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Extraction of Cellulose from Sugarcane Bagasse Across Agricultural and Forestry

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ABSTRACT

This study investigates the sustainable cellulose extraction from sugarcane bagasse across agricultural, forestry, and plantation sectors. Sugarcane bagasse, a by-product of sugar production, emerges as a promising source of cellulose, offering avenues for value addition and waste reduction within these industries. Three extraction methods were evaluated: soxhlet extraction using ethanol, kraft pulping with $NaOH/Na_2S$, and iCEL machine producing cellulose, extractive, and lignin. Quantitative analysis reveals that soxhlet extraction yields the highest purity of cellulose (75.86±1.54%), followed by the iCEL machine (50.20 ± 12.49%), while kraft pulping shows comparatively lower purity (48.42±3.95%) due to incomplete delignification. Morphological examination indicates that soxhlet extraction preserves cellulose's native properties, including its white colour and fibrous morphology akin to raw cotton.

In contrast, kraft pulping induces degradation, leading to yellowing and lignification of the cellulose. Fourier transform infrared spectroscopy confirms the presence of characteristic cellulose peaks in all samples, with additional peaks indicating residual non-cellulosic components, especially in kraft cellulose. Soxhlet extraction is optimal due to its simplicity, higher purity, and non-destructive nature. Despite its industrial prevalence, kraft pulping exhibits lower efficiency in cellulose extraction. While the iCEL method shows promise, further optimization is needed to enhance consistency. Future research directions may include adapting soxhlet parameters for nanocellulose production and characterizing material properties for diverse applications. Economic feasibility and environmental impact assessments are crucial for the commercialization of lab protocols, thereby supporting sustainable cellulose production from abundant agricultural residues like sugarcane bagasse. In conclusion, this study underscores the importance of exploring efficient and sustainable methods for cellulose extraction from sugarcane bagasse, with implications for promoting circular economy principles and fostering sustainable development across agricultural, forestry, and plantation sectors.

Keywords: Sugarcane bagasse, Soxhlet extraction, Kraft pulping, iCEL machine

INTRODUCTION

Sugarcane (Saccharum officinarum) is a well-known base material for producing white sugar. Sugarcane juice is a revitalising beverage due to its high vitamin, carbohydrate, and amino acid content. Due to variable amounts of hydrophilic components, sugarcane juice's status as a nutritional beverage is well-established. In addition, sugarcane juice's chemical profile reveals numerous phytochemicals with immense potential for pharmacological research. Sugarcane is among the top ten most-planted crops in the globe. Nearly one billion tonnes are harvested annually worldwide (Ahlfeld, 1996). Cellulose extraction from sugarcane bagasse is gaining significant attention across the agricultural, forestry, and plantation sectors due to its potential for sustainable development and resource optimization. Sugarcane bagasse, a fibrous by-product of sugarcane processing, is traditionally used as a low-value fuel or disposed of as waste. However, recent advancements in biotechnology and materials science have highlighted its value as a rich source of cellulose, a versatile biopolymer with extensive applications. The agricultural sector benefits from this process by converting waste into valuable products, thus enhancing the overall profitability of sugarcane cultivation. In forestry, cellulose extraction from sugarcane bagasse provides an alternative to wood-based cellulose, contributing to forest conservation and reducing deforestation pressures.

Meanwhile, plantation sectors are exploring this process to diversify their product portfolios and create sustainable practices aligned with global environmental standards. This comprehensive approach to cellulose extraction promotes a circular economy and addresses critical environmental challenges such as waste management and carbon footprint reduction. By integrating these sectors in the cellulose extraction process, significant strides can be made towards achieving sustainable agricultural practices, preserving natural resources, and fostering innovation in bio-based materials.

MATERIALS AND METHODS

Sugarcane bagasse is the fibrous residue remaining after sugarcane juice extraction from stems. In this case, it is the primary raw material for producing cellulose. The Sugarcane are separated from the tough skin and dried in the oven for 24 hours or until completely dried before being grinded into fine powder.

Extracting Cellulose with different methods

Extracting cellulose via Kraft pulping method

Kraft pulping is a widely employed method for cellulose extraction from sugarcane bagasse (SCB). In this process, SCB is treated with a mixture of sodium hydroxide (NaOH) and sodium sulfide (Na2S) under elevated temperature and pressure. The alkaline environment breaks down lignin and hemicellulose, leaving behind cellulose Fibers.

The resulting pulp is then subjected to a bleaching stage using agents like chlorine, chlorine dioxide, or hydrogen peroxide to remove residual lignin and enhance cellulose purity. The kraft pulping method is known for its efficiency in delignification and is a cornerstone in the paper and pulp industry due to its high cellulose yield.

Extracting cellulose via Soxhlet Extraction method

Soxhlet extraction is a solvent-based method for cellulose extraction from SCB. In this process, dried and finely ground SCB is placed in a Soxhlet extractor. Ethanol and water, is continuously cycled through the SCB in the extractor. The solvent selectively dissolves non-cellulosic components, such as extractives and some hemicellulose.

The extracted solution is then filtered to separate the cellulose from the solvent and impurities. The cellulose is subsequently washed, dried, and weighed. Soxhlet extraction is known for its simplicity and effectiveness in removing impurities from cellulose samples.

Extracting cellulose via Integrated Cellulose, Extractive and Lignin (iCEL) method

The iCEL machine represents an integrated approach for comprehensive cellulose extraction from SCB. In this method, SCB undergoes a series of steps within the iCEL machine. Initially, the bagasse is fed into the machine, where solvent-based extraction removes extractives like waxes and resins. Following this, the remaining material undergoes a delignification process within the machine, selectively dissolving lignin and enriching the cellulose content. The final step involves meticulous separation to isolate the extracted

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cellulose. The iCEL machine is designed for efficiency, incorporating a closed-loop system to minimize solvent usage and often employing environmentally friendly solvents. This integrated approach streamlines the extraction process, making it a promising technology for obtaining high-purity cellulose from SCB in a sustainable and resource-efficient manner.

Characterization Cellulose from Sugarcane Bagasse

Fourier Transform Infrared Spectroscopy (FTIR) analysis of cellulose

Fourier Transform Infrared Spectroscopy (FTIR) analysis of cellulose involves preparing the sample by drying and grinding the cellulose into a fine powder, then mixing it with potassium bromide (KBr) to form a transparent pellet. This pellet is placed in an FTIR spectrometer, where its spectrum is recorded over the range of 4000-400 cm^{-1}.The resulting spectrum is analyzed to identify characteristic absorption bands, such as O-H stretching around 3400 cm^{-1} and C-H stretching around 2900 cm^{-1}, confirming the presence and purity of the cellulose. The process includes subtracting a background spectrum to account for any KBr and atmospheric gases absorbance, ensuring accurate identification of cellulose-specific peaks.

Morphological Properties of Cellulose

Characterizing cellulose from sugarcane bagasse using stereo microscopy involves a detailed examination of the structural features and morphology of the extracted cellulose fibers. Stereo microscopy, also known as dissecting or low-magnification microscopy, offers a three-dimensional view of the cellulose structure. The cellulose sample is carefully mounted on a microscope stage, and a stereo microscope with dual optical pathways is utilized to observe the fibers. This method allows for the visualization of the cellulose's surface topography, fiber dimensions, and potential irregularities, providing insights into the quality and purity of the extracted cellulose. Through stereo microscopy, researchers can assess the integrity and characteristics of cellulose fibers derived from sugarcane bagasse, contributing valuable information for further applications in industries such as paper and textile.

RESULTS AND DISCUSSION

Cellulose Extraction of Sugarcane Bagasse with Different Methods

Table 1 directly compares the performance of three methods for extracting cellulose from biomass samples: Soxhlet extraction, kraft pulping, and iCEL pulping. Various metrics evaluate the efficiency and characteristics of cellulose obtained from each process. Soxhlet extraction, which uses solvents to remove extractives, achieved the highest removal rate of 6.68%, leaving behind holocellulose composed mainly of cellulose and hemicellulose. Kraft and CEL pulping processes more aggressively remove non-cellulose components, including extractives and lignin. The kraft process yielded the highest average cellulose content at 70.55%, with minimal hemicellulose content. In contrast, the iCEL process resulted in a cellulose content of 50.20% but retained a significant amount of hemicellulose at 27.98% on average.

Table 1. Comparison of Extracting Cellulose from Three Different Methods

Sample	Extractives (%)	Extractive Free (%)	Holocellulose (%)	Hemicellulose (%)	Lignin (%)	Cellulose (%)
SC	6.68 ± 0.42	10.07 ± 2.01	81.65 ± 1.61	5.79 ± 0.4	1.7 ± 0.44	75.86 ± 1.54
KC	0.00	10.79 ± 1.08	0.00	0.00	0.00	48.42 ± 3.95
CC	0.00	7.41 ± 4.13	87.03 ± 3.53	27.98 ± 3.73	0.00	50.20 ± 12.49

Notes: SC (Soxhlet Cellulose), KC (Kraft Cellulose), CC (iCEL Cellulose)

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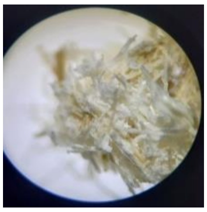
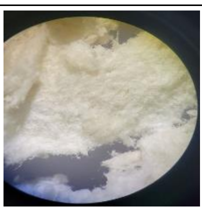
Thus, kraft pulping outperformed iCEL pulping regarding cellulose specificity and purity. However, iCEL pulping maintained higher utilization of the overall biomass by retaining hemicellulose sugars while liberating cellulose. The choice of process depends on the desired end use of the cellulose and the acceptability of hemicellulose contaminants. The consistency of results also differed between processes. Soxhlet extraction showed the lowest variability in cellulose yield, with a standard deviation of just 1.54%, which is expected for this mild chemical extraction method. In contrast, the harsher pulping processes exhibited wider variability in cellulose yields, with standard deviations of 3.95% and 12.49% for kraft and iCEL, respectively. Further optimization for consistency is needed for these more complex pulping processes. In summary, Soxhlet extraction reliably recovers cellulose while retaining hemicellulose and minimal lignin contaminants. Kraft pulping specifically maximizes the purification and isolation of cellulose but sacrifices hemicellulose yield and consistency. Finally, the iCEL biochemical method recovers usable cellulose and hemicellulose as a combined renewable source stream, though purity and consistency need improvement. The choice of process ultimately depends on whether high-specificity cellulose or total utilization of biomass sugars is more desirable for the intended application.

Morphological Properties of Cellulose from Sugarcane Bagasse

As seen in Table 2, cellulose extracted via Soxhlet, iCEL, and kraft pulping techniques exhibit noticeable visual differences under low and high magnification stereo microscopy. Soxhlet-extracted cellulose appears white to slightly yellowish at 1.5x and 3.0x zoom, with a fluffy, cotton-like texture. This mild ethanol-based extraction preserves the native morphology of cellulose I crystals aggregated into microfibrils. Similarly, the iCEL method produces cellulose with an off-white colour and fibrous texture by removing non-cellulosic binders like lignin and some hemicelluloses while minimizing cellulose degradation, resulting in a similar cotton-like appearance. In contrast, kraft-derived cellulose exhibits a yellowish tinge at low magnification and appears golden-yellow at 3X zoom. The kraft fibers are more individualized and look wood-like due to residual lignin and lignin degradation products that resist alkaline extraction. The flat, ribbon-shaped fibres suggest partial fragmentation of the cell walls and coalescing of micro fibrils, as the harsh kraft process depolymerizes cellulose and alters its crystalline arrangement. This yellowish coloration and coarse texture indicate that kraft pulping extensively modifies the sugarcane bagasse's ultrastructure and cellulose assembly compared to the milder Soxhlet and iCEL methods, which better preserve the innate cellulose properties.

Table 5. Cellulose was derived from three different methods under stereo microscopy

Sample	1.5x	3.0x
SC		
KC		
CC		

Notes: SC (Soxhlet Cellulose), KC (Kraft Cellulose), CC (iCEL Cellulose)

Fourier Transform Infrared Spectroscopy (FTIR) of Cellulose from Sugarcane Bagasse

The Fourier Transform Infrared (FTIR) spectroscopy results characterize the functional groups present in Figure 1, a cellulose extracted via three methods from sugarcane bagasse. The FTIR spectrum shows distinctive peaks corresponding to specific chemical bonds in the cellulose samples. A broad, intense peak from 3000-3500 cm^{-1} is visible in all samples, indicating O-H stretching vibration of hydroxyl groups, which signifies the presence of primary aliphatic alcohols integral to cellulose. Specifically, at the wavenumber range of 3000-3500 cm^{-1}, SC1 shows a medium-intense peak at 3330.03 cm^{-1} corresponding to inorganic phosphate and primary aliphatic alcohol. KC1 also exhibits a medium-intense peak in this range, indicating primary aliphatic alcohol, alkynes monosubstituted, and aliphatic hydrocarbon. CC1 displays a similar medium-intense peak as SC1. This absorption range also suggests the presence of alkynes with monosubstituted groups or phosphates from residual extractives. The peak intensity suggests abundant hydrogen bonding in crystalline cellulose I.

All samples exhibit smaller peaks within 1000-1500 cm^{-1} associated with various functionalities. For instance, a medium peak at 1160 cm^{-1} in KC cellulose corresponds to the C-O stretch in aliphatic ethers within lignin or hemicelluloses, indicating surviving non-cellulosic entities. A defining cellulose peak at 895-896 cm^{-1} in SC and KC samples is due to β-glycosidic linkages between glucose monomers, verifying the cellulose structure. A comparable peak at 1018 cm^{-1} in CC cellulose also indicates the C-O stretch in cellulose. Overall, strong broad hydroxyl peaks combined with smaller peaks indicating glycosidic bonds and ester linkages demonstrate the extraction of intact cellulose macromolecules using the three techniques. Medium peaks suggest the Soxhlet method performed slightly better in removing non-cellulosic components. However, all samples confirm the presence of cellulose functionality alongside low quantities of residual biomass constituents.

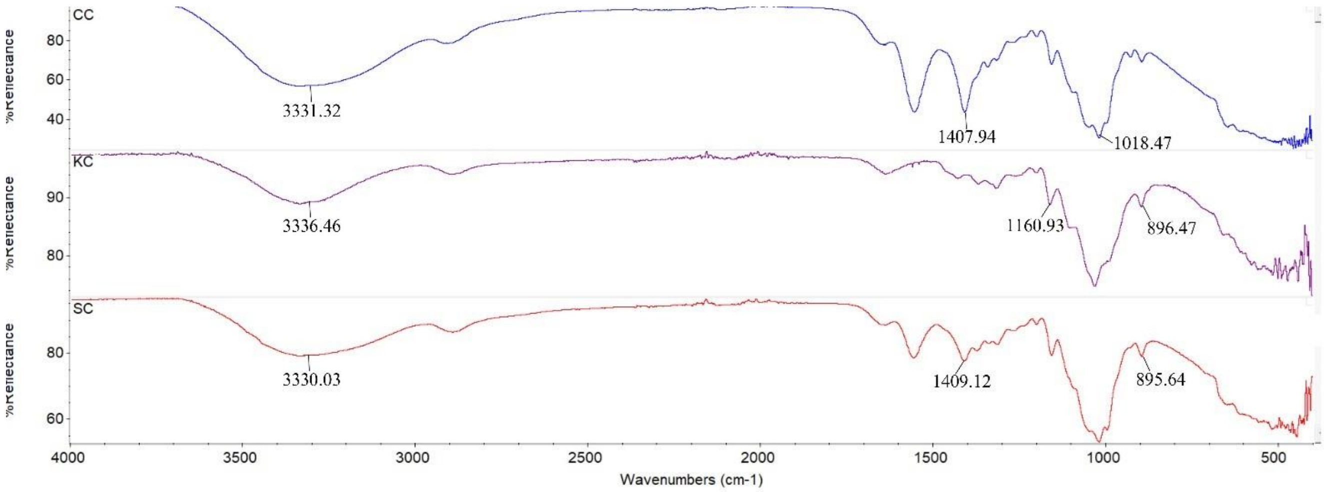


Figure 1. FTIR spectrum of cellulose from three different methods derived from sugarcane bagasse

CONCLUSIONS

The study compared three methods for extracting cellulose from sugarcane bagasse: Soxhlet extraction, kraft pulping, and the iCEL machine. Quantitative analysis showed that Soxhlet extraction achieved the highest purity at 75.86 ± 1.54% and demonstrated superior consistency across samples. In contrast, kraft pulping yielded 48.42 ± 3.95% cellulose with higher variability, indicating incomplete delignification. The iICEL machine performed between these values at 50.20 ± 12.49% cellulose. Stereo microscopy revealed distinct morphological differences: Soxhlet and iCEL samples retained the native white colour and fluffy, cotton-like texture of pure cellulose, while kraft pulping caused yellowing and lignification, suggesting more extensive alteration of the cell wall ultrastructure. FTIR spectroscopy confirmed characteristic cellulose peaks in all samples, with additional peaks indicating residual non-cellulosic components, particularly in kraft cellulose. Overall, the mild nature of Soxhlet extraction. Its efficiency, reproducibility, and product purity make it optimal for extracting high-value cellulosic feedstocks for biorefineries despite requiring more time than kraft pulping and the iCEL machine, which produces cellulose faster but with lower purity and consistency.

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