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Comparative Chemical Characterization of Cellulose Extracted from Pineapple Leaves, Corn Cobs, and Bamboo

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1 Introduction

Lignocellulosic-based materials have garnered significant attention from scholars and industries due to their widespread presence, affordability, and inherent environmental benefits. The agro-industrial processes generate large amounts of cellulosic wastes, and strategic valorization of these cellulosic by-products offers a two-fold potential of reducing ecological impacts, even as it provides economic gains [1]. The growing attention to the preservation of natural resources and the development of recycling has renewed interest in natural materials, particularly those from renewable sources. It is possible to attribute this re-emergence to increased awareness of the environment and the global shift towards environmentally friendly practices and sustainable development [2]. Lignocellulosic materials and industrial solid wastes [3] have attracted considerable academic interest.

Cellulose is the most abundant polysaccharide produced by plants and microorganisms [4]. It is the main component of lignocellulosic biomass and the most widespread natural polysaccharide, playing structural roles in plants. It is renewable, biodegradable, and exhibits good thermal stability up to about 260 °C. It is produced commercially on a large scale owing to its diverse industrial applications. Chemically, cellulose $(C_6H_{10}O_5)$ n is a linear polysaccharide composed of β-D-glucose units linked by β (1→4) glycosidic bonds. It forms a structural matrix in plant cell walls, is found in wood and stems, and exists in its purest form in cotton (90%) and wood (40–50%) [5]. Its properties include biodegradability, recyclability, renewability, biocompatibility, and high mechanical strength [6].

Despite the significant amount of research devoted to cellulose extraction, comparative studies evaluating the behaviour of different agro-waste feedstocks when subjected to a standardized extraction process are limited. Past studies on pineapple leaves, corn cobs, and bamboo stems have been conducted independently of each other. Still, there are no systematic comparisons of their cellulose yields, structural characteristics, and extraction efficiencies using consistent chemical-mechanical treatments within the existing literature. This gap does not contribute to a thorough understanding of the effects of the inherent composition of biomass on extraction performance. It therefore hinders the identification of the optimal feedstock for scalable industrial processes. This study offers a unique contribution by comparing cellulose from pineapple leaves, corn cobs, and bamboo stems under the same extraction conditions. The unified approach highlights biomass-specific differences and identifies the most suitable feedstock for scalable production of cellulose. The aim of the current study is to isolate and characterize cellulose of various botanical sources that is, pineapple leaf, corn cobs, and bamboo stem. The structure of the methodology is that a comparative evaluation is carried out of the efficiency of the chemical and mechanical extraction pathways with production aimed at the high-purity cellulose, along with the assessment undertaken on the characterized conditions in terms of scalability to the production at the industrial scale. The basic structural, chemical, and morphological properties of the isolated cellulose are defined through Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and stereomicroscopy, thereby demonstrating its suitability for advanced applications in biocomposites, nanomaterials, and sustainable packaging. By utilizing these biomass resources, the study will help create value-added materials, which will not only help in the conservation of the environment but also in economic productivity by reducing agricultural waste materials and providing alternative raw materials to the industrial sectors. This research enhances agro-waste valorization by identifying underutilized biomass sources suitable for industrial cellulose production and supporting the development of sustainable, cost-effective materials.

2 Experimental Section

2.1 Materials

Pineapple leaves (PL), Bamboo stems (BS), and Corn cobs (CC) were collected from local sources. The reagents used for the chemical treatment of plant materials were NaOH (Analytical grade, Research-Lab Fine Chem Industries, India), NaOCl (Analytical grade, Daejung Chemicals & Metals Co., LTD, Korea), and H2SO4 (Analytical grade, Research-Lab Fine Chem Industries, Mumbai 400 002, India).

2.2 Methods

Pretreatment of raw materials

The plant materials were washed with distilled water and oven-dried at 60 ^{0}C for 12 hours. They were then ground into a fine powder. The leaf fibres were then sieved using a sieve set to a uniform size of approximately 0.063 mm.

Hot water treatment (HWT)

The plant materials were treated with hot water at 90 °C for 1 hour and then oven-dried at 60 °C until they reached a constant weight.

Alkali treatment (AT)

Plant fibers were treated with 1 M NaOH at 90 °C for 2 hours, maintaining a 1:20 g/ml fiber-to-solution ratio. Subsequently, all the alkali-treated fibers were thoroughly washed under distilled water to neutralize pH and eliminate excess alkali deposits. After washing, the fibers were dried in an oven for 24 hours to remove residual moisture.

Bleach treatment (BT)

The pulps were further treated with 2.5 % w/v NaOCl at 80 °C for 1 hour with a 1:20 g/ml fiber to solution ratio. Finally, the bleached-treated fibers (BT) were washed repeatedly with hot distilled water to remove residual lignin and neutralize pH, and dried in an oven at 60 °C until constant weight.

Acid treatment (ACT)

After the chemical treatments, the BT fibers obtained from three plant materials were used for acid hydrolysis. The hydrolysis was performed at 45 °C for 60 minutes under constant stirring. Each gram of BT fiber was treated with 10 mL of 64% H_2SO_4. The obtained cellulose (ACT) was labelled depending on the plant material (ACT-PL, ACT-CC, ACT-BS).

2.3 Materials Characterization

Chemical composition analysis of raw plant fibers

The process involved the removal of extractives, strong acid hydrolysis of hemicellulose under non-heated conditions, and high-temperature dilute acid hydrolysis. First, 120 mL of distilled water and 1 g of the dried sample (A) were heated in a water bath at 100 °C for one hour. The mixture was filtered, and the residue was washed with hot water. The dried residue was oven-dried to a constant weight and designated as (B). Next, 150 mL of 0.5 M H_2SO_4 was added to residue (B), and the suspension was heated in a water bath at 100 °C for one hour. The solution was filtered, the residue was washed with distilled water, then dried to constant weight and designated as (C). In a water bath, the residue (C) was soaked with 10 mL of 72% H_2SO_4 at room temperature for 4 hours. Subsequently, 150 mL of 0.5 M H_2SO_4 was added, and the mixture was heated at 100 °C in a water bath for 2 hours. The residue obtained was filtered, washed with distilled water until neutral pH, and oven-dried at 105 °C to constant weight, yielding residue (D). Finally, residue (D) was placed in a furnace at 600 °C until fully converted to ash, which was weighed and designated as (E) [7]. The percentage chemical composition of raw fibers was calculated according to equations [1]– [5].

$$\text{Hot water soluble (\%)} = (A-B)/A \times 100 \quad [1]$$

$$\text{Hemicellulose (\%)} = (B-C)/A \times 100 \quad [2]$$

$$\text{Cellulose (\%)} = (C-D)/A \times 100 \quad [3]$$

$$\text{Lignin (\%)} = (D-E)/A \times 100 \quad [4]$$

$$\text{Ash (\%)} = E/A \times 100 \quad [5]$$

Yield percentage analysis (%)

The extraction yield percentage of HWT fibers, AT fibers, BT fibers, and ACT fiber was calculated using equation (6), considering the mass of raw plant powder and the mass of AT, BT, and ACT [8].

$$\text{Yield (\%)} = (M1-M2)/M3 \times 100 \quad [6]$$

M1= Mass of treated fibers within a weighing container

M2= Mass of weighing container

M3=Mass of raw plant powder

Fourier Transform Infrared (FTIR) Analysis

The Raw, HWT, AT, BT, and ACT fiber samples of three different plant fibers were analyzed for their functional groups using Fourier Transform Infrared Spectroscopy (Bruker Alpha II FTIR Spectrometer) with wavenumbers from 4000 to 400 cm^{-1}.

X-ray diffractometer (XRD) analysis

The samples' crystallinity was examined using X-ray diffraction with Cu Kα radiation (λ = 1.5406 Å) generated by the Rigaku Ultima IV X-ray Diffractometer. The samples were scanned at an operating voltage of 40 kV and 30 mA in the 2θ range of 100–800.

3 Results and Discussion

Chemical composition analysis of raw plant fibers

The compositional comparison of pineapple (P), corncob (C), and bamboo (B) fibers showed significant differences affecting their biorefinery use. Hot water solubility was highest in corncob (3.19 ± 0.01%), followed by bamboo (2.60 ± 0.02%) and pineapple (1.29 ± 0.09%), reflecting corncob's higher content of water-soluble compounds, likely hemicellulose and sugars. Cellulose content was highest in pineapple (51.68 ± 0.45%), followed by bamboo (47.03 ± 0.15%) and corncob (46.27 ± 0.32%), indicating its potential as a high-fermentable glucose source for biofuel production. Hemicellulose was highest in corncob (32.08 ± 0.07%), then bamboo (27.00 ± 0.10%) and pineapple (15.70 ± 0.01%), correlating with corncob's high solubility and reactivity in pretreatment. Lignin content was highest in bamboo (12.04 ± 0.05%), followed by pineapple (10.09 ± 0.01%) and corncob (8.97 ± 0.06%), suggesting bamboo may need more intensive pretreatment. Overall, pineapple is high in cellulose, corncob in hemicellulose, and bamboo in lignin, which should guide feedstock selection for specific bioprocesses.

Yield Percentage

Bamboo stems treated with hot water (HWT) showed the highest mean yield (98.17 ± 0.26%), significantly higher ($p < 0.05$) than other treatments. HWT is a mild pretreatment that removes soluble sugars while retaining cellulose, hemicellulose, and lignin, resulting in maximum recovery. Yields from bleach-treated (BT) corncob (91.52 ± 1.17%), HWT pineapple (90.62 ± 0.13%), and HWT corncob (90.42 ± 0.03%) were similar ($p > 0.05$) but lower than HWT bamboo. The lowest yield was observed for alkali-treated (AT) pineapple (40.81 ± 0.69%) due to its high cellulose but low hemicellulose and lignin content, making it more susceptible to solubilization. In contrast, corn cobs (70.23 ± 1.11%) and bamboo stems (68.94 ± 1.30%) retained more mass due to their compact, lignified structure and higher hemicellulose content. Overall, yield depends on both biomass type and treatment, with HWT preserving most material and AT causing substantial losses in less dense structures [9].

FTIR Analysis

Figure 1 shows the FTIR spectra of cellulose from three different biomasses. In all three different FTIR spectra, a broad band around 3300-3500 cm^{-1} corresponds to O-H stretching vibrations of hydroxyl groups involved in hydrogen bonding. Aliphatic C-H stretches are observed around 2800-2900 cm^{-1}, and the carbonyl band of hemicellulose/lignin appears at 1700-1720 cm^{-1}. Absorptions near 1600-1635 cm^{-1} correspond to water/adsorbed moisture or conjugated C=C vibrations, while aryl ether/ester or lignin-related bands appear around 1230-1245 cm^{-1}. Finally, the C-O/C-O-C stretching vibrations of the cellulose pyranose ring are observed at a wavenumber range of 1000–1030 cm^{-1}. Hot-water treatment (HWT) caused slight reductions in the absorption bands at 1700-1720 cm^{-1} and 1230-1245 cm^{-1}, indicating the partial removal of extractives and soluble hemicellulose components in all three plant fibers. More pronounced spectral changes were observed after alkali treatment (AT), where the disappearance of the 1700-1720 cm^{-1} carbonyl band and the marked attenuation of the 1230-1245 cm^{-1} lignin-related band confirmed effective hemicellulose solubilization and partial delignification. Bleaching treatment (BT) further eliminated lignin-associated absorptions and enhanced the intensity of cellulose-specific peaks, demonstrating progressive lignin removal and cellulose enrichment in the treated fibers.

In acid-treated cellulose (ACT) obtained via acid hydrolysis, characteristic bands corresponding to hemicellulose and lignin were absent. In contrast, the cellulose fingerprint band (1030 cm^{-1}) became sharper and more intense, indicating the removal of amorphous components and the preservation of crystalline cellulose. Additionally, the narrowing of the O-H stretching band suggested modifications in hydrogen-bonding networks, consistent with increased crystallinity. Across all feedstocks, the consistent disappearance of non-cellulosic peaks and sharpening of cellulose bands confirm successful purification and isolation of cellulose microcrystals, validating the effectiveness of the applied pretreatment and hydrolysis sequence.

XRD Analysis

To investigate the crystalline structure of raw lignocellulosic fibers from pineapple, corn cob, and bamboo, and to assess the impact of acid hydrolysis on their crystallinity, X-ray diffraction (XRD) analysis was conducted, as shown in Figure 2. The diffractograms of all raw fibers displayed broad diffraction peaks over a pronounced amorphous background, characteristic of

semi-crystalline cellulose embedded within amorphous hemicellulose and lignin fractions. Raw pineapple fiber showed peaks at 2θ, 15.95^0, 22.0^0, and 34.5^0, corn cob at 15.65^0, 22.05^0, and 34.25^0, and bamboo at 12.05^0, 21.1^0, and 34.3^0. Following acid hydrolysis, the resulting cellulose (ACTs) retained the same peak positions, confirming preservation of the crystal lattice. The intensity and sharpness of the peaks, particularly near 22^0, increased significantly. This enhancement reflects an increase in crystallinity due to the selective removal of amorphous regions during hydrolysis, leaving behind highly ordered, acid-resistant crystalline cellulose domains. These results demonstrate that acid hydrolysis effectively isolated the crystalline regions from all three biomass sources, providing clear evidence for the formation of cellulose nanomaterials. The peak sharpness and intensity increase align with previous studies on acid-treated cellulose from plant fibers [10], [11].

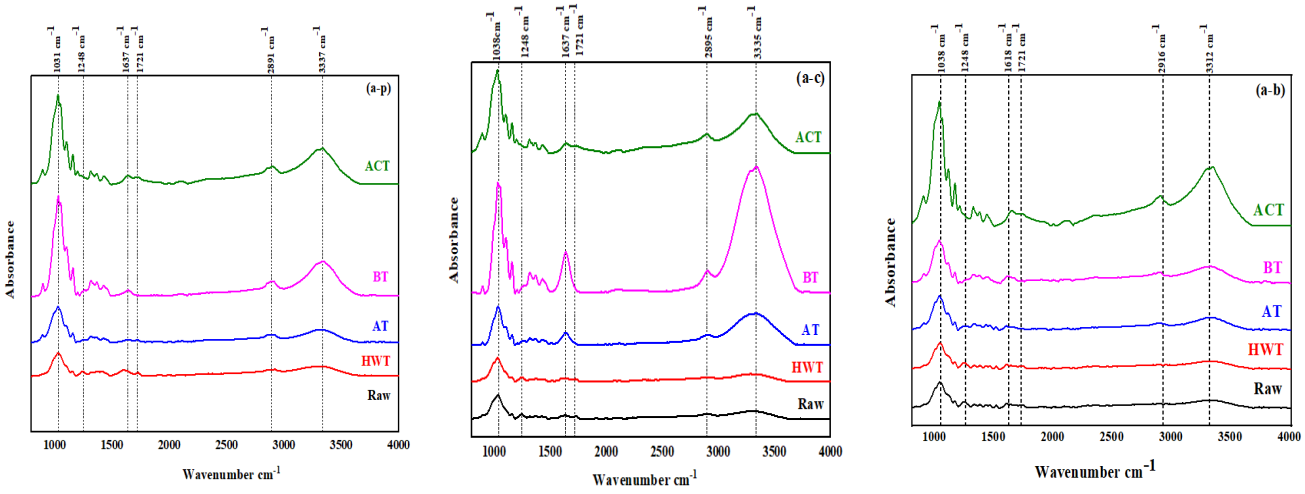

Figure 1. FTIR analysis of cellulose extracted from three different biomasses, (a-p); Pineapple, (a-c); Corncob, (a-b); Bamboo stems.

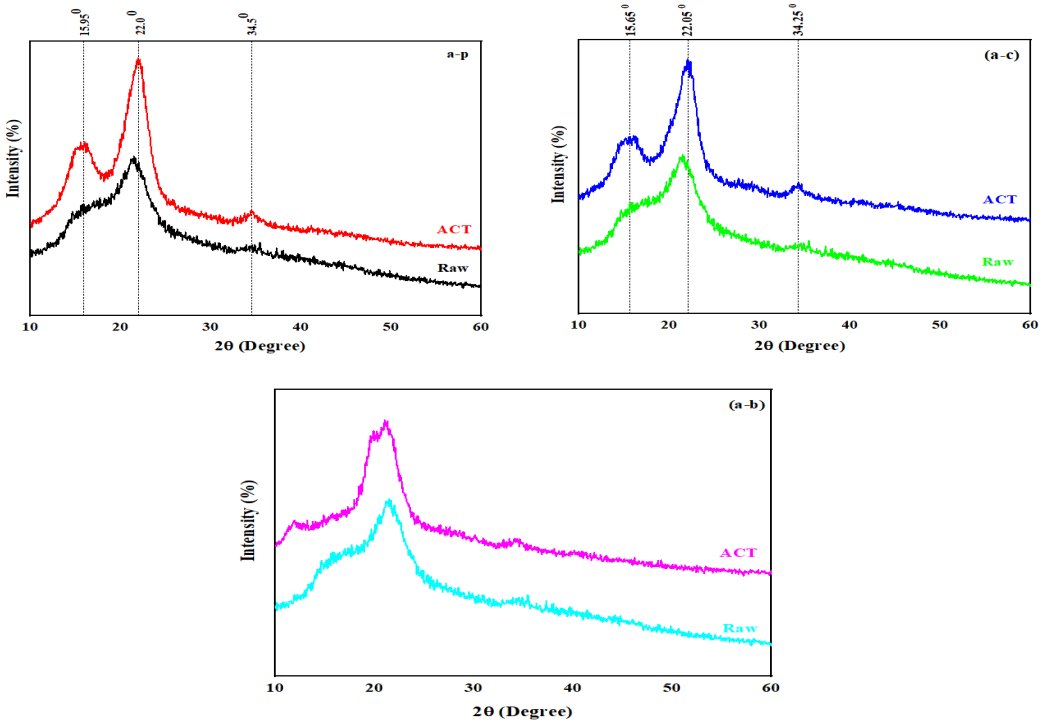

Figure 2. XRD spectrums of (a-p) pineapple leaf raw fiber and ACT (acid-treated cellulose) ;(a-b) raw corn cob fiber and ACT (acid-treated cellulose) ;(a-c) raw bamboo stem fiber and ACT (acid-treated cellulose).

Table 1: Chemical composition analysis of different plant materials (pineapple leaves, corn cobs, and bamboo stems) based on hot water soluble, cellulose, hemicellulose, and lignin contents (dry weight basis).

Parameter	Pineapple (P)	Corncob (C)	Bamboo (B)
Hot water soluble (%)	1.29 ± 0.09^{l}	3.19 ± 0.01^{j}	2.60 ± 0.01^{k}
Cellulose (%)	51.68 ± 0.45^{a}	46.27 ± 0.32^{c}	47.03 ± 0.15^{b}
Hemicellulose (%)	15.70 ± 0.01^{f}	32.08 ± 0.07^{d}	27.00 ± 0.10^{e}
Lignin (%)	10.09 ± 0.01^{h}	8.97 ± 0.06^{i}	12.04 ± 0.05^{g}

4 Conclusions

Cellulose was extracted from pineapple leaves, corn cobs, and bamboo stems. Its chemical and structural properties were characterized. Pineapple leaves showed the highest cellulose content (80.35%) but the lowest yield (40.81%), while corn cobs and bamboo had higher yields (70.23% and 68.94%) but lower cellulose contents (46.27% and 57.03%). The higher hemicellulose and lignin content in corn cobs and bamboo explained their resistance to alkali treatment. Sequential processing—hot-water, alkaline, bleaching, and acid hydrolysis-produced progressively finer, lighter fibers, with pineapple and bamboo showing the greatest defibrillation. FTIR confirmed the removal of lignin and hemicellulose, while XRD indicated an increase in crystallinity, verifying the formation of cellulose nanocrystals. Morphological evidence revealed bamboo's dense fibrous structure and pineapple's flexible, amorphous nature, making it ideal for starch-based composites. Overall, variations in composition and structure highlight how each biomass affects cellulose yield and properties, guiding the optimal selection of feedstocks for bioplastic production. The extraction approach developed here not only enables consistent cellulose recovery from diverse biomass types but also yields material characteristics that support industrial scalability and application in sustainable products.

Declaration of Competing Interest

The authors declare no competing interests.

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Malika Dissanayaka; Conceptualization, Data analysis, Visualization, Writing – original draft. **Amaya Wijesinghe**; Data analysis. **Chathuranga Senarathna**; Supervision, review & editing.

Keywords

Pineapple leaves, Bamboo stems, Corncobs, Cellulose extraction, Characterization

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