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# Enhancing Quality of Cellulose Isolated from Banana Peels Incorporating Use of Microwave Radiation Over Conventional Method

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## Abstract

Cellulose, a renewable biopolymer, can be sustainably recovered from agricultural residues such as banana peels, which are abundantly available but often discarded as waste. Conventional methods of cellulose extraction are labour-intensive, require prolonged heating, and consume significant amounts of chemicals, posing environmental and economic challenges. In this study, a microwave-assisted approach was investigated for cellulose isolation 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 revealed that microwave-assisted extraction significantly enhanced efficiency, yielding 86.43% cellulose compared to ~83% obtained conventionally, while reducing the total processing time from 455 minutes to 22 minutes (14 Minutes excluding time for cycle reptation). FTIR analysis confirmed the effective removal of lignin and hemicellulose, XRD analysis indicated retention of cellulose structure with a crystallinity index of 56.8%, and SEM observations demonstrated smoother, cleaner, and similar morphology in microwave-treated cellulose compared to conventionally processed samples. The findings highlight that microwave radiation provides not only superior cellulose purity and structural quality but also considerable advantages in energy efficiency and process sustainability. The cellulose obtained was suitable for applications in packaging, composites, and

nanocellulose production. This paper established microwave-assisted treatment as a scalable, eco-friendly, and time-efficient alternative to conventional processes for the valorization of banana peel waste into high-value cellulose.

## 1. INTRODUCTION

Cellulose is the most abundant natural polymer, and banana peels represent a promising agro-waste source for its sustainable recovery. With the rising demand for eco-friendly and cost-effective processes, the use of microwave radiation has emerged as an efficient alternative. Microwaves provide rapid, uniform heating that accelerates delignification and hemicellulose removal, thereby reducing both treatment time and chemical consumption compared to conventional hot-plate or reflux methods.

Microwave-assisted isolation not only shortens processing steps from hours to minutes but also yields cellulose with high purity, crystallinity, and thermal stability. This approach leverages the abundant availability of banana peels while addressing waste management challenges, contributing to value-added utilization of agricultural residues. As a result, microwave radiation was gaining attention as a green and scalable technique for cellulose extraction, offering advantages in energy efficiency, process sustainability, and potential applications in biocomposites, films, and nanocellulose production.

In comparison to conventional heating methods, microwave radiation offers several distinct advantages that make it preferable for cellulose isolation from banana peels. Conventional methods rely on external conduction and convection, leading to slow and uneven heat transfer, higher chemical usage, and extended treatment durations. In contrast, microwave energy penetrates directly into the material, causing rapid molecular vibration and volumetric heating. This not only accelerates delignification and hemicellulose removal but also minimizes degradation of cellulose itself.

By integrating microwave-assisted treatment, the isolation process ultimately reduces water consumption and contribution to wastewater generation thereby reducing the environmental footprint of cellulose production as reagents with lower concentration were used. Furthermore, highly crystalline and pure cellulose, making it suitable for advanced applications such as biocomposites, packaging films, and nanocellulose-based materials. Thus, microwave radiation provides a greener, cost-effective, and scalable pathway for converting banana peel waste into valuable cellulose resources, aligning with the principles of sustainable material recovery and circular economy.

Banana processing generates a large volume of lignocellulosic residues such as peels, pseudostems, and rachis, which were rich in cellulose but often discarded as waste. Several studies have demonstrated that these residues can serve as sustainable feedstocks for cellulose recovery. Conventional processes typically employ sequential solvent extraction,

alkaline delignification, and oxidative bleaching, producing cellulose suitable for paper, bio-composites, and reinforcement applications (Li et al., 2015; Malinen et al., 2014; Faradilla et al., 2016). However, these methods require long treatment times, high energy input, and large amounts of chemicals, limiting their economic and environmental sustainability (Sun et al., 2004; Elanthikkal et al., 2010). Characterization techniques including FTIR, XRD, and SEM have consistently confirmed effective removal of hemicellulose and lignin and recovery of cellulose with moderate-to-high crystallinity under these conventional conditions (Szymańska-Chargot et al., 2017; Yadav and Chiu, 2019).

Recent studies have further highlighted the potential of agro-waste-derived cellulose for value-added applications. Ma'ruf et al. (2023) demonstrated the conversion of cassava peel into functional cellulose acetate membranes, confirming the potential of agro-waste as a source of value-added cellulose materials, while Yadav and Pal (2025) showed that NaCl pretreatment significantly enhanced biomass conversion efficiency in cabbage waste. Although these studies emphasize chemical modification and pretreatment strategies, the effect of microwave-assisted extraction on cellulose quality has been little explored.

Building on this context, the present paper was designed with the aim of isolating cellulose from banana peels through both conventional reflux methods and a microwave-assisted process at 600 W power, enabling a direct comparison of efficiency and product quality. Specifically, the objectives of this work are: (i) to optimize the sequential 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 characteristics of the isolated cellulose obtained by the two approaches; and (iii) to assess the potential advantages of microwave-assisted treatment in terms of energy consumption, processing time, and sustainability. Through these objectives, the study seeks to establish microwave radiation as a viable, eco-friendly alternative to conventional methods for the valorization of banana peel waste into high-value cellulose.

To overcome these drawbacks, microwave-assisted processing has gained increasing attention as a tool for process intensification. Microwave radiation enables rapid volumetric heating, accelerating alkali penetration and lignin removal, and reducing reaction times from hours to minutes (Ndruru et al., 2019; Zhou et al., 2017). Comparative studies have shown that microwave-assisted delignification and bleaching can achieve similar or higher cellulose purity with lower chemical dosages and substantially reduced energy consumption (Sudiana et al., 2017; Esmaeili et al., 2017; Rasheed et al., 2019). Reports on banana residues as well as other agro-wastes such as rice husk, sugarcane bagasse, and almond shells highlight the generalizability of this approach (Meng et al., 2018; Moradian et al., 2017; Valdés et al., 2023).

Optimized protocols usually employ mild alkali concentrations (2–6% NaOH) with short radiation cycles at 600–800 W and limited repetition, followed by peroxide bleaching at alkaline pH (Kumar et al., 2021). These conditions balance efficiency and cellulose preservation, whereas excessive power or prolonged radiation may cause depolymerization or fiber damage (Wu et al., 2019; Zhang et al., 2018).

In terms of material quality, cellulose obtained via microwave-assisted methods exhibits improved whiteness and brightness, higher crystallinity indices, and cleaner fiber surfaces compared to conventionally treated samples (Xie et al., 2016; Beltramino et al., 2016; Lani et al., 2016). Morphological studies further confirm reduced lignin encrustation and better fibrillation readiness, which are advantageous for subsequent conversion into nanocellulose (Rahman et al., 2017; Sharma et al., 2020). The resulting nanocellulose demonstrates high aspect ratios, good crystallinity, and thermal stability, making it well-suited for reinforcement of biopolymer films, hydrogels, and packaging materials (Serratos et al., 2022; Jonoobi et al., 2015; Kargarzadeh et al., 2017). In addition to improved product properties, microwave-assisted processes address sustainability challenges by reducing energy use, reaction time, and wash water volumes, thereby lowering the overall environmental footprint (Bastos et al., 2020; Bilal and Iqbal, 2019).

Despite these advantages, gaps remain in the literature. Many studies vary multiple process factors simultaneously, complicating direct comparison between microwave and conventional heating (Park et al., 2010; Pereira et al., 2015). Comprehensive energy balances and techno-economic assessments are also limited, and scale-up challenges such as uneven heating and penetration depth need further attention (Borovikova et al., 2015; Liu et al., 2018). Moreover, there was a lack of systematic studies correlating the structural properties of banana-derived cellulose with its performance in end-use applications (Hotor et al., 2024; Abolore et al., 2024). Against this backdrop, the present study is designed to directly compare conventional and microwave-assisted cellulose isolation from banana peels using identical chemical treatments. By standardizing alkali and bleaching conditions and varying only the heating mode, this research aims to provide clear insights into yield, purity, crystallinity, morphology, and sustainability metrics, thereby evaluating the true potential of microwave radiation as a green and efficient alternative for cellulose valorization from banana waste.

## **2. MATERIALS AND METHODOLOGY:**

### **2.1 Materials and Experimental Setup**

Banana peels, collected from local sources, were washed thoroughly, cut into small pieces, and treated with potassium metabisulphite to prevent microbial activity. The material was dried in shade, ball-milled, and sieved to obtain a uniform 200-mesh powder. Analytical grade ethanol, potassium hydroxide (KOH), hydrogen peroxide (30%), and mild acid for neutralization were used as reagents. Equipment employed included a laboratory microwave oven (ME731K / XEU Solo, 20 L), a hot air oven, vacuum filtration unit, and standard glassware.

## 2.2 Methodology

Cellulose isolation was carried out through three sequential steps: liquefaction, delignification, and bleaching. To establish a direct comparison, the same chemical recipes were used for both conventional and microwave treatments. Chemicals with lower strength were used in MAE. Total quantity of chemicals was divided into smaller fractions and extraction was carried out with multiple extraction method to impart novelty in process. Moreover, instead of using high energy radiations (W) comparatively lower energy microwave radiations were used for longer time duration to improve extraction process.

- Liquefaction: Ten grams of banana peel powder were suspended in 100 ml of 10% ethanol and subjected to microwave heating at 600 W for 2 minutes, cycle repeated 3 times. MAE was carried out between 500W to 800W, Experimental optimization revealed that cellulose yield increased with microwave power up to 600 W, beyond which no significant improvement was achieved and signs of thermal degradation were observed, justifying the selection of 600 W as the optimum microwave power, the results obtained were proved to be aligned with results Kumar et. al. (2021). For conventional comparison, refluxing was carried out 200ml 70% ethanol at 70 °C for 2–3 h. Under microwave radiation, rapid darkening of the liquor and browning of the residue indicated efficient removal of soluble extractives in a fraction of the time required by conventional heating (Rfer Fig. 1).
- Delignification: The liquefied residue was treated with 100 ml 3% KOH at a solid-to-liquid ratio of 1:20 and exposed to microwave heating at 600 W for 3 minutes, cycle was repeated twice. The treated biomass turned light tan, became fibrous in texture, and rinsed to neutral pH with fewer washing cycles than conventionally treated material. In contrast, conventional delignification with 200ml 4% KOH at 80–90 °C required 2 h to achieve comparable results (Rfer Fig. 1).

Following flowchart (Fig.1) gives overall methodology for Cellulose Isolation from Banana Peels.

<p style="text-align: center;">Banana peel collection</p> <p style="text-align: center;">→ Washing → Drying (60°C) → Grinding &amp; sieving (&lt;1 mm), milling</p>
<p style="text-align: center;">Liquefaction (Defatting)</p> <p style="text-align: center;">→ Conventional: 10 gram Banana Peel Powder + 200 ml, 70% Ethanol at 70°C, 2–3 hr</p> <p style="text-align: center;">→ Microwave: 10 gram Banana Peel Powder+ 300 ml (3X100ml), 10% Ethanol 600 W, 3×2 min cycles</p>
<p style="text-align: center;">Delignification (Alkali treatment)</p> <p style="text-align: center;">→ Conventional: 200ml 4% KOH, 80–90°C, 3 h</p> <p style="text-align: center;">→ Microwave: 200ml (2x100ml) 3% KOH 600 W, 2×4 min cycles</p>
<p style="text-align: center;">Bleaching</p> <p style="text-align: center;">→ pH 10–11</p> <p style="text-align: center;">→ Conventional: 200ml 10% H<sub>2</sub>O<sub>2</sub>, 70°C, 2 h</p> <p style="text-align: center;">→ Microwave: 200ml 3% H<sub>2</sub>O<sub>2</sub>, 600 W, 2–4 min cycles</p>
<p style="text-align: center;">Neutralization &amp; Washing</p> <p style="text-align: center;">→ Distilled water rinse until pH ~7</p>
<p style="text-align: center;">Drying</p> <p style="text-align: center;">→ Oven at 60°C</p>
<p style="text-align: center;">Characterization</p> <p style="text-align: center;">→ FTIR, XRD, SEM</p>
<p style="text-align: center;">Comparative Analysis</p> <p style="text-align: center;">→ Yield, Purity, Energy, Time, Sustainability</p>

Fig. 1: Research Methodology Flowchart: Cellulose Isolation from Banana Peels

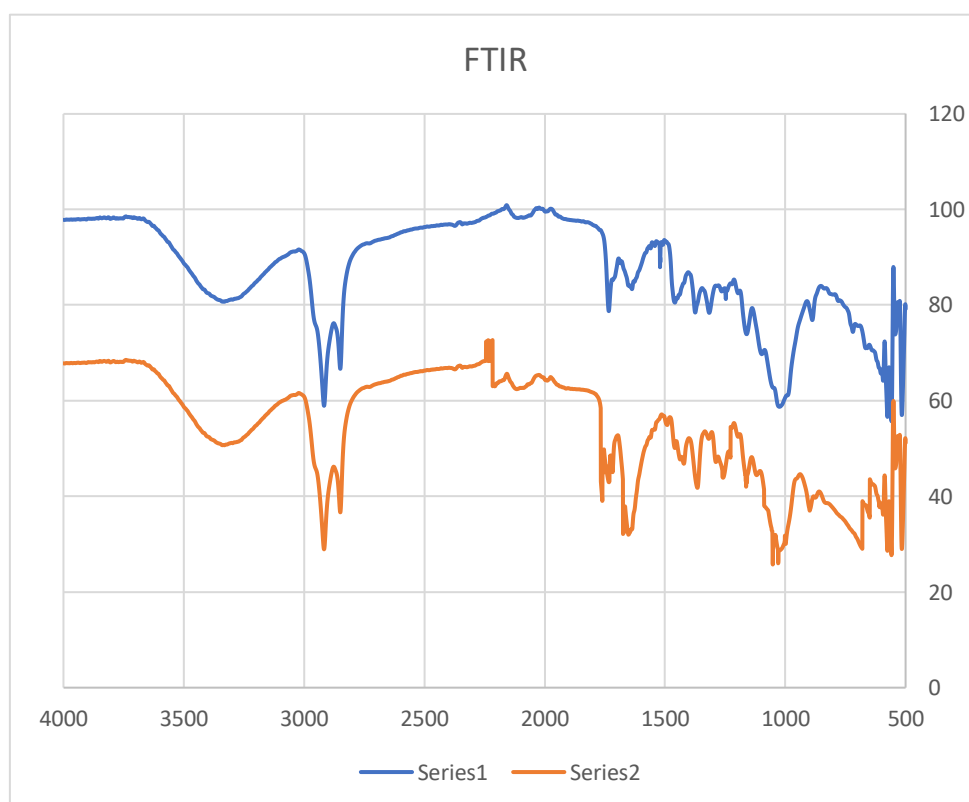
- Bleaching: The alkali-treated residue was treated with 3% hydrogen peroxide (100ml) adjusted to alkaline pH (10–11) and irradiated at 600 W for 4 minutes, repeated twice. Within two cycles, the sample became off-white, and the filtrate was nearly colorless, indicating removal of residual lignin chromophores. In comparison, conventional bleaching required 200ml 10% H<sub>2</sub>O<sub>2</sub> at 70 °C for 4h to produce similar whiteness (Rfer Fig. 1).

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

For characterization FTIR, XRD, and SEM analyses were employed to confirm the removal of non-cellulosic components, evaluate crystallinity, and examine morphological changes in the treated samples. The final comparative analysis emphasized differences in yield, reaction time, reagent consumption, and quality of cellulose obtained through conventional versus microwave-assisted methods. This structured approach not only validates microwave radiation as a faster and more energy-efficient technique but also highlights 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 was shown in Fig. 2.



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 <sup>-1</sup> )	Assigned functional group / vibration	Analytical implication	Structural inference
~1519	Aromatic C=C stretching (lignin)	Complete disappearance indicates disruption of 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 band indicates chemical stability of cellulose chains	Confirms preservation of 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-(1→4) glycosidic linkage	Presence confirms maintenance of inter-unit linkage	Demonstrates retention of native cellulose connectivity

The FTIR spectrum of the microwave-treated cellulose showed as given in Table 1 disappearance of lignin-associated bands at ~1519 cm<sup>-1</sup> and ~1247 cm<sup>-1</sup>, confirming removal of aromatic C=C and carbonyl groups. Characteristic cellulose absorption bands were retained, including ~1161 cm<sup>-1</sup> (C–O–C stretching), ~1052 cm<sup>-1</sup> (C–O stretching), and ~898 cm<sup>-1</sup> (β-(1→4) glycosidic bond). These changes demonstrated effective delignification and isolation of cellulose.

**2.3.2 Scanning Electron Microscopy (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  $\mu\text{m}$ . 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  $\mu\text{m}$ , indicating incomplete removal of non-cellulosic components.

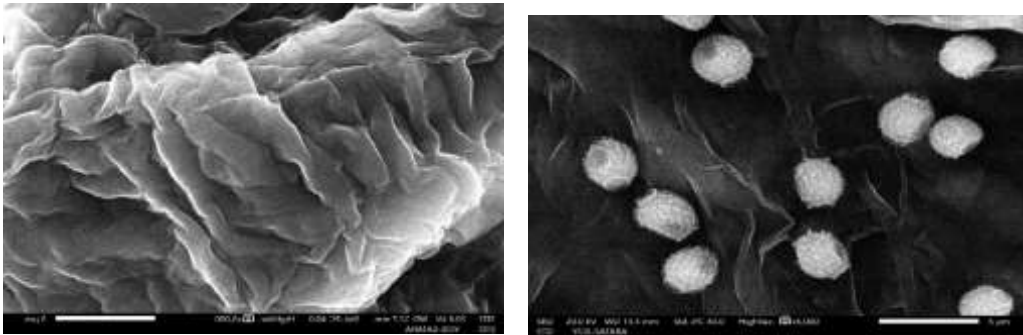


Fig. 3: SEM of Cellulose by Conventional and Microwave Methods

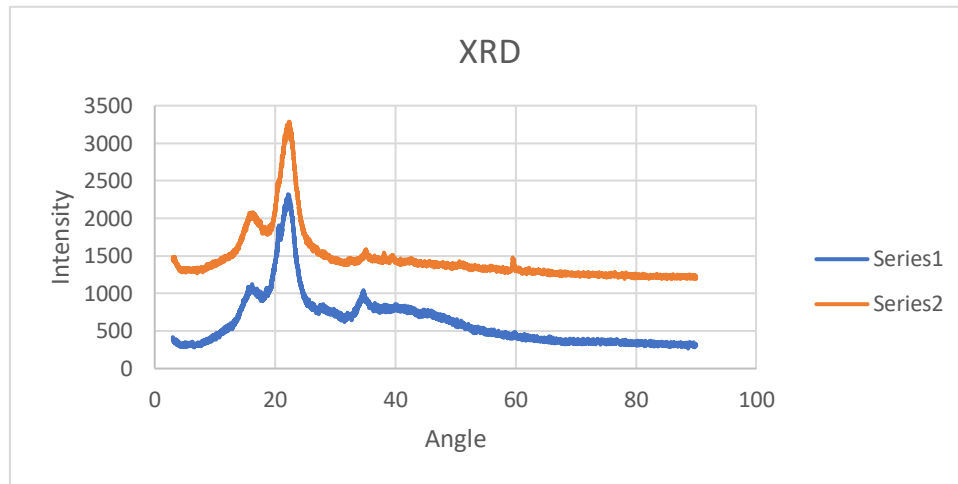
Table 2: Quantitative fibre size distribution

Sample	Diameter range ( $\mu\text{m}$ )	Mean diameter ( $\mu\text{m}$ )	Distribution characteristic
Conventional treatment	10–200	~95	Broad, heterogeneous distribution
Microwave treatment (600 W)	5–100	~42	Narrow, uniform distribution

In contrast, cellulose isolated using microwave radiation at 600 W displayed significantly improved morphology. The fibers were cleaner, smoother, and partially fibrillated, with fewer surface deposits and greater uniformity. Fiber diameters were reduced to 5–100  $\mu\text{m}$ , given in Table 2 consistent with effective delignification and hemicellulose removal. These morphological improvements correlate with the higher cellulose purity (86.43%) and crystallinity (56.8%) obtained at 600 W compared to the conventional process.

**2.3.3 XRD Analysis:** XRD for finding crystalline structure and crystal size of isolated cellulose was taken on (Rigaku, MiniFlex) with Cu K $\alpha$  radiation ( $\lambda = 1.54059\text{\AA}$ ). The diffractogram of cellulose isolated at 600 W exhibited main peaks, shown in Fig.4 at  $2\theta \approx 22.0\text{--}22.5^\circ$ , characteristic of cellulose. The calculated crystallinity index was 56.8% for cellulose by MAE method, reflecting a higher crystalline fraction relative cellulose by conventional method i.e. 37.48%. The value was found to be comparable to literature reports for banana pseudostem cellulose (Faradilla et al., 2016; Hayati et

al., 2017), indicating that microwave pretreatment selectively removed amorphous lignin and hemicellulose while retaining the crystalline structure of cellulose.



Series 1: Microwave Method, Series 2: Conventtional Method

Fig. 4: X-Ray Diffraction Spectra for Cellulose

Crystallinity index for Conventional Mathod: (Series-I)

Crystallinity Index (CrI) Calculation (*Segal Method*)

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

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

Where:

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

From Fig 4

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

Calculated Crystallinity Index

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

The crystallinity index of the cellulose sample was calculated to be approximately 37.48%, indicating a crystalline structure with a balanced distribution of crystalline and amorphous domains. This level of crystallinity was favourable for maintaining mechanical stability while allowing sufficient flexibility.

Crystallinity index for Microwave Assisted Extraction Method:

Crystallinity Index (CrI) Calculation (*Segal Method*)

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

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

Where:

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

Calculated Crystallinity Index

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

The crystallinity index of the cellulose sample was calculated to be approximately 56.8%, indicating a crystalline structure with a balanced distribution of crystalline and amorphous domains. This level of crystallinity was favourable for maintaining mechanical stability while allowing sufficient flexibility, which was advantageous for membrane fabrication and related material applications.

### 2.3.4 Quantitative Outcomes at 600 W microwave radiation with MAE

Lignin content decreased substantially in the microwave sample as shown in Table 3, which was evident from its lighter appearance and improved washing efficiency. The product yield and quality achieved at 600 W exceeded those

of the conventional method despite drastically shorter treatment time. Microwave Assisted Extraction saves around 78.57% ethanol, 25% alkali and 70% H<sub>2</sub>O<sub>2</sub>. Overall, 58% chemical load of waste was reduced with MAE.

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

Method	Conditions	Cellulose content (%)	Processing time	Product appearance	Crystallinity Index (%)	Chemicals Consumed per 10gm bpp
Microwave	600 W, 22 min (i.e. 0.17 kWh)	86.43	22 min	Off-white, fibrous	56.8	Ethanol (30ml), KOH (6 gms), H <sub>2</sub> O <sub>2</sub> (6ml)
Conventional	80–90 °C, 7.5 h (i.e. 7.5kWh)	~83.0	455 min	Tan, less uniform	37.48	Ethanol (140ml), KOH (8gms), H <sub>2</sub> O <sub>2</sub> (20ml)

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 microwave method (approximately 97.7%) compared to conventional heating method as shown in Table 3.

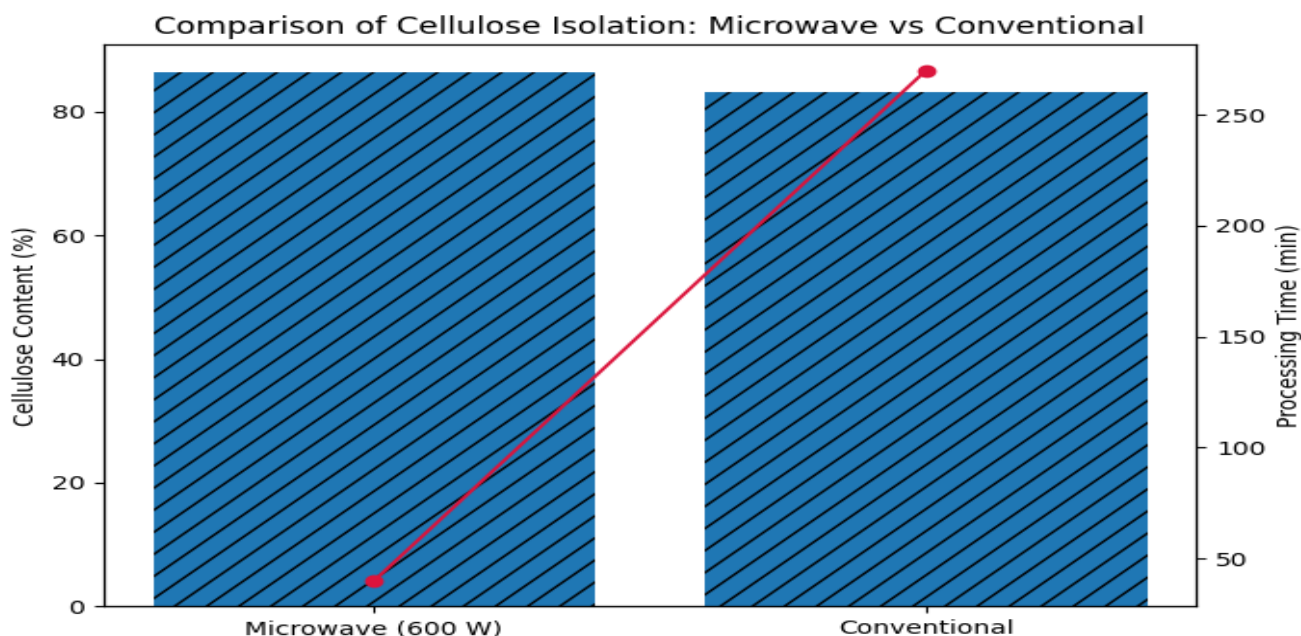


Fig. 5: Comparison of Cellulose Isolation w. r. t. time and percentage cellulose for both methods

Fig. 5 compared the cellulose content (%) and processing time (minutes) obtained by conventional heating and microwave-assisted isolation at 600 W. The bar chart (blue) represents cellulose content, while the line plot (red) indicates the corresponding processing time for each method.

All experiments were conducted in triplicate, and the results were reported as mean  $\pm$  standard deviation. The mean cellulose content obtained by conventional extraction was  $83.12 \pm 0.68\%$ , while microwave-assisted extraction yielded  $86.43 \pm 0.51\%$ . The standard deviations were calculated using the sample standard deviation formula to quantify experimental variability among independent replicates. To evaluate whether the observed difference in cellulose content between the two extraction methods was statistically significant, an independent two-tailed Student's *t*-test was performed. The analysis resulted in a mean difference of 3.31%, with 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 threshold, indicating that the increase in cellulose content achieved through microwave-assisted extraction was statistically significant. While the numerical improvement was modest, the result was reproducible and supported by quantitative statistical validation.

### 3. RESULTS AND DISCUSSION

#### a) Effect of Microwave Radiation on Cellulose Yield

Cellulose was successfully isolated from banana peel powder using microwave radiation at 600 W, and the results were compared with those obtained through conventional chemical treatment. The microwave-assisted process yielded a cellulose content of 86.43%, whereas the conventional route produced  $\sim 83\%$ . The improved yield was attributed to the rapid volumetric heating effect of microwaves, which enhanced delignification and hemicellulose removal. In addition, the total processing time was reduced from 455 minutes (7.5 Hrs) (conventional) to only 22 minutes (microwave), representing a reduction of more than 95%. This finding clearly demonstrated the process intensification achieved by microwave heating, providing both higher cellulose purity and greater time efficiency.

This improvement was attributed to the unique heating mechanism of microwaves, where energy couples directly with polar molecules, generating volumetric heating through dipole rotation and ionic conduction. Such rapid heating accelerates bond cleavage, chromophore degradation, and mass transfer processes, enabling faster delignification and bleaching.

### **b) Structural and Chemical Analysis (FTIR and XRD)**

The structural and chemical characteristics of the cellulose isolated from banana peels were analyzed using FTIR and XRD. The FTIR spectrum of the microwave-treated cellulose showed the disappearance of lignin-associated peaks at  $1519\text{ cm}^{-1}$  and  $1247\text{ cm}^{-1}$ , confirming effective delignification and hemicellulose removal, while characteristic cellulose absorption bands at  $1161\text{ cm}^{-1}$  (C–O–C pyranose ring),  $1052\text{ cm}^{-1}$  (C–O stretching), and  $898\text{ cm}^{-1}$  ( $\beta$ -(1 $\rightarrow$ 4) glycosidic linkage) were retained, indicating preservation of the cellulose structure. XRD analysis further confirmed the presence of the native cellulose polymorph, with distinct diffraction peaks observed around  $2\theta \approx 22.0\text{--}22.5^\circ$  with 56.8% was slightly higher than that of conventionally treated samples, reflecting the selective removal of amorphous regions and the formation of a more ordered structure. These results collectively demonstrate that microwave-assisted isolation not only enhances the purity and structural order of cellulose but also significantly reduces processing time compared to conventional methods.

### **c) Surface Morphology (SEM Analysis)**

SEM observations supported the spectroscopic findings. Untreated banana peel fibers exhibited compact, rough surfaces with visible deposits of lignin and hemicellulose. After conventional treatment, the surface retains irregular textures and embedded debris, with diameters ranging from 10–200  $\mu\text{m}$ . In contrast, microwave-treated cellulose at 600 W showed smoother surfaces, exposed fibrils, and uniform fiber bundles, with diameters reduced to 5–100  $\mu\text{m}$ . The cleaner and fibrillated morphology was consistent with higher cellulose content and crystallinity.

The conventionally treated cellulose exhibited irregular fiber surfaces with rough textures and residual particles, indicating incomplete removal of lignin and hemicellulose. The fiber bundles appeared partly compacted and fragmented, with visible deposits covering the surface. These features suggest that the conventional process, despite prolonged heating, results in partial delignification and limited fibrillation.

In contrast, the microwave-assisted sample displayed cleaner, smoother, and more fibrillated fibers. The surface appeared uniform, with fewer impurities and clearer exposure of microfibrils. The microwave treatment effectively disrupted lignin–carbohydrate linkages, leading to enhanced fiber separation and surface purification.

Overall, the SEM analysis confirms that microwave-assisted isolation significantly enhances surface morphology, producing cellulose with cleaner surface that were more suitable for downstream applications such as nanocellulose production and composite reinforcement.

#### d) Comparative Performance and Sustainability

Overall, microwave-assisted isolation at 600 W produced cellulose of higher purity, better crystallinity, and improved morphology in a fraction of the time required by conventional heating use of less concentrated solutions reduces load of pollutants in waste water. The reduced washing cycles and shorter process duration also imply lower energy and water consumption, making the method more environmentally sustainable. These advantages position microwave radiation as a scalable and eco-friendly alternative for isolation of cellulose from agro-waste i.e. banana peel.

#### 4. CONCLUSIONS

This study demonstrated the successful isolation of cellulose from banana peels using microwave radiation at 600W, offering a superior alternative to conventional thermal processing. The microwave-assisted method achieved a higher cellulose content (86.43%) with improved crystallinity (56.8%) and cleaner fiber morphology, while reducing the total processing time by 95%. FTIR confirmed the effective removal of lignin and hemicellulose, XRD verified the retention of cellulose I structure, and SEM revealed smoother, fibrillated fibers compared to conventional samples.

The findings clearly establish microwave radiation as a rapid method (around 95% time was saved), energy-efficient (energy saving of approximately 97.7%) compared to conventional heating methods, demonstrating the superior energy efficiency of microwave-assisted cellulose extraction, and sustainable technique for cellulose isolation. Overall, 58% chemical load of waste was reduced with MAE ultimately reducing water usage for washings and cleanings. The method not only enhances yield and quality but also contributes to waste valorization and environmental sustainability. The cellulose obtained through this approach was suitable for a wide range of applications, including biocomposites, packaging films, and nanocellulose production.

**Author Contributions:** Conceptualization, 1 and 3.; methodology, 1.; software, 1 and 2.; validation, 1., 2 and 3.; formal analysis, 1; investigation, 1; resources, 1 and 3; data curation, 1,2 and 3; writing—original draft preparation, 1; writing—review and editing, 1,2 and 3; visualization, 1,2 and 3; supervision, 3; project administration, 1 and 3. All authors have read and agreed to the published version of the manuscript.

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