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Enhancing the Quality of Cellulose Isolated from Banana Peels by Incorporating the Use of Microwave Radiation over the Conventional Method

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ABSTRACT

Cellulose, a renewable biopolymer, can be sustainably extracted from agricultural residues such as banana peels, which are plentiful yet often discarded as waste. Traditional extraction methods are laborious, require prolonged heating, and consume large quantities of chemicals, posing environmental and economic concerns. In this study, a microwave-assisted technique was explored for cellulose extraction from banana peels and compared with conventional thermal treatment under identical chemical conditions. The process involved sequential liquefaction, delignification, and bleaching, with microwave radiation applied at 600 W. Results showed that microwave-assisted extraction significantly improved efficiency, yielding 86.43% cellulose compared to approximately 83% with conventional methods, while reducing processing time from 455 min to just 22 min (excluding 14 min for cycle repetition). FTIR analysis confirmed effective removal of lignin and hemicellulose, XRD indicated preservation of cellulose structure with a crystallinity index of 56.8%, and SEM images revealed smoother, cleaner, and similarly textured cellulose in microwave-treated samples compared to conventional ones. These findings demonstrate that microwave radiation not only enhances cellulose purity and structural quality but also offers significant benefits in energy savings and process sustainability. The resulting cellulose is suitable for applications in packaging, composites, and nanocellulose production. This research establishes microwave-assisted treatment as a scalable, eco-friendly, and time-efficient alternative to traditional methods for converting banana peel waste into high-value cellulose.

1. INTRODUCTION

Cellulose is the most abundant natural polymer, and banana peels are a promising agricultural waste resource for its sustainable extraction. With increasing demand for environmentally friendly and cost-effective methods, microwave radiation has become an efficient alternative. Microwaves enable rapid and uniform heating, which enhances delignification and hemicellulose removal, thereby decreasing both processing time and chemical use compared to traditional hot-plate or reflux techniques.

Microwave-assisted isolation significantly reduces processing time from h to min while producing cellulose with high purity, crystallinity, and thermal stability. This method exploits the abundant availability of banana peels and addresses waste management issues, promoting the valorization of agricultural residues. Consequently, microwave radiation has gained recognition as an environmentally friendly and scalable technique for cellulose extraction, offering benefits in energy efficiency, process sustainability, and potential uses in biocomposites, films, and nanocellulose production.

Compared to traditional heating methods, microwave radiation provides several advantages that make it preferable for extracting cellulose from banana peels.

Conventional processes depend on external conduction and convection, resulting in slow, uneven heating, higher chemical consumption, and longer treatment times. In contrast, microwave energy penetrates directly into the material, inducing rapid molecular vibrations and volumetric heating. This accelerates delignification and hemicellulose removal while reducing cellulose degradation.

By employing microwave-assisted treatment, the process also lowers water consumption and wastewater generation, decreasing the environmental impact of cellulose production due to the use of lower reagent concentrations. Additionally, this method yields highly crystalline and pure cellulose suitable for advanced applications such as biocomposites, packaging films, and nanocellulose-based materials. Overall, microwave radiation offers a greener, cost-effective, and scalable approach for transforming banana peel waste into valuable cellulose resources, supporting sustainable material recovery and the circular economy.

Banana processing generates significant amounts of lignocellulosic residues such as peels, pseudostems, and rachis, which are rich in cellulose but often considered waste. Numerous studies have shown that these residues can be sustainable sources for cellulose extraction. Traditional methods typically involve sequential solvent extraction, alkaline delignification, and oxidative bleaching, resulting in cellulose appropriate for paper manufacturing, bio-composites, and reinforcement materials (Li et al. 2015, Malinen et al. 2014, Faradilla et al. 2016). However, these approaches are time-consuming, energy-intensive, and use large quantities of chemicals, which challenge their economic viability and environmental impact (Alkhorayef et al. 2020, Elanthikkal et al. 2010). Characterization techniques such as FTIR, XRD, and SEM have consistently verified the effective removal of hemicellulose and lignin and the recovery of cellulose with moderate to high crystallinity under these conventional treatments (Szymańska-Chargot et al. 2017, Yadav & Chiu 2019).

Recent research has further emphasized the potential of agro-waste–derived cellulose for valuable applications. Ma'ruf et al. (2023) demonstrated the transformation of cassava peel into functional cellulose acetate membranes, confirming agro-waste as a promising source of cellulose materials with added value. Similarly, Yadav & Pal (2025) found that NaCl pretreatment significantly improved biomass conversion efficiency in cabbage waste. While these studies focus on chemical modification and pretreatment techniques, the impact of microwave-assisted extraction on the quality of cellulose remains underexplored.

Building on this context, the present study aims to isolate cellulose from banana peels using both traditional reflux techniques and a microwave-assisted process at 600 W. This allows for a direct comparison of efficiency and product quality. Specifically, the objectives are: (i) to optimize the steps of liquefaction, delignification, and bleaching for banana peel biomass under both conventional and microwave conditions, (ii) to evaluate and compare the yield, purity, and structural features of the cellulose obtained by each method, and (iii) to explore the potential benefits of microwave-assisted treatment in terms of energy use, processing time, and sustainability. Through these aims, the research seeks to demonstrate microwave radiation as an eco-friendly alternative for converting banana peel waste into high-value cellulose.

To address these limitations, microwave-assisted processing has increasingly been adopted as a method for process intensification. Microwave radiation facilitates rapid volumetric heating, boosting alkali penetration and lignin removal, which shortens reaction times from h to min (Ndruru et al. 2019, Zhou et al. 2017). Comparative research indicates that microwave-assisted delignification and bleaching can produce comparable or higher cellulose purity while using lower chemical dosages and significantly reducing energy consumption (Sudiana et al. 2017, Esmaeili et al. 2017, Rasheed et al. 2019). Studies on banana residues and other agro-wastes such as rice husk, sugarcane bagasse, and almond shells demonstrate the broad applicability of this approach (Meng et al. 2018, Moradian et al. 2017). Typically, optimized protocols utilize mild alkali concentrations (2–6% NaOH) with short radiation cycles at 600–800 W and limited repetitions, followed by peroxide bleaching at alkaline pH (Kumar et al. 2021). These conditions strike a balance between efficiency and cellulose preservation, whereas excessive power or prolonged exposure may lead to depolymerization or fiber damage (Li et al. 2018). In terms of material quality, cellulose produced through microwave-assisted methods shows enhanced whiteness and brightness, increased crystallinity, and cleaner fiber surfaces relative to conventionally treated samples (Xie et al. 2016, Beltramino et al. 2016, Lani et al. 2016). Morphological analyses further confirm reduced lignin encrustation and improved fibrillation readiness, which benefit subsequent nanocellulose production (Rahman et al. 2017). The nanocellulose derived from this process exhibits high aspect ratios, excellent crystallinity, and thermal stability, making it ideal for reinforcing biopolymer films, hydrogels, and packaging materials (Jonoobi et al. 2015, Kargarzadeh et al. 2017). Beyond enhancing product properties, microwave-assisted techniques address sustainability by decreasing energy consumption, reaction duration, and wash water volumes, thus reducing the environmental footprint (Bastos et al. 2020, Bilal & Iqbal 2019).

Despite these advantages, gaps remain in the existing literature. Many studies vary multiple process factors simultaneously, making direct comparisons between microwave and conventional heating difficult (Park et al. 2010, Pereira et al. 2015). Additionally, comprehensive energy balances and techno-economic assessments are limited, and scale-up challenges such as uneven heating and penetration depth require further investigation (Borovikova et al. 2015, Liu et al. 2018). Furthermore, there is a lack of systematic studies linking the structural properties of banana-derived cellulose to its performance in end-use applications (Choi et al. 2020, Gañán et al. 2012). In this context, the present study aims to directly compare conventional and microwave-assisted cellulose extraction from banana peels, using identical chemical treatments. By standardizing alkali and bleaching conditions while only varying the heating mode, this research seeks to provide clear insights into yield, purity, crystallinity, morphology, and sustainability, thereby assessing the true potential of microwave radiation as a green and efficient alternative for cellulose valorization from banana waste.

2. MATERIALS AND METHODS

2.1. Materials and Experimental Setup

Banana peels, sourced locally, were thoroughly washed, chopped into small pieces, and treated with potassium meta-bisulphite to inhibit microbial growth. The material was then shade-dried, ball-milled, and sieved to produce a consistent 200-mesh powder. Reagents used included analytical-grade ethanol, potassium hydroxide (KOH), 30% hydrogen peroxide, and a mild acid for neutralization. The equipment utilized comprised a laboratory microwave oven (ME731K / XEU Solo, 20 L), a hot air oven, a vacuum filtration apparatus, and standard laboratory glassware.

2.2. Methodology

Cellulose isolation was performed through three consecutive steps: liquefaction, delignification, and bleaching. To facilitate a direct comparison, identical chemical protocols were applied for both conventional and microwave treatments. Lower-strength chemicals were employed in microwave-assisted extraction (MAE). The total chemical quantities were divided into smaller portions, and multiple extraction methods were used to introduce novelty into the process. Furthermore, instead of utilizing high-energy radiation (W), comparatively lower-energy microwave radiation was applied over extended periods to enhance the extraction process.

- Liquefaction was performed by suspending ten gs of banana peel powder in 100 mL of 10% ethanol, followed by microwave heating at 600 W for 2 min, with the cycle repeated three times. MAE was conducted across a power range of 500 W to 800 W, and experimental optimization showed that cellulose yield increased with microwave power up to 600 W. Beyond this level, no significant improvements were observed, and signs of thermal degradation appeared, justifying the selection of 600 W as the optimal microwave power. The results aligned with those reported by Kumar et al. (2021). For comparison, conventional extraction involved refluxing 200 mL of 70% ethanol at 70°C for 2–3 h. Under microwave irradiation, rapid darkening of the liquor and browning of the residue indicated efficient removal of soluble extractives in a much shorter time than conventional heating (see Fig. 1).
- Delignification: The liquefied residue was treated with 100 mL of 3% KOH at a solid-to-liquid ratio of 1:20 and subjected to microwave heating at 600 W for 3 min, with the cycle repeated twice. The treated biomass became light tan, adopted a fibrous texture, and was rinsed to neutral pH with fewer washing cycles than conventionally treated material. In contrast, traditional delignification using 200 mL of 4% KOH at 80–90°C required two hours to achieve similar results. The flowchart (Fig. 1) gives the overall methodology for cellulose isolation from banana peels.
- Bleaching: The alkali-treated residue was treated with 3% hydrogen peroxide (100 mL), adjusted to an alkaline pH (10–11), and irradiated at 600 W for 4 min, repeated twice. After two cycles, the sample became off-white, and the filtrate was nearly colorless, indicating removal of residual lignin chromophores. In comparison, conventional bleaching required 200 mL of 10% H_2O_2 at 70°C for 4 h to achieve similar whiteness (Fig. 1).

Neutralization and thorough washing ensured removal of residual chemicals, and controlled drying preserved the integrity of the cellulose fibers.

FTIR, XRD, and SEM analyses were utilized for characterization to verify the removal of non-cellulosic components, assess crystallinity, and observe morphological changes in the treated samples. The final comparative analysis highlighted differences in yield, reaction time, reagent consumption, and cellulose quality between conventional and microwave-assisted methods. This systematic approach not only confirms microwave radiation as a faster and more energy-efficient technique but also underscores its potential for sustainable biomass valorization.

2.3. Characterization of Cellulose

2.3.1. FTIR Spectroscopy

When both the samples were subjected to FTIR Model Ruker alpha Eco-ATR, the spectra observed are shown in Fig. 2.

Banana peel collection
→ Washing → Drying (60°C) → Grinding & sieving (<1 mm), milling

Liquefaction (Defatting)
→ Conventional: 10 g Banana Peel Powder + 200 mL, 70% Ethanol at 70°C, 2–3 h
→ Microwave: 10 g Banana Peel Powder+ 300 mL (3X100 mL), 10% Ethanol 600 W, 3×2 min cycles

Delignification (Alkali treatment)
→ Conventional: 200 mL 4% KOH, 80–90°C, 3 h
→ Microwave: 200 mL (2x100 mL) 3% KOH 600 W, 2×4 min cycles

Bleaching
→ pH 10–11
→ Conventional: 200 mL 10% H2O2, 70°C, 2 h
→ Microwave: 200 mL 3% H202, 600 W, 2–4 min cycles

Neutralization & Washing
→ Distilled water rinse until pH ~7

Drying
→ Oven at 60°C

Characterization
→ FTIR, XRD, SEM

Comparative Analysis
→ Yield, Purity, Energy, Time, Sustainability

Fig. 1: Research methodology flowchart: Cellulose isolation from banana peels.

The FTIR spectrum of the microwave-treated cellulose, as presented in Table 1, showed the disappearance of the lignin-associated bands at ~1519 cm^{-1} and ~1247 cm^{-1}, confirming the removal of aromatic C=C and carbonyl groups. At the same time, the characteristic cellulose absorption bands were retained, including ~1161 cm^{-1} (C–O–C stretching), ~1052 cm^{-1} (C–O stretching), and ~898 cm^{-1} (β-(1→4) glycosidic bond). These spectral changes confirmed effective delignification and successful isolation of cellulose.

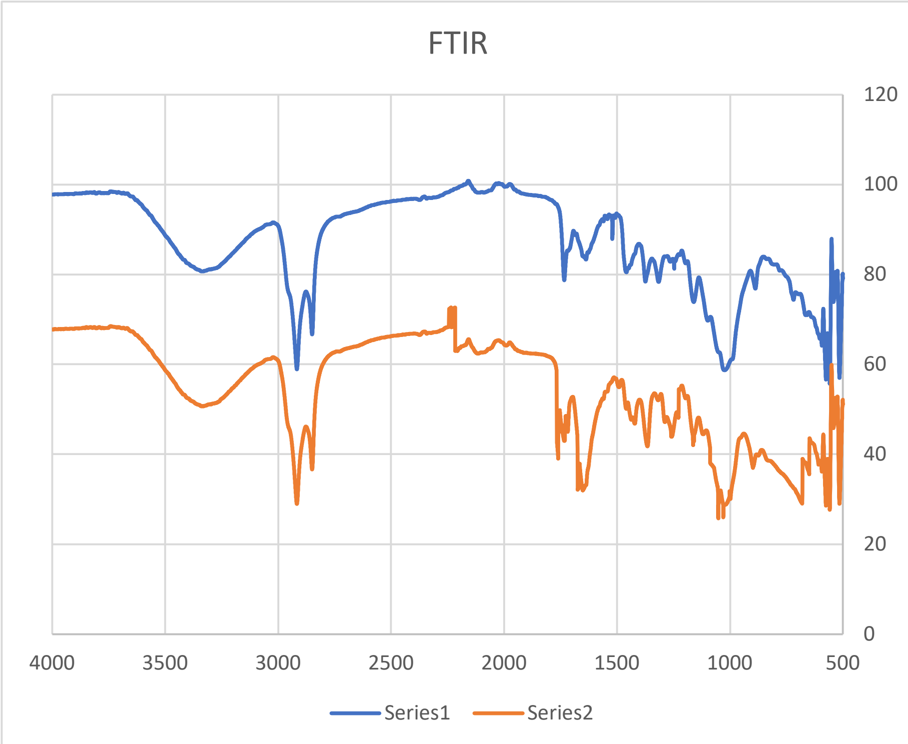
2.3.2. Scanning Electron Microscopy (SEM)

SEM was used to examine the surface morphology of cellulose fibers obtained from banana peels. FESEM: JEOL JSM-IT 200 was used to find particle size and surface morphology. The untreated fibers appeared compact, rough, and covered with impurities such as lignin, hemicellulose, and mineral deposits, with fiber sizes often exceeding 200 µm. After conventional chemical treatment, partial cleaning was observed; however, the fibers remained irregular and rough, with embedded fragments, as seen in Fig. 3, and diameters ranging from 10–200 µm, indicating incomplete removal of non-cellulosic components.

Compared to traditional methods, cellulose isolated using microwave radiation at 600 W showed significantly improved morphology. The fibers were cleaner, smoother, and exhibited partial fibrillation, with fewer surface deposits and enhanced uniformity. Fiber diameters ranged from 5 to 100 µm, as detailed in Table 2, reflecting effective delignification and hemicellulose removal. These morphological enhancements are linked to higher cellulose purity of 86.43% and crystallinity of 56.8%, both achieved at 600 W.

2.3.3. XRD Analysis

XRD analysis was conducted to determine the crystalline structure and crystal size of the isolated cellulose using



Series 1: Conventional Method, Series 2: Microwave Method

Fig. 2: FTIR absorption spectra by two methods.

Table 1: Analytical interpretation of FTIR spectral features of microwave-treated cellulose.

Wavenumber [cm⁻¹]	Assigned functional group/vibration	Analytical implication	Structural inference
~1519	Aromatic C=C stretching (lignin)	Complete disappearance indicates disruption of the aromatic lignin framework	Confirms effective removal of lignin-rich aromatic domains
~1247	C–O stretching of aryl–alkyl ether/ carbonyl groups (lignin/hemicellulose)	Loss of peak reflects cleavage of lignin–carbohydrate linkages	Demonstrates selective delignification and hemicellulose elimination
~1161	C–O–C asymmetric stretching (cellulose backbone)	Persistence of the band indicates chemical stability of cellulose chains	Confirms preservation of the cellulose polymeric framework
~1052	C–O stretching (pyranose ring of cellulose)	Retained intensity signifies intact glucose ring structure	Indicates negligible cellulose depolymerization during microwave treatment
~898	β-(4→1) glycosidic linkage	Presence confirms maintenance of inter-unit linkage	Demonstrates retention of native cellulose connectivity

a Rigaku MiniFlex instrument with Cu Kα radiation (λ= 1.54059Å). The diffractogram of cellulose isolated at 600 W displayed prominent peaks, as shown in Fig. 4, at approximately 22.0–22.5° 2θ, which are characteristic of cellulose. The calculated crystallinity index was 56.8% for cellulose extracted via the MAE method, indicating a higher crystalline content compared to cellulose obtained by the conventional method, which was 37.48%. These results are consistent with reports in the literature for banana pseudostem cellulose (Faradilla et al. 2016, Hayati et al. 2017), suggesting that microwave pretreatment effectively removed amorphous lignin and hemicellulose while preserving the crystalline structure of cellulose.

Crystallinity index for Conventional Method: (Series-I)

Crystallinity Index (CrI) Calculation (Segal Method)

The crystallinity index of cellulose was calculated using the Segal method, expressed as:

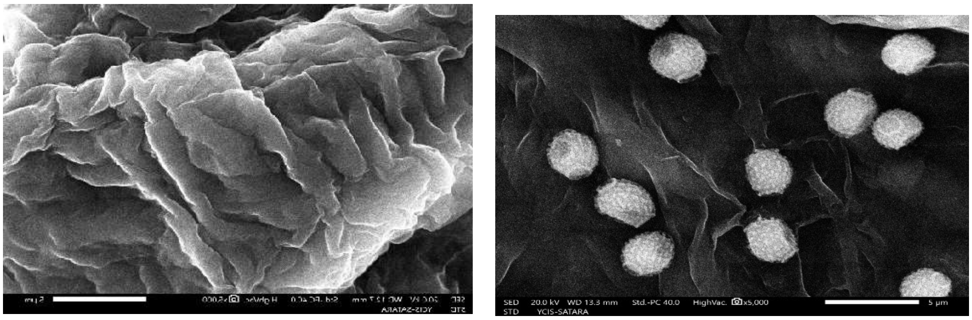
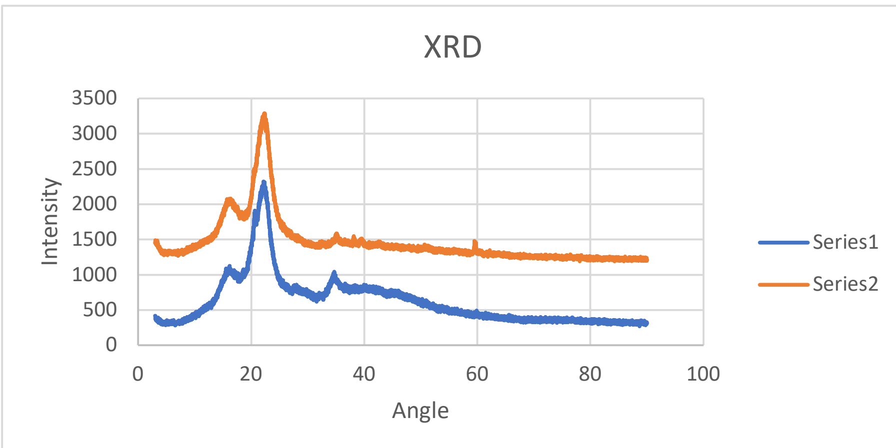


Fig. 3: SEM of cellulose by conventional and microwave methods.

Table 2: Quantitative fibre size distribution.

Sample	Diameter range [μm]	Mean diameter [μm]	Distribution characteristic
Conventional treatment	10–200	~95	Broad, heterogeneous distribution
Microwave treatment (600 W)	5–100	~42	Narrow, uniform distribution



Series 1: Microwave Method, Series 2: Conventional Method

Fig. 4: X-Ray diffraction spectra for cellulose.

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

Where:

- I_{200} is the maximum intensity of the (200) crystalline peak at $2\theta \approx 22.6°$
- I_{am} is the intensity of the amorphous region, typically taken at $2\theta \approx 18°$

From Fig. 4:

- $I_{200} \approx 3215$ (strongest peak at 22.6) for
- $I_{am} \approx 2010$ (average of the nearby medium-intensity region)

Calculated Crystallinity Index

$$\mathrm{CrI} = \frac{3215 - 2010}{3215} \times 100 = 37.48\%$$

The crystallinity index of the cellulose sample was determined to be approximately 37.48%, reflecting a crystalline structure with a balanced mix of crystalline and amorphous regions. This level of crystallinity supports mechanical stability while preserving adequate flexibility.

Crystallinity index for the microwave-assisted extraction method:

Crystallinity Index (CrI) calculation (Segal Method)

The crystallinity index of cellulose was calculated using the Segal method, expressed as:

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

Where:

- I_{200} is the maximum intensity of the (200) crystalline peak at $2\theta \approx 22.6°$,

- I_{am} is the intensity of the amorphous region, typically taken at $2\theta \approx 18°$.
- From Fig. 4
- $I_{200} \approx 3215$ (strongest peak at 22.6) for
- $I_{am} \approx 2010$ (average of the nearby medium-intensity region)

Calculated Crystallinity Index

$$CrI = \frac{2350 - 1015}{2350} \times 100 = 56.8\%$$

The crystallinity index of the cellulose sample was determined to be approximately 56.8%, reflecting a crystalline structure with a balanced mixture of crystalline and amorphous regions. This level of crystallinity effectively supports mechanical stability while maintaining adequate flexibility, which is beneficial for membrane fabrication and related material applications.

2.3.4. Quantitative Outcomes at 600 W Microwave Radiation with MAE

Lignin content significantly decreased in the microwave-treated sample, as evidenced by its lighter appearance and enhanced washing efficiency detailed in Table 3. The product yield and quality at 600 W surpassed those achieved by conventional methods, despite the notably shorter treatment duration. Microwave-Assisted Extraction (MAE) conserves approximately 78.57% of ethanol, 25% of alkali, and 70% of H_2O_2. Overall, MAE reduces chemical waste load by 58%.

Though direct energy metering was not conducted, energy consumed was statistically calculated considering power and time. Total energy consumption was reduced from 7.5 kWh to 0.17 kWh with the microwave method (approximately 97.7%) compared to the conventional heating method, as shown in Table 3.

Fig. 5 illustrates the comparison between cellulose content (%) and processing time (min) achieved through conventional heating and microwave-assisted isolation at 600 W. The blue bar chart depicts cellulose content, while the red line plot shows the corresponding processing time for each method.

All experiments were performed in triplicate, with results expressed as mean ± standard deviation. Conventional extraction produced an average cellulose content of 83.12 ± 0.68%, whereas microwave-assisted extraction yielded 86.43

Table 3: Comparison of conventional and microwave (600 W) cellulose isolation.

Method	Conditions	Cellulose content [%]	Processing time	Product appearance	Crystallinity Index [%]	Chemicals Consumed per 10 g bpp
Microwave	600 W, 22 min [i.e. 0.17 kWh]	86.43	22 min	Off-white, fibrous	56.8	Ethanol [30 mL], KOH [6 g], H_2O_2 [6 mL]
Conventional	80–90°C, 7.5 h [i.e. 7.5 kWh]	~83.0	455 min	Tan, less uniform	37.48	Ethanol [140 mL], KOH [8g], H_2O_2 [20 mL]

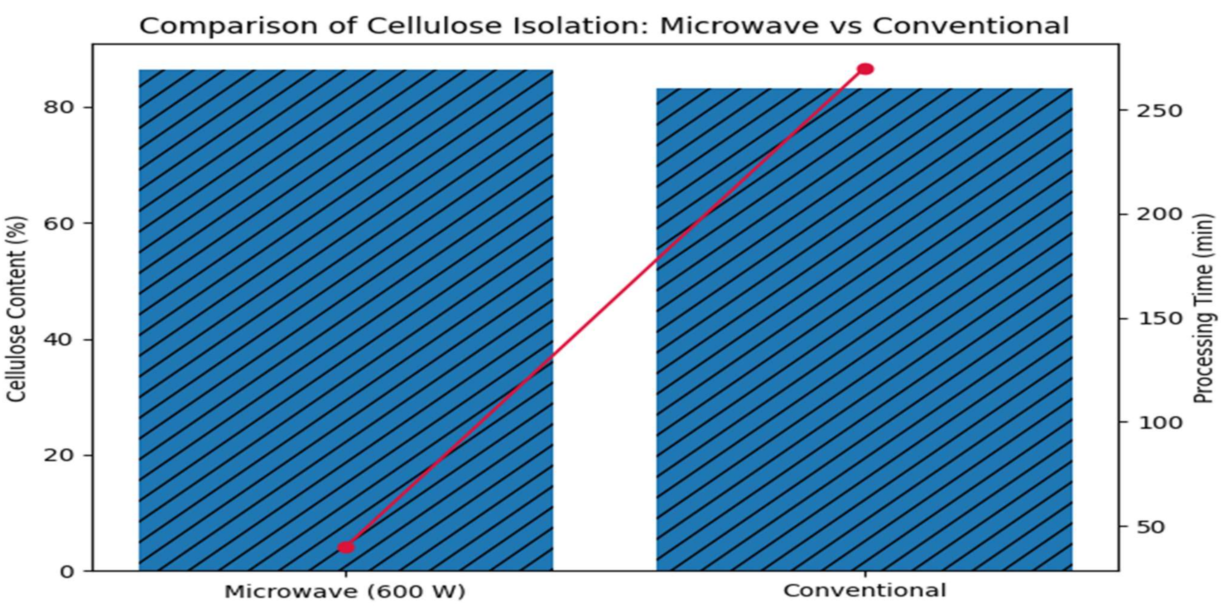


Fig. 5: Comparison of cellulose isolation w. r. t. Time and percentage of cellulose for both methods.

± 0.51%. The standard deviations were calculated using the sample standard deviation formula to assess variability among replicates. An independent two-tailed Student's t-test was conducted to determine if the difference in cellulose content between methods was statistically significant. The test revealed a mean difference of 3.31%, a t value of 6.32, and 4 degrees of freedom. The corresponding two-tailed p value ($p = 0.0032$), obtained from the Student's t distribution, was below the 0.05 significance level, indicating that microwave-assisted extraction significantly increased cellulose content. Although the numerical difference was modest, the results were reproducible and supported by rigorous statistical validation.

3. RESULTS AND DISCUSSION

3.1. Effect of Microwave Radiation on Cellulose Yield

Cellulose was effectively extracted from banana peel powder using 600 W microwave radiation, with results compared to those obtained through traditional chemical treatment. The microwave-assisted process yielded a cellulose content of 86.43%, surpassing the approximately 83% achieved via conventional methods. This higher yield was due to the rapid volumetric heating caused by microwaves, which improved delignification and hemicellulose removal. Furthermore, the overall processing time was significantly reduced from 455 min (7.5 h) with the conventional method to just 22 min with microwave aid, a reduction exceeding 95%. This clearly demonstrates the process intensification enabled by microwave heating, resulting in higher cellulose purity and enhanced time efficiency. The advantages are attributed to the microwave's unique heating mechanism, which involves direct energy coupling with polar molecules, inducing volumetric heating through dipole rotation and ionic conduction. This rapid heating accelerates bond cleavage, chromophore degradation, and mass transfer, facilitating faster delignification and bleaching.

3.2. Structural and Chemical Analysis (FTIR and XRD)

The structural and chemical properties of cellulose extracted from banana peels were examined using FTIR and XRD techniques. The FTIR spectrum of the microwave-treated cellulose showed the disappearance of lignin-related peaks at 1519 cm^{-1} and 1247 cm^{-1}, indicating successful delignification and hemicellulose removal. Meanwhile, characteristic cellulose absorption bands at 1161 cm^{-1} (C–O–C pyranose ring), 1052 cm^{-1} (C–O stretching), and 898 cm^{-1} (β-(1→4) glycosidic linkage) remained, signifying the cellulose structure was preserved. XRD analysis confirmed the presence of native cellulose polymorph, with distinct diffraction peaks at $2\theta \approx 22.0–22.5°$, and a crystallinity index of 56.8%, slightly higher than that of conventionally treated samples. This reflects the removal of amorphous regions and the formation of a more ordered structure. Overall, these findings demonstrate that microwave-assisted isolation enhances the purity and structural order of cellulose while significantly reducing processing time compared to traditional methods.

3.3. Surface Morphology (SEM Analysis)

SEM observations corroborated the spectroscopic results. Untreated banana peel fibers displayed compact, rough surfaces with apparent deposits of lignin and hemicellulose. Following conventional treatment, the surface maintained irregular textures and embedded debris, with diameters spanning 10–200 μm. Conversely, microwave-treated cellulose at 600 W demonstrated smoother surfaces, exposed fibrils, and uniform fiber bundles, with diameters reduced to 5–100 μm. This cleaner, fibrillated morphology aligned with increased cellulose content and crystallinity. The cellulose subjected to conventional treatment showed irregular fiber surfaces with rough textures and residual particles, indicating incomplete lignin and hemicellulose removal. Fiber bundles appeared partially compacted and fragmented, with deposits visible on the surface. These features suggest that, despite prolonged heating, the conventional process only achieved partial delignification and limited fibrillation. In contrast, the microwave-assisted sample exhibited cleaner, smoother, and more fibrillated fibers. The surface was uniform, with fewer impurities and clearer microfibril exposure. Microwave treatment effectively disrupted lignin–carbohydrate linkages, enhancing fiber separation and surface purification. Overall, SEM analysis confirms that microwave-assisted isolation markedly improves surface morphology, yielding cellulose with cleaner surfaces better suited for downstream applications such as nanocellulose production and composite reinforcement.

3.4. Comparative Performance and Sustainability

Overall, microwave-assisted isolation at 600 W yielded cellulose with higher purity, enhanced crystallinity, and improved morphology in a fraction of the time required by conventional heating. Using less concentrated solutions also reduces pollutant loads in wastewater. Additionally, the shorter process and fewer washing cycles lead to lower energy and water consumption, making this method more environmentally sustainable. These benefits position microwave radiation as a scalable and eco-friendly alternative for extracting cellulose from agro-waste, such as banana peel.

4. CONCLUSIONS

This study demonstrated the successful extraction of cellulose from banana peels using microwave radiation at 600W, providing a superior alternative to traditional thermal methods. The microwave-assisted approach achieved a higher cellulose content (86.43%) with enhanced crystallinity (56.8%) and cleaner fiber morphology, while drastically reducing processing time by 95%. FTIR analysis confirmed the effective removal of lignin and hemicellulose, XRD verified the preservation of cellulose I structure, and SEM images showed smoother, fibrillated fibers compared to conventional samples.

The results clearly position microwave radiation as a quick (saving around 95% of processing time), energy-efficient (approximately 97.7% energy saving) method compared to conventional heating, highlighting its superiority in energy conservation and sustainability for cellulose isolation. Additionally, chemical waste was reduced by 58%, which lowered water consumption during washing and cleaning steps. This method not only improves yield and quality but also promotes waste valorization and environmental sustainability. The cellulose produced is suitable for diverse applications such as biocomposites, packaging films, and nanocellulose production.

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6. REFERENCES

Alkhorayef, M., Al-Zahrani, S.M. and Khan, W.S., 2020. Microwave-assisted extraction and characterization of cellulose nanocrystals from agricultural residues: a review. *Cellulose*, 27(16), pp.9157-9179. [DOI]

Bastos, V., Costa, A.O.S., Silva, R.F., Tavares, T. and Pintado, M.E., 2020. Microwave-assisted pretreatment of lignocellulosic biomass for bioethanol production: a review. *Renewable and Sustainable Energy Reviews*, 119, p.109564. [DOI]

Beltramino, F., Roncero, M.B., Vidal, T., Valls, C. and Montané, D., 2016. Extraction and characterization of cellulose nanocrystals from soybean hulls by microwave-assisted treatments. *Carbohydrate Polymers*, 153, pp.236-243. [DOI]

Bilal, M. and Iqbal, H.M.N., 2019. Lignocellulosic biomass: green fuels, chemicals and materials via integrated biorefinery approaches. *Renewable and Sustainable Energy Reviews*, 107, pp.123-132. [DOI]

Borovikova, E., Pantic, M., Kostic, M. and Nikolic, T., 2015. Microwave-assisted production of cellulose nanocrystals. *Carbohydrate Polymers*, 122, pp.280-288. [DOI]

Choi, S., Lee, D. and Kim, J., 2020. Isolation of cellulose nanofibers from banana peel and their reinforcement effect in biodegradable films. *Industrial Crops and Products*, 155, p.112799. [DOI]

Elanthikkal, S., Gopalakrishnapanicker, U., Varghese, S. and Guthrie, J.T., 2010. Cellulose microfibres produced from banana plant wastes: isolation and characterization. *Carbohydrate Polymers*, 80(3), pp.852-859. [DOI]

Esmaeili, H., Hashemi, S.J., Esmaeilzadeh, Z. and Yeganeh, A., 2017. Microwave-assisted delignification and nanofibrillation of lignocellulosic fibers. *Industrial Crops and Products*, 109, pp.241-248. [DOI]

Faradilla, R.H.F., Lee, G., Rawal, A., Hutomo, T., Stenzel, M.H. and Arcot, J., 2016. Nanocellulose characteristics from the inner and outer layer of banana pseudostem prepared by TEMPO-mediated oxidation. *Cellulose*, 23(5), pp.3023-3037. [DOI]

Gañán, P., Cruz, J., Garbizu, S., Arbelaiz, A., Llano-Poncio, C. and Mondragon, I., 2012. Treatment of banana fiber for use in composite materials. *Composites Part B: Engineering*, 43(4), pp.1909-1916. [DOI]

Hayati, N., Rahman, A., Chieng, B.W. and Rahman, N.A., 2017. Extraction and characterization of cellulose nanocrystals from tea leaf waste fibers. *Polymers*, 9(11), p.588. [DOI]

Jonoobi, M., Harun, J., Mathew, A.P., Hussein, M.Z.B., Oksman, K. and Dufresne, A., 2015. Comparative study of cellulose nanofiber and nanocrystal production from different biomass sources. *Cellulose*, 22(2), pp.935-951. [DOI]

Kargarzadeh, H., Mariano, M., Huang, J., Lin, N., Ahmad, I., Dufresne, A. and Thomas, S., 2017. Recent developments in nanocellulose-based biodegradable polymers and nanocomposites. *Carbohydrate Polymers*, 181, pp.403-416. [DOI]

Kumar, A., Negi, Y.S., Bhardwaj, N.K. and Choudhary, V., 2021. Microwave-assisted extraction of cellulose from pineapple leaf waste. *International Journal of Biological Macromolecules*, 190, pp.208-218. [DOI]

Lani, N.S., Ngadi, N., Johari, A. and Jusoh, M., 2016. Isolation, characterization and application of nanocellulose from banana fiber: a review. *Cellulose*, 23(4), pp.2191-2212. [DOI]

Li, T., Chen, C., Broda, S. and Lozano-García, D.F., 2018. High-efficiency microwave-assisted delignification of wheat straw. *Bioresource Technology*, 268, pp.390-396. [DOI]

Li, W., Zhang, Y., Li, J., Zhou, Y., Li, R. and Zhou, W., 2015. Characterization of cellulose from banana pseudostem by heterogeneous liquefaction. *Carbohydrate Polymers*, 132, pp.513-519. [DOI]

Liu, H., Saleh, A.S., Zou, D. and Zhao, H., 2018. Microwave-assisted ionic liquid pretreatment for cellulose extraction. *Carbohydrate Polymers*, 181, pp.778-785. [DOI]

Malinen, R.O., Sarkar, M.A.R., Ibne, F., Imam, A. and Khan, M.Z.H., 2014. Papermaking from banana pseudostem: characterization and comparison. *Journal of Natural Fibers*, 11(3), pp.199-211. [DOI]

Ma'ruf, A., Puspawiningtiyas, E., Afifah, D.N. and Diaz, E., 2023. Synthesis and characterization of cellulose acetate membrane from cassava peel for microfiltration. *Nature Environment and Pollution Technology*, 22(3), pp.1513-1518. [DOI]

Meng, F., Wang, G., Du, X., Wang, Z., Xu, S. and Zhang, Y., 2018. Preparation and characterization of cellulose nanofibers and nanocrystals from liquefied banana pseudostem residue. *Composites Part B: Engineering*, 160, pp.341-347. [DOI]

Moradian, M., Madadi, M., Pourrahim, S., Hosseinabadi, R. and Fathi, M., 2017. Microwave-assisted extraction of cellulose nanocrystals from rice husk. *Carbohydrate Polymers*, 175, pp.1-8. [DOI]

Ndruru, S.T.C.L., Wahyuningrum, D., Bundjali, B. and Arcana, I.M., 2019. Green simple microwave-assisted extraction of cellulose from Theobroma cacao L. husk. *IOP Conference Series: Materials Science and Engineering*, 541, p.012012. [DOI]

Park, S., Baker, J.O., Himmel, M.E., Parilla, P.A. and Johnson, D.K., 2010. Cellulose crystallinity index: measurement techniques and impact. *Biotechnology for Biofuels*, 3, p.10. [DOI]

Pereira, P.H.F., Corrêa, A.C., de Oliveira, A.C., de Lima Éder, M. and Ramos, G.R., 2015. Cellulose extraction by alkaline-peroxide method. *Carbohydrate Polymers*, 130, pp.95-103. [DOI]

Rahman, M.M., Jahan, M.S., Eshita, Y.J., Khanday, W.A. and Das, A.K., 2017. Isolation and characterization of cellulose from banana peel and fabrication of biocomposites. *International Journal of Biological Macromolecules*, 98, pp.588-596. [DOI]

Rasheed, S., Un Nisa, F., Javed, M., Raza, W. and Ijaz, A., 2019. Microwave-assisted extraction of cellulose from sugarcane bagasse. *Industrial Crops and Products*, 137, pp.13-21. [DOI]

Sudiana, I.N., Mitsudo, S., Susilowati, P.E., Trisna, I.G.A.A.M. and Suyasa, I.W.B., 2017. Fast microwave-assisted pretreatment for bioconversion of sawdust lignocellulose to glucose. *Journal of Physics: Conference Series*, 846, p.012013. [DOI]

Szymańska-Chargot, M., Chylińska, M., Gdula, K., Kozioł, A. and Zdunek, A., 2017. Isolation and characterization of cellulose from different fruit and vegetable pomaces. *Polymers*, 9(10), p.495. [DOI]

Xie, J., Hse, C., de Hoop, C.F., Hu, T.Q. and Shupe, T.F., 2016. Isolation and characterization of cellulose nanofibers from bamboo using microwave liquefaction combined with chemical treatment and ultrasonication. *Carbohydrate Polymers*, 151, pp.725-734. [DOI]

Yadav, M. and Chiu, F., 2019. Cellulose nanocrystals reinforced κ-carrageenan-based UV-resistant films: transparent bionanocomposites for sustainable packaging applications. *Carbohydrate Polymers*, 211, pp.181-194. [DOI]

Yadav, S. and Pal, J., 2025. Sustainable biomass conversion: impact of NaCl pretreatment on cabbage waste. *Nature Environment and Pollution Technology*, 24(2), pp.1-8. [DOI]

Zhou, L., Budarin, V., Fan, J., Sloan, R. and Macquarrie, D., 2017. Efficient method of lignin isolation using microwave-assisted acidolysis and characterization of the residual lignin. *ACS Sustainable Chemistry & Engineering*, 5(5), pp.3768-3774. [DOI]