reference for the pure NCC investigated in this study.

The relatively narrow variation in band gap among the samples indicates that changing the sulfuric acid concentration within the investigated range produced only a modest change in the measured optical response. The observed variation should therefore be regarded as an experimental optical characteristic

of the resulting NCC rather than direct evidence of a change in crystallinity or particle size. Establishing a structural explanation for this variation would require complementary characterization techniques.

5.3. Implications for Materials Science and Applied Physics

The combined optical and mechanical results provide a materials-level perspective on the influence of acid hydrolysis conditions on OPEFB-derived NCC. The optical characterization demonstrates that the material exhibits a measurable response in the near-UV region, while the tensile measurements show that the resulting NCC can be processed into macroscopic films with different mechanical responses depending on the hydrolysis condition.

From the perspective of materials science, the simultaneous consideration of optical and mechanical properties is relevant for cellulose-based functional materials in which optical response must be accompanied by sufficient mechanical integrity. Among the hydrolysis conditions investigated, the 30 wt% H₂SO₄ treatment provided a more balanced combination of optical and mechanical characteristics than the higher acid concentration. This finding provides a useful basis for further optimization of the hydrolysis process. However, the present study evaluates the material at the characterization stage and does not directly demonstrate the fabrication or performance of an optical sensor or optoelectronic device. Therefore, the results should be considered as preliminary materials-level information for further development rather than direct evidence of device applicability. Further studies can investigate the relationship between the material properties obtained here and actual device performance.

5.4. Limitations and Future Work

A major limitation of the present study is the absence of complementary structural and morphological characterization. Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and particle-size analysis would provide additional information regarding crystallinity, morphology, and particle dimensions. These data are important for establishing a more direct relationship between sulfuric acid concentration, structural changes, optical properties, and mechanical behavior.

Accordingly, the changes in optical band gap and mechanical properties observed in this study cannot be conclusively attributed to changes in crystallinity or particle size. Future research should combine UV–Vis and tensile characterization with structural, morphological, and particle-size analyses to clarify the mechanisms underlying the effects of acid concentration. Such an integrated characterization approach would also provide a stronger basis for optimizing OPEFB-derived NCC for specific functional-material applications.

6. Conclusion

Nanocrystalline cellulose (NCC) was synthesized from oil palm empty fruit bunch (OPEFB) through sequential delignification, bleaching, and sulfuric acid hydrolysis at 30 wt% and 40 wt%. The optical and mechanical characterization showed that the hydrolysis condition influenced the properties of the resulting NCC films. The optical analysis indicated a slight variation in the absorption wavelength and optical band gap among the samples, with band gap values of 4.25 eV for commercial NCC, 4.26 eV for OPEFB-derived NCC hydrolyzed with 30 wt% H₂SO₄, and 4.29 eV for the 40 wt% sample. The mechanical characterization showed that increasing the sulfuric acid concentration resulted in a reduction in tensile strength and Young's modulus, while the elongation behavior varied between the hydrolysis conditions. Among the conditions investigated, 30 wt% H₂SO₄ provided a more balanced combination

of optical and mechanical properties. These findings demonstrate that the hydrolysis condition is an important processing parameter in controlling the properties of OPEFB-derived NCC films. However, because structural and morphological characterization was not performed, the observed changes in optical and mechanical properties cannot be directly attributed to variations in crystallinity or particle size. Further studies incorporating XRD, SEM/TEM, and particle-size analysis are therefore needed to establish the relationship between the hydrolysis condition, structural characteristics, and functional properties of OPEFB-derived NCC.

Authors Contribution

Wahyu Dian Laksanawati: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Ranti An Nisaa:** Investigation, Data curation, Validation. **Advent Triyanti Halawa:** Investigation, Formal analysis. **Novika Aszyamilatul Utami:** Writing – review & editing

Ethical statement

This study was carried out using oil palm empty fruit bunch (OPEFB) biomass as the raw material and involved only laboratory-based material preparation and characterization. No human participants, animals, or clinical procedures were involved in this research. Therefore, ethical approval was not required for this study.

Declaration of AI Use

The authors used generative artificial intelligence (GenAI) to improve the clarity and readability of the manuscript. All AI-assisted content was carefully reviewed, edited, and verified by the authors. The authors take full responsibility for the accuracy, originality, scientific integrity, and entire content of the final manuscript.

Conflict of Interest

The authors declare that there are no conflicts of interest, either financial or non-financial, related to this study. This research was carried out independently, and all findings presented in this paper reflect the authors' own work and interpretations without any external influence.

References

- Adiati, R. F., Nikmatin, S., Irmansyah, Nuradilla Putri, N., & Anandiwa, S. A. (2024). Optical and Electrical Properties of OPEFB Alkali Cellulose and PVA Composite. *Journal of Fibers and Polymer Composites*, 3(2), 91–100. <https://doi.org/10.55043/jfpc.v3i2.211>
- Asmoro, N. W., Hidayat, C., Ariyanto, T., & Millati, R. (2025). Extraction of Nanocrystalline Cellulose from Oil Palm Empty Fruit Bunches Using Sulfuric Acid Hydrolysis Method. *IOP Conference Series: Earth and Environmental Science*, 1460(1), 0–11. <https://doi.org/10.1088/1755-1315/1460/1/012022>
- Aulia, F., Marpongahtun, & Gea, S. (2013). Studi Penyediaan Nanokristal Selulosa Dari Tandan kosong sawit (TKS). *Jurnal Saintia Kimia*, 1(2), 1–5.
- Chen, Z., Yan, T., & Pan, Z. (2020). Review of Flexible Strain Sensors Based on Cellulose Composites for Multi-Faceted Applications. In *Cellulose* (Vol. 28, Issue 2). Springer Netherlands. <https://doi.org/10.1007/s10570-020-03543-6>
- Dyah Kencana Wulan, P. P., Ismojo, Khumaeroh, Syabila, A. N., Handayani, A. S., & Ratnawati. (2024). Sustainable extraction of cellulose nanocrystals from empty palm oil bunches via low-acid

hydrolysis. *Results in Engineering*, 24(July). <https://doi.org/10.1016/j.rineng.2024.103012>

- Farooq, A., Patoary, M. K., Zhang, M., Mussana, H., Li, M., Naeem, M. A., Mushtaq, M., Farooq, A., & Liu, L. (2020). Cellulose from sources to nanocellulose and an overview of synthesis and properties of nanocellulose/zinc oxide nanocomposite materials. *International Journal of Biological Macromolecules*, 154, 1050–1073. <https://doi.org/10.1016/j.ijbiomac.2020.03.163>
- Gupta, A., Khodayari, A., Van Duin, A. C. T., Hirn, U., Van Vuure, A. W., & Seveno, D. (2022). Cellulose Nanocrystals: Tensile Strength and Failure Mechanisms Revealed Using Reactive Molecular Dynamics. *Biomacromolecules*, 23(6), 2243–2254. <https://doi.org/10.1021/acs.biomac.1c01110>
- Hartati, N., Kurniawan, E., Trisna, M., & Noviarni, I. (2023). Isolasi, Karakterisasi, dan Aplikasi Nanokristal Selulosa : Review. *Sains Sutha Journal*, 1(2), 29–38.
- Hidayah, N., & Wusko, I. U. (2020). Characterization and Analysis of Oil Palm Empty Fruit Bunch (OPEFB) Waste of PT Kharisma Alam Persada South Borneo. *Traditional Medicine Journal*, 25(3), 154–158. <https://doi.org/10.22146/mot.52715>
- Indarti, E., Marwan, & Wan Rosli, W. D. (2019). Morphological and Optical Properties of Polylactic Acid Bionanocomposite Film Reinforced with Oil Palm Empty Fruit Bunch Nanocrystalline Cellulose. *Journal of Physics: Conference Series*, 1295(1). <https://doi.org/10.1088/1742-6596/1295/1/012053>
- Ismail, F., Othman, N. E. A., & Wahab, N. A. (2023). Morphology and Dispersion Stability of Nanocellulose Extracted from Oil Palm Empty Fruit Bunch Fibre by High-Pressure Homogenization. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 102(2), 120–128. <https://doi.org/10.37934/arfmts.102.2.120128>
- Kamel, S., & Khattab, T. (2020). Recent Advances in Cellulose-Based Biosensors for Medical Diagnosis. *Biosensors*, 10(67), 1–26. <https://doi.org/10.3390/bios10060067>
- Maghfirah, A., Fahma, F., Lisdayana, N., Yunus, M., Kusumaatmaja, A., & Kadja, G. T. M. (2022). On the Mechanical and Thermal Properties of Poly(Vinyl Alcohol) – Alginate Composite Yarn Reinforced with Nanocellulose from Oil Palm Empty Fruit Bunches. *Indonesian Journal of Chemistry*, 22(1), 114–125. <https://doi.org/10.22146/ijc.67881>
- Mohamad Haafiz, M. K., Hassan, A., Arjmandi, R., Marliana, M. M., & Nurul Fazita, M. R. (2016). Exploring the potentials of nanocellulose whiskers derived from oil palm empty fruit bunch on the development of polylactid acid based green nanocomposites. *Polymers and Polymer Composites*, 24(9), 729–734. <https://doi.org/10.1177/096739111602400908>
- Mohammad Padzil, F. N., Lee, S. H., Ainun, Z. M. A. ari, Lee, C. H., & Abdullah, L. C. (2020). Potential of oil palm empty fruit bunch resources in nanocellulose hydrogel production for versatile applications: A review. *Materials*, 13(5). <https://doi.org/10.3390/ma13051245>
- Moon, R. J., Martini, A., Nairn, J., Simonsen, J., & Youngblood, J. (2011). Cellulose nanomaterials review: Structure, properties and nanocomposites. In *Chemical Society Reviews* (Vol. 40, Issue 7). <https://doi.org/10.1039/c0cs00108b>
- Orelma, H., Hokkanen, A., Leppänen, I., Kammiovirta, K., Kapulainen, M., & Harlin, A. (2020). Optical cellulose fiber made from regenerated cellulose and cellulose acetate for water sensor applications. *Cellulose*, 27(3), 1543–1553. <https://doi.org/10.1007/s10570-019-02882-3>
- Poulose, A., Parameswaranpillai, J., George, J. J., Gopi, J. A., Krishnasamy, S., Dominic C. D, M., Hameed, N., Salim, N. V., Radoor, S., & Sienkiewicz, N. (2022). Nanocellulose: A Fundamental

Material for Science and Technology Applications. *Molecules*, 27(22), 1–27.
<https://doi.org/10.3390/molecules27228032>

Shanmugarajah, B., Kiew, P. L., Chew, I. M. L., Choong, T. S. Y., & Tan, K. W. (2015). Isolation of Nanocrystalline Cellulose (NCC) from palm oil empty fruit bunch (EFB): Preliminary result on FTIR and DLS analysis. *Chemical Engineering Transactions*, 45, 1705–1710.
<https://doi.org/10.3303/CET1545285>

Yuni Hendrawati, T., Umar, E., Ilmar Ramadhan, A., Meta Sari, A., Salsabila, M., Suryani, R., & Budhi Rahardja, I. (2023). Sintesis Dan Karakterisasi Nanoselulosa Serbuk Dari Tandan Kosong Kelapa Sawit Menggunakan Ultrasonifikasi. *Jurnal Teknologi*, 15(1), 160–166.
<https://dx.doi.org/10.24853/jurtek.15.1.159-166>