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Md. Redwanul Islam

redwan.tex@aust.edu

Ahsanullah University of Science and Technology (AUST)

Fahmida -E-Karim

Ahsanullah University of Science and Technology (AUST)

Md. Reajul Islam

Bangladesh University of Textiles

Amit Chakrabortty

Ahsanullah University of Science and Technology (AUST)

Md. Zawad Ibna Jalil

Ahsanullah University of Science and Technology (AUST)

Samio Hossain

Ahsanullah University of Science and Technology (AUST)

Atiq Shahriar

Ahsanullah University of Science and Technology (AUST)

Md. Nakib Hossen

Bangladesh Council of Scientific and Industrial Research

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Extracting and Characterizing Natural Fibers from Bamboo Sheath

Md. Redwanul Islam[1], Fahmida-E-Karim[1], Md. Reajul Islam[2], Amit Chakrabortty[1], Md. Zawad Ibna Jalil[1], Samio Hossain[1], Atiq Shahriar[1], Md. Nakib Hossen[3]

[1]*Department of Textile Engineering, Ahsanullah University of Science and Technology (AUST), Dhaka, Bangladesh.*
[2]*Department of Yarn Engineering, Bangladesh University of Textiles (BUTEX), Dhaka, Bangladesh.*
[3]*Science Laboratory (BCSIR), Joypurhat, Bangladesh.*

Corresponding author: Md. Redwanul Islam, Email: redwan.tex@aust.edu, ORCID: https://orcid.org/0000-0002-2143-409X

Abstract:

The increasing demand for sustainable and renewable textile materials has encouraged the exploration of underutilized lignocellulosic resources as alternatives to conventional natural fibers. In this study, natural fibers extracted from bamboo sheath were investigated to evaluate their mechanical, structural, morphological, chemical, and moisture-related properties. The extracted bamboo sheath fiber exhibited a tensile strength of 23.14 N, which was substantially higher than those of jute (8.04 N) and hemp (7.41 N), indicating its promising mechanical performance for fiber-based applications. Fourier transform infrared spectroscopy (FTIR) analysis identified characteristic absorption bands at 3326 cm^{-1}, 2924 cm^{-1}, 1332 cm^{-1}, and 1023 cm^{-1}, corresponding primarily to O–H stretching, aliphatic C–H groups, C–H deformation/bending, and C–O/C–O–C vibrations, respectively, confirming the lignocellulosic nature of the extracted fiber. X-ray diffraction (XRD) analysis revealed a crystallinity index of approximately 40%, indicating the presence of an organized crystalline cellulose structure. Scanning electron microscopy (SEM) demonstrated a relatively rough surface morphology, which may provide favorable interfacial characteristics for composite applications. Chemical composition analysis showed 71.27% cellulose, 15.01% hemicellulose, 11.30% lignin, and 2.42% waxes and impurities. Furthermore, the water absorbency of bamboo sheath fiber was 183.56%, compared with 230% for jute and 190% for hemp, demonstrating comparatively lower moisture uptake while retaining substantial water absorption capacity. Overall, the combined mechanical, structural, morphological, chemical, and moisture-related characteristics indicate that bamboo sheath is a promising and underutilized source of natural fiber for sustainable textile, composite, and other value-added applications.

Keywords:

Bamboo sheath, natural fiber, fiber extraction, Fiber characterization, Lignocellulosic fiber.

Introduction:

The growing demand for sustainable and environmentally responsible materials has intensified research into renewable resources that can reduce dependence on petroleum-based and other non-renewable materials(Mori, 2023; Popescu et al., 2024; Rajendran et al., 2025). The textile, composite, packaging, automotive, and construction industries have traditionally relied heavily on synthetic fibers and materials because of their high strength, durability, dimensional stability, and relatively consistent properties. However, the extensive use of synthetic materials has raised significant environmental concerns due to their dependence on fossil resources, energy-intensive manufacturing processes, limited biodegradability, and accumulation of persistent waste(Ahmed et al., 2025; Kaufmann et al., 2025; Manalu et al., 2025; Sayam et al., 2026). Consequently, increasing attention has been directed toward natural fibers derived from renewable biomass as potential alternatives or complementary materials to conventional synthetic fibers. Natural lignocellulosic fibers are particularly attractive because they are renewable, relatively lightweight, biodegradable under appropriate conditions, and generally require less energy for production than many synthetic fibers(Dias et al., 2025; Fahmida-E-Karim et al., 2026; Fahmida-E-Karim, Islam, & Md. Redwanul Islam, 2025; Y. Feng et al., 2024; M. R. Islam et al., 2025; Karim et al., 2023, 2024; Santos et al., 2024; Shifa & Zhang, 2026).

Among the various natural fibers, jute, hemp, flax, sisal, bamboo, kenaf, coir, and other lignocellulosic fibers have been extensively investigated because of their favorable mechanical properties and potential for value-added applications. These fibers primarily consist of cellulose, hemicellulose, lignin, pectin, waxes, and other minor constituents, with their properties strongly influenced by chemical composition, fiber morphology, crystallinity, extraction technique, maturity, growing conditions, and processing history(Ajayi et al., 2025; Eleutério et al., 2025; Elfaleh et al., 2023; Puttegowda, 2025; Sayam, 2026). Cellulose is particularly important because its highly ordered molecular structure contributes to the strength and stiffness of lignocellulosic fibers. Hemicellulose and lignin, on the other hand, influence fiber flexibility, moisture interaction, thermal behavior, and interfacial characteristics. Therefore, understanding the chemical and structural composition of a natural fiber is essential for determining its suitability for specific applications(Kamdem Tamo et al., 2025; Sayam, 2026; Wu et al., 2017).

Bamboo is one of the most rapidly renewable lignocellulosic resources and is widely distributed in tropical and subtropical regions. It has traditionally been used for construction, furniture, handicrafts, household products, paper, and various industrial applications. The rapid growth rate and high biomass productivity of bamboo make it an attractive renewable resource. In addition to the culm, bamboo generates substantial quantities of sheath material during growth, harvesting, and processing(Ahmad et al., 2025; Dai et al., 2026; Emamverdian et al., 2020). Bamboo sheaths are generally considered an underutilized biomass resource, despite containing significant quantities of cellulose and other structural components. In many cases, discarded bamboo sheath becomes agricultural or processing waste, which may be burned, decomposed, or disposed of without substantial value addition. Converting this underutilized biomass into useful natural fibers could therefore contribute to waste reduction, resource efficiency, and the development of

sustainable materials(Dantas et al., 2025; Fahmida-E-Karim et al., 2026; Fahmida-E-Karim, Islam, Roy, et al., 2025; Koley et al., 2025; Uddin et al., 2026).

Bamboo sheath is structurally different from the mature bamboo culm and possesses fibrous tissues that can potentially be separated and utilized as reinforcement or textile-related material. The extraction of fibers from bamboo sheath provides an opportunity to transform a relatively low-value biomass residue into a functional material with potential applications in textiles, bio-composites, nonwoven products, packaging materials, insulation, and other value-added products(Geremew et al., 2024; Irawan et al., 2025; B. Singh et al., 2023; Wang, 2017). However, the suitability of bamboo sheath fiber for these applications cannot be determined solely from its origin. Detailed characterization is necessary to establish its mechanical performance, chemical composition, surface morphology, molecular structure, crystallinity, and interaction with moisture(Geremew et al., 2024; A. Khan et al., 2024; Roy et al., 2026).

The mechanical properties of natural fibers are particularly important when considering their use as reinforcement materials. Tensile strength provides an indication of the ability of a fiber to withstand an applied load before failure, while the fiber structure and chemical constituents influence its load-bearing behavior. Compared with conventional natural fibers, a newly extracted fiber should therefore be evaluated against established materials such as jute and hemp to determine its relative performance. Jute is one of the most widely used bast fibers and has considerable importance in Bangladesh and other jute-producing countries. Hemp is another important lignocellulosic fiber recognized for its strength and versatility. A comparative evaluation with jute and hemp can provide a useful reference for assessing the mechanical and moisture-related performance of bamboo sheath fiber(Kurpińska et al., 2022; Nurul Fazita et al., 2017; Shaik et al., 2025; Temesgen et al., 2026; Zaid & Ben Kahla, 2026).

In particular, a clear research gap exists in the integrated characterization of bamboo sheath fiber, where mechanical, chemical, structural, morphological, and moisture-related properties are evaluated together. The relationship between the cellulose-rich chemical composition of bamboo sheath and its tensile performance, crystallinity, surface morphology, and water absorbency has not been sufficiently established. Furthermore, limited comparative information is available regarding how bamboo sheath fiber performs against established natural fibers such as jute and hemp under comparable testing conditions. This lack of comparative characterization makes it difficult to assess the practical potential of bamboo sheath fiber as an alternative or complementary natural fiber. Therefore, the specific research gap addressed in this study is the lack of comprehensive experimental characterization and comparative evaluation of natural fibers extracted directly from bamboo sheath. To address this gap, the present study investigates the tensile strength, chemical composition, FTIR characteristics, XRD crystallinity, SEM surface morphology, and water absorbency of bamboo sheath fiber, with jute and hemp serving as reference natural fibers for selected properties. The resulting characterization provides a scientific foundation for assessing bamboo sheath as an underutilized and potentially sustainable source of natural fiber for future value-added applications.

Materials and Methods:

Materials:

The materials here used are given below:

(a) Bamboo Sheath, (b) NaOH, (c) Pan



Fig. 1 Materials used in the research work

Fig. 1 shows the materials used in the research work. Here (a) Bamboo Sheath (which has been collected from Narail, Bangladesh), (b) NaOH has been purchased from Hatkhola market, Dhaka, Bangladesh and (c) The Pan has been purchased from the super shop, Bangladesh.

Methods:

The main materials Bamboo Sheath was collected by the author Md. Redwanul Islam from his native village. As their family cultivated the bamboo plant, which is located in Narail, Khulna, Bangladesh.

Tensile Strength Test:

Tensile strength is the greatest pulling force that a textile fiber can sustain before snapping, and it is an important indicator of a fabric's durability and performance. Rather of using typical engineering measurements, textile scientists assess this quality as tenacity, which measures breaking strength relative to fiber thickness in units such as newton (N). High tensile strength is required because it keeps fibers from breaking under the intense mechanical stress of production and directly assures that the finished fabric can withstand everyday wear, washing, and abrasion(Elmogahzy & Farag, 2018; Farag & Elmogahzy, 2009; GUPTA, 2008; Meredith, 1952; Patti & Acierno, 2023). Test Method ASTM D3822, which uses test specimens with gage lengths of 10 mm [0.4 in.](Fibers & Use, 2026), is deemed adequate for acceptance testing of commercial shipments since it has been widely utilized in the trade. This test technique is for

measuring the tensile characteristics of natural and man-made single textile fibers that are long enough to be mounted in a tensile testing equipment.

FTIR Test:

An FTIR (Fourier-Transform Infrared Spectroscopy) test for cellulose and hemicellulose fiber is an analytical technique for detecting, distinguishing, and quantifying these two structural polysaccharides in a plant matrix. Because both molecules are carbohydrates with comparable chemical linkages, an FTIR spectrum shows unique overlapping peaks, allowing scientists to assess biomass composition, monitor extraction quality, and analyze agricultural leftovers(Hong et al., 2021; Javier-Astete et al., 2021; Szymanska-Chargot et al., 2015; Tsaousis et al., 2025). To validate cellulose, scientists analyze the mid-infrared region (4000 cm^{-1} to 400 cm^{-1}) for unique "fingerprint" bands. ASTM E1252 covers the foundational laboratory practices for qualitative material characterization using infrared spectroscopy(Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis, 2026). This standard outlines the specific methodologies used to evaluate organic polymers, functional groups, and chemical compositions.

Table 1 Wavelength (cm^{-1}) with corresponding functional group for FTR.

SI.	Wavelength / Peak (cm^{-1})	Corresponding Functional Group	What it Indicates
1.	~3300 – 3400	O-H stretching	Hydroxyl groups and hydrogen bonding in cellulose(Q. Feng et al., 2017; Mao et al., 2024).
2.	~2900	C-H stretching	General organic matter and aliphatic chains in the fiber (indicates cellulose and hemi-cellulose)(Hind, 2023; Md Salim et al., 2021).
3.	~1735	C=O ester/carbonyl	Presence of pectin or aging/degradation(Guo et al., 2024; Obodo-Ovie et al., 2025).
4.	~1155 & ~1105	C-C ring / C-O-C ether	The glycosidic linkages that make up the polysaccharide chain of cellulose(Dahman, 2017).
5.	~1375	C-H bending (Symmetric)	Present in both, but shifts or drops in intensity can signal the degradation or removal of hemicellulose during chemical treatments(Bouramdane et al., 2022; Kamdem Tamo et al., 2025; Lupoi et al., 2015; Md Salim et al., 2021).
6.	~1030 – 1050	C-O and C-C stretching	Primary marker for Cellulose. Strongest peak of the carbohydrate

			ring skeletal vibrations, reflecting the glucose framework(Lei et al., 2026; Lu et al., 2025; Mohammadi et al., 2026; Shahidi & Athiyappan, 2025).

FTIR test is an essential analytical tool because it provides a rapid, non-destructive, and chemical-free "molecular fingerprint" that instantly identifies a material's composition and purity. By measuring how infrared light interacts with chemical bonds, it eliminates the need for slow, destructive wet-chemistry methods, allowing industries to immediately differentiate closely related components like cellulose and hemicellulose. Table 1 represents the Wavelength (cm^{-1}) with corresponding functional group or verifying raw material quality, monitoring the success of chemical pre-treatments, detecting trace contaminants, and analyzing material failures in a matter of minutes.

XRD Test:

An XRD test (X-ray Diffraction) is a non-destructive analytical technique for determining the crystalline structure, chemical content, and physical characteristics of materials. Scientists may map out the precise arrangement of atoms inside a substance by shooting an X-ray beam at it and monitoring how the waves bounce off (diffract) the atomic layers(Mohammadi et al., 2026). It functioned efficiently as an atomic fingerprint for solids. An XRD test for natural fibers is a specific study that determines a fiber's internal molecular structure by comparing the proportion of ordered, strong crystalline cellulose to disordered, flexible amorphous material. This ratio, known as the Crystallinity Index, has a direct impact on the fiber's total mechanical strength, stiffness, and durability, making it critical for determining how effectively a plant or animal fiber can reinforce environmentally friendly materials(Closse et al., 2024; Oladele et al., 2026; Raja, 2025). Furthermore, the test is used to assess the efficacy of chemical treatments (such as alkali washing) by monitoring the removal of natural impurities like as wax and lignin, as well as to assist textile makers in predicting how well the fiber will absorb moisture and industrial dyes. The Crystallinity Index (CI) or Degree of Crystallinity is computed using several ways based on analytical technology (typically X-ray Diffraction, or XRD) and material type (such as cellulose or polymers). The two most commonly utilized formulas are the Area Integration Method and the Segal Peak Height Method. Here Area Integration Method has been used(Salem et al., 2023; Vydrina et al., 2023).

$$\text{Crystallinity Index (CI)\%} = \frac{Area\ under\ the\ sharp\ crystalline\ peaks}{Total\ area\ under\ the\ entire\ curve} \times 100\% \quad \text{.....(i)(Kovalev et al., 2017)}$$

The above equation (i) expresses the Crystallinity Index (CI) in Area Integration Method.

SEM Test:

SEM (Scanning Electron Microscopy) is a cutting-edge materials research technology that generates highly detailed, 3D-like pictures of a sample's surface at high magnifications using a concentrated beam of high-energy electrons rather than light. This test allows researchers and engineers to examine tiny surface textures and map changes in material composition(Paredes, 2014; Sacco et al., 2025). It is an important tool for failure analysis, contamination management, and electronics inspection, but it requires samples to be dry, vacuum-stable, and electrically conductive, which generally means coating non-metal items with a microscopically thin layer of gold or carbon. Scanning Electron Microscopy (SEM) tests a fiber's surface by using a focused beam of electrons to map its topography, morphology, defect distribution, and elemental composition at nanometer-scale resolution. Allowing researchers to inspect physical features such as surface roughness, micro-cracks, and manufacturing flaws that optical microscopes cannot resolve. This test also provides a visual fingerprint of the surface, identifying contaminants, coatings, or finishes of natural fibers(Ali et al., 2023; Patil et al., 2022).

2.2.5 Surface Roughness by image-j:

Fiber surface roughness describes the microscopic irregularities, grooves, peaks, valleys, and fibrils present on a fiber surface. It is important because it affects fiber–matrix adhesion, mechanical interlocking, wettability, water absorption, and composite strength(M. A. Khan et al., 2026; Marques et al., 2026; Moumakwa et al., 2026; Péczi-Kovács et al., 2026). Surface roughness is also useful for evaluating the effectiveness of chemical treatments such as NaOH treatment, which can remove lignin, hemicellulose, waxes and impurities from natural fibers. To measure surface roughness in ImageJ, open the fiber image, convert it to 8-bit grayscale, draw a straight line across the fiber surface, and select Analyze → Plot Profile to obtain the gray-value profile. In natural-fiber research, parameters such as Ra (average roughness) and Rq (root-mean-square roughness) are commonly used to quantify surface characteristics(Thandavamoorthy et al., 2023). Here Ra and Rq parameters were used to quantify the surface roughness of the extracted fibers. Higher Ra and Rq values indicate greater surface irregularity and the presence of more pronounced peaks and valleys, whereas lower values indicate a comparatively smoother and more uniform surface.

Chemical Composition Test:

A chemical composition test is a scientific process used to determine the exact elemental or molecular makeup of a material, revealing both what chemical ingredients are present and in what precise quantities. Operating like a "chemical blueprint," this type of testing breaks a

sample down to its fundamental parts using specialized laboratory techniques. For a natural fiber, a chemical composition test is used to break down the material into its fundamental biological and organic building blocks to verify its purity, quality, and origin(Thandavamoorthy et al., 2023). Because natural fibers are harvested from living organisms rather than manufactured in a lab, their chemical signatures vary wildly depending on whether they come from plants. Plant-based fibers: testing measures the exact ratios of cellulose (the structural sugar that makes up the majority of the fiber), hemicellulose, and lignin (the rigid polymer that gives woody plants their stiffness). The primary ASTM standard for identifying and analyzing the chemical or blend composition of natural fibers is ASTM D629. This test outlines chemical dissolution and separation procedures to determine the exact percentages of natural fibers (such as cotton, hemp, flax, ramie, silk, and wool). It evaluates how these fibers dissolve or behaves when treated with specific chemical solvents(Li et al., 2024; Machado & Knapic, 2017; Sayam, 2026; Sorieul et al., 2016).

Water Absorbency Test:

A water absorbency test evaluates how effectively a material absorbs, retains, or resists moisture by measuring physical changes—typically weight gain or liquid travel distance—after liquid exposure(J. P. Singh & Verma, 2017). This testing is essential across diverse industries to ensure quality and real-world performance. Water absorbency testing is necessary for natural fibers because most natural fibers contain hydrophilic components such as cellulose and hemicellulose, which have a strong affinity for water. The test determines the fiber's ability to absorb and retain moisture and provides important information about its hydrophilic nature, surface characteristics, dimensional stability, durability, and application suitability(S. Islam et al., 2024; López-Borrell et al., 2023; Mohammed et al., 2023). Changes in water absorbency can also indicate the removal or modification of non-cellulosic components such as lignin, hemicellulose, and waxes during chemical treatment. In natural-fiber-reinforced composites, high water absorption may cause fiber swelling, weakening of the fiber–matrix interface, dimensional instability, and deterioration of mechanical properties. Therefore, water absorbency is an important parameter for evaluating the performance of natural fibers and determining their suitability for textile, bio-composite, insulation, and construction applications(Prasetya et al., 2026; Temesgen et al., 2026; Tezara et al., 2021).

$$\text{Water Absorbency\%} = \frac{Wet\ Weight - Dry\ Weight}{Dry\ Weight} \times 100\% \quad \text{.....(ii)(Prasetya et al., 2026)}$$

By the inputting the wet and dry condition weight of the samples on the equation (ii) the water absorbency% can be measured.

Process of fiber Extraction and Characterization:

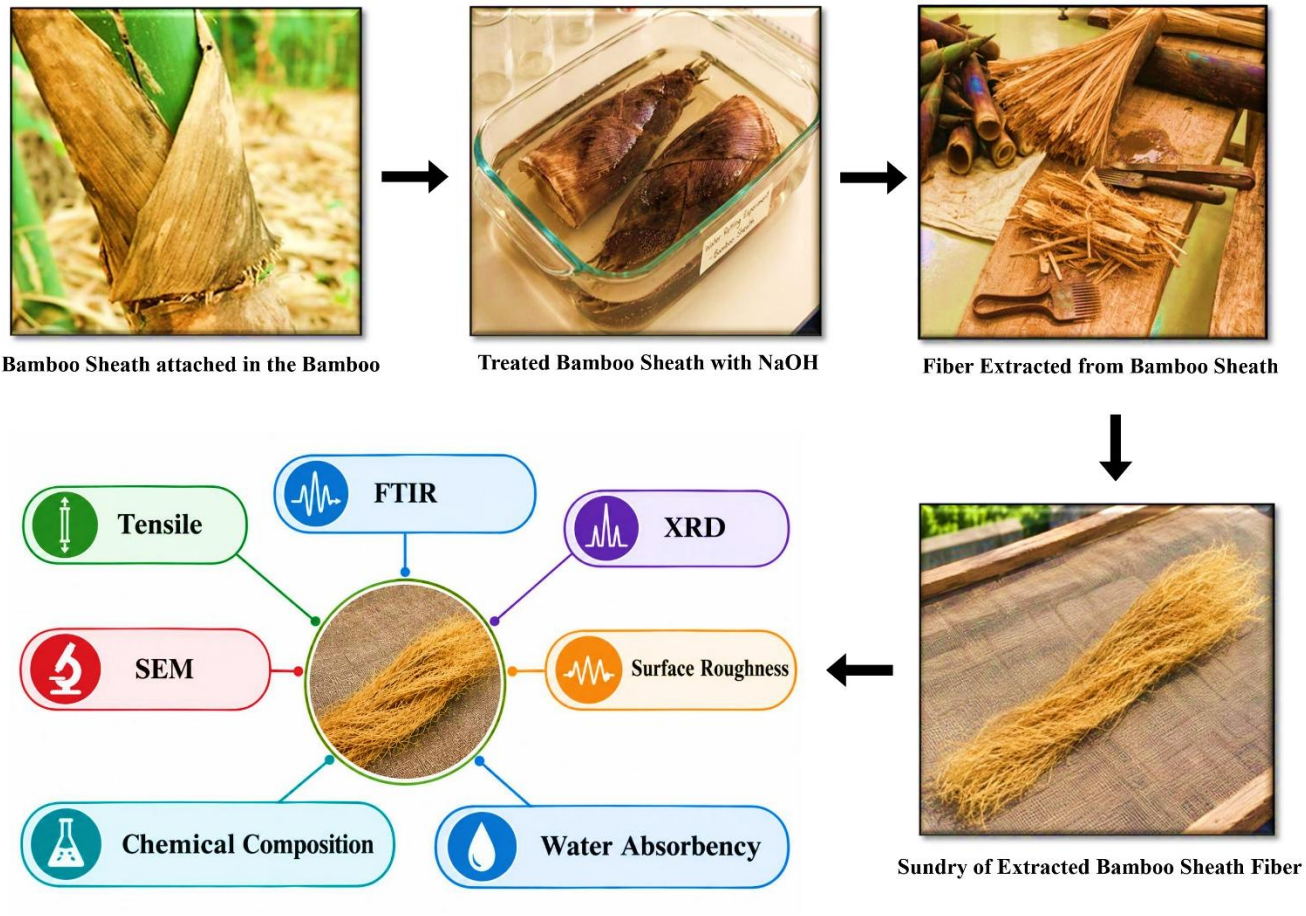


Fig. 2 Fiber extraction and characterization process from bamboo sheath.

Fig. 2 expresses the process flowchart illustrates the experimental methodology for extracting natural fibers from bamboo sheaths and subsequently characterizing their physicochemical and mechanical properties. The extraction workflow begins with the harvesting of raw bamboo sheaths directly attached to the bamboo plant, followed by chemical modification via an alkali treatment using a sodium hydroxide (NaOH) solution to solubilize non-cellulosic constituents. The treated sheaths then undergo mechanical fiber extraction (combing and mechanical separation) to yield isolated fiber bundles, which are subsequently sun-dried to reduce moisture content and stabilize the physical structure. After drying, the purified bamboo sheath fibers are subjected to a comprehensive battery of characterization techniques to assess the fibers quality. Tensile Testing to evaluate mechanical strength and elastic modulus; Scanning Electron Microscopy (SEM) to examine surface morphology and cross-sectional features; Chemical Composition Analysis to quantify cellulose, hemicellulose, and lignin content; FTIR Spectroscopy to monitor functional group changes post-alkali treatment; X-ray Diffraction (XRD) to measure the crystallinity index; Surface Roughness Analysis to assess interfacial

bonding capability; and Water Absorbency Testing to measure the moisture sorption behavior of the fibers.

Results and Discussions

Tensile Strength analysis:

Fig. 3 highlights tensile strength test results. Where jute and hemp fibers exhibited nearly identical, near-linear load–extension responses, reflecting predominantly elastic deformation without intermediate structural failure, and reached comparable peak loads of 8.04 N and 7.41 N, respectively, at around 3.9 mm extension, followed by an abrupt drop indicative of brittle fracture. In contrast, the bamboo sheath fiber demonstrated a considerably higher load-bearing capacity, reaching a maximum tensile strength of 23.14 N—nearly three times that of jute or hemp—but displayed a distinctly non-linear, multi-stage failure profile marked by an initial plateau, a sharp peak, and a series of serrated load drops and partial recoveries extending up to roughly 3.5 mm before complete fracture. This saw-tooth pattern is characteristic of composite, multi-filament fiber bundles in which individual fibrils fail sequentially rather than simultaneously, allowing partial load transfer to intact fibrils and thereby enhancing overall toughness and energy absorption despite a more complex failure mode(Chen et al., 2026; Ghanavati et al., 2026; Sayah Irani et al., 2025). Overall, while jute and hemp behave as more homogeneous, elastically deforming fibers with lower ultimate strength and abrupt catastrophic failure, bamboo sheath fiber exhibits superior strength and toughness attributable to its bundled fibrillar architecture, making it a mechanically more robust candidate among the three for applications requiring high tensile performance and energy dissipation.

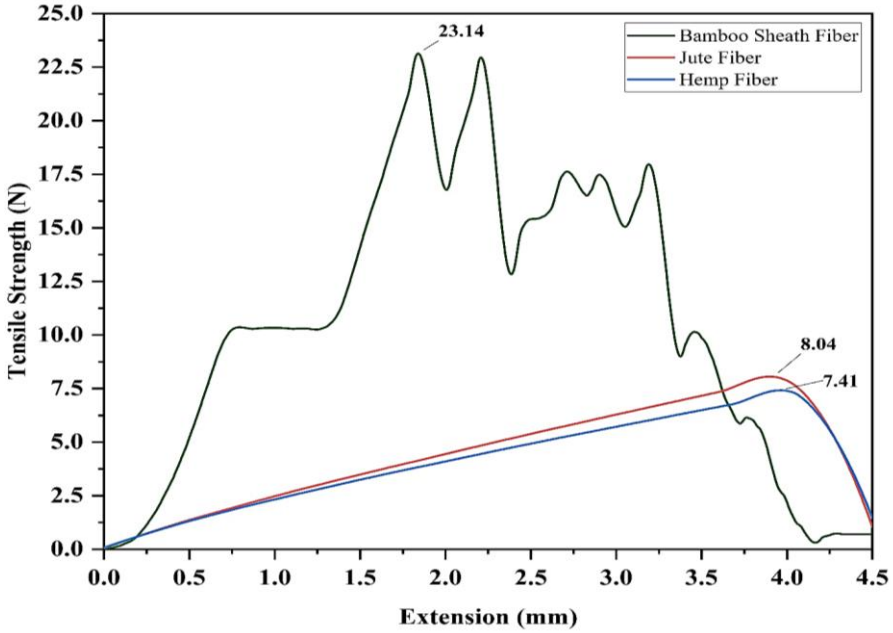


Fig. 3 Tensile Strength analysis

FTIR analysis:

Fig. 4 expresses the FTIR spectra of bamboo sheath, jute, and hemp fibers reveal the characteristic absorption signatures of natural lignocellulosic materials, dominated by cellulose, hemicellulose, and lignin functional groups. Across all three fibers, a broad band in the 3100–3700 cm^{-1} region corresponds to hydrogen-bonded O–H stretching vibrations, with hemp and jute fiber showing deeper, more red-shifted peaks (~3153, ~3154 cm^{-1}) compared to bamboo (~3326 cm^{-1}), suggesting a denser hydrogen-bonding network and potentially higher crystallinity in the bast fibers. The C–H stretching region, clearly resolved near 2924 cm^{-1} in bamboo, appears at unusually lower wavenumbers (~2487, ~2515 cm^{-1}) in hemp and jute fiber, a discrepancy that may reflect combination bands, mineral impurities, or baseline artifacts rather than standard aliphatic C–H vibrations. In the fingerprint region, all three fibers display strong, sharp bands between 950 to1023 cm^{-1}, assigned to C–O–C pyranose ring and glycosidic linkage stretching, confirming cellulose as the dominant structural component, while bands near 1217 to 1332 cm^{-1} reflect C–O and C–H deformation modes associated with lignin and hemicellulose content(Bouramdane et al., 2022; Chakraborty et al., 2022; Vitharanage & Noothalapati, 2026). Overall, jute and hemp exhibit nearly identical, sharply resolved spectral profiles consistent with their shared bast-fiber origin, whereas bamboo sheath fiber shows broader and less-resolved peaks throughout, hinting at a more heterogeneous or less crystalline structure.

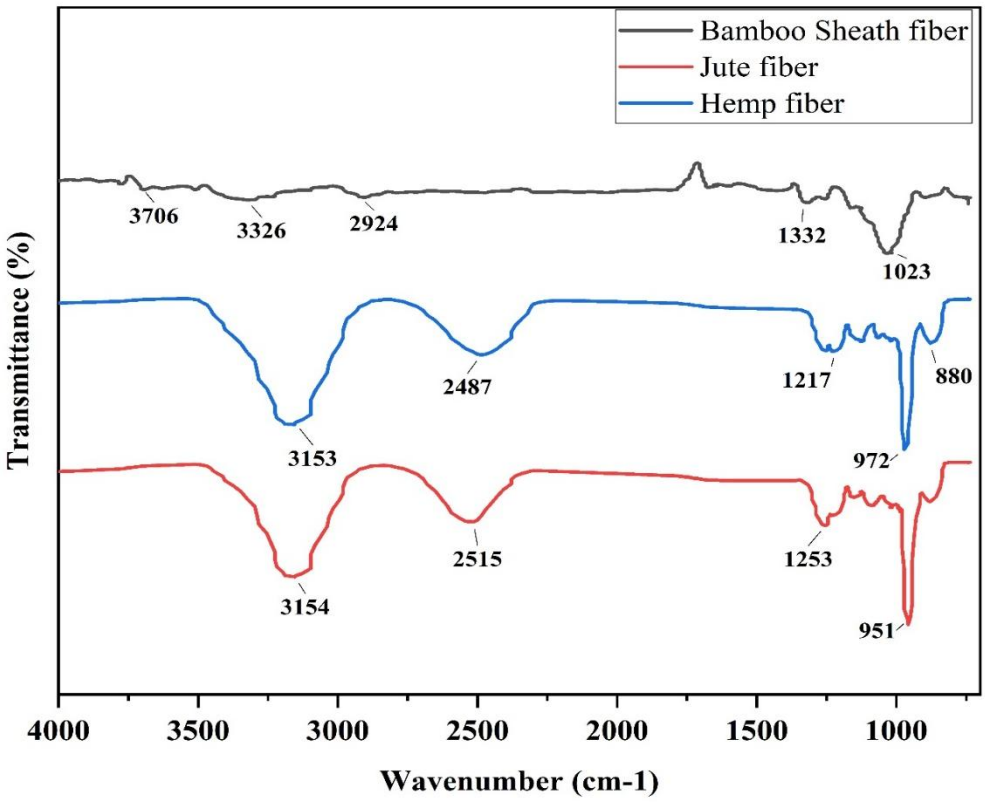


Fig. 4 FTIR analysis

XRD analysis:

Fig. 5 shows the XRD patterns of bamboo sheath, jute, and hemp fibers all display the characteristic diffraction profile of native cellulose I, marked by two principal reflections: a broad peak near 15–17° (2θ), corresponding to the overlapping crystallographic planes and a sharper, more intense peak near 20–23° (2θ), corresponding to the (002) plane, which is the primary indicator of cellulose crystallinity. A weaker reflection near 34–35° (2θ), attributable to the (004) plane, is also visible in all three fibers. The broad underlying background across each spectrum reflects the amorphous constituents of the fiber—largely hemicellulose, lignin, pectin, and disordered cellulose regions—that do not diffract coherently. Applying area integration method using the (002) peak intensity and the amorphous trough near 18° (2θ) as reference points, yields a crystallinity index of approximately 40% for bamboo sheath fiber, consistent with the reported value, while jute and hemp show comparatively higher intensity ratios between their crystalline peaks and amorphous baselines. This suggests that bamboo sheath fiber possesses a lower degree of crystalline order than the bast fibers, likely due to its role as a protective, non-load-bearing tissue with higher amorphous content and less axially ordered microfibrils in contrast to jute and hemp, whose bast origin favors densely packed, highly aligned cellulose microfibrils and correspondingly sharper, more resolved (002) reflections. Overall, the data support a structural hierarchy in which jute and hemp exhibit higher crystallinity and more ordered cellulose packing than bamboo sheath fiber(Eichhorn et al., 2001; Vembaian & Muthukkumaran, 2026, 2026).

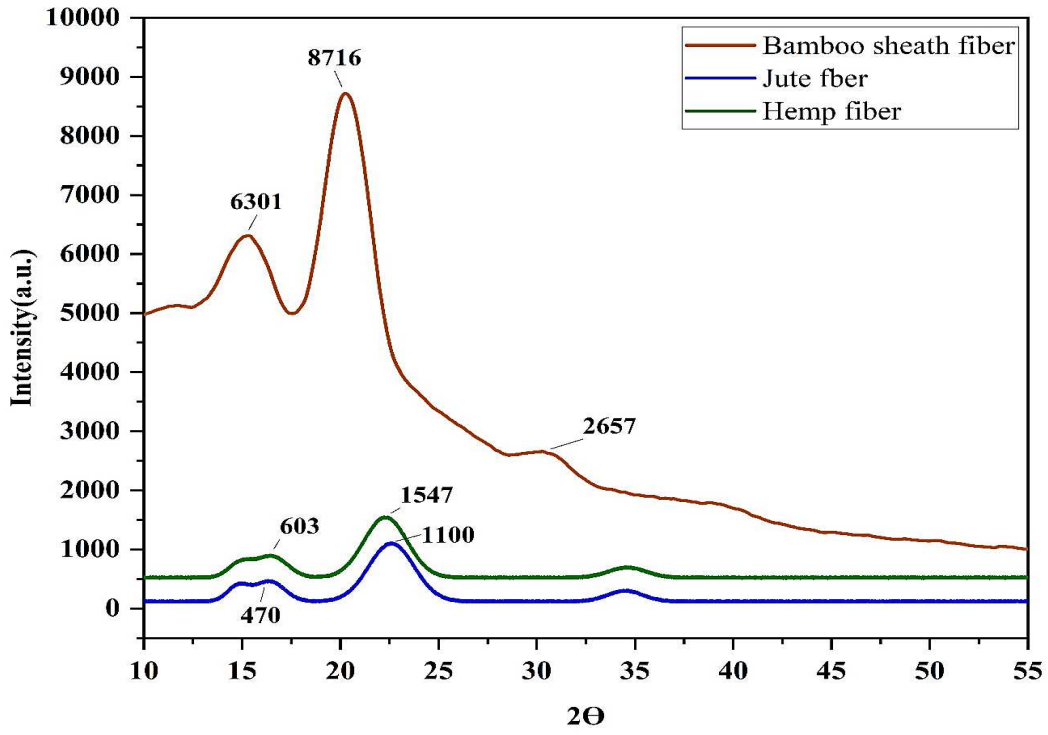


Fig. 5 XRD analysis

SEM analysis:

Fig. 6 expresses the SEM micrographs of bamboo sheath fiber at 200× and 500× magnification reveal a rough, longitudinally striated surface composed of multiple parallel micro-fibrils bundled together, interspersed with globular surface deposits attributed to residual waxes, pectin, and amorphous lignin/hemicellulose debris. This morphology is broadly consistent with other natural bast fibers such as jute, hemp etc., which similarly exhibit a fibrillar, multicellular architecture arising from their common origin as vascular bundle fibers bound by a lignin–hemicellulose–pectin matrix. Jute and hemp, in contrast, often show comparatively rougher surfaces with visible nodes/joints and greater impurity loading similar to bamboo sheath fiber, reflecting their higher lignin content relative to ramie/flax. The presence of surface deposits on bamboo sheath fiber, as with untreated jute and kenaf, indicates that chemical/mechanical extraction alone leaves behind non-cellulosic residues, which potentially enhancing initial matrix interlocking through increased roughness. Overall, bamboo sheath fiber shares the characteristic fibrillar bundle morphology of the bast fiber family but shows intermediate surface roughness and impurity content, positioning it mechanically and morphologically between the finer, cleaner ramie/flax fibers and the course, more heavily lignified jute/kenaf fibers, which has direct implications for its expected interfacial adhesion and reinforcement efficiency in polymer composites(Grant et al., 2026; Samir et al., 2022).

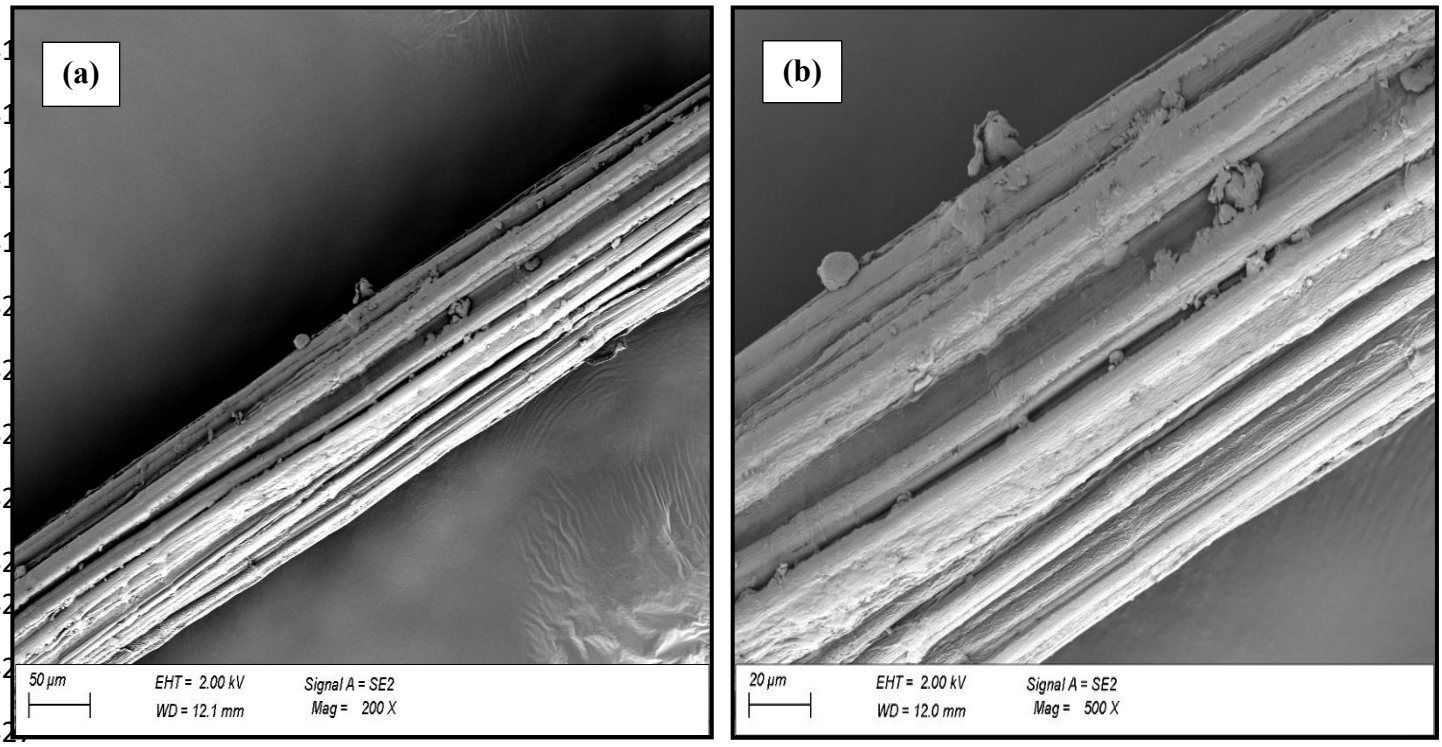


Fig. 6 SEM analysis (a) in 200X and (b) in 500X megapixel

Surface Roughness:

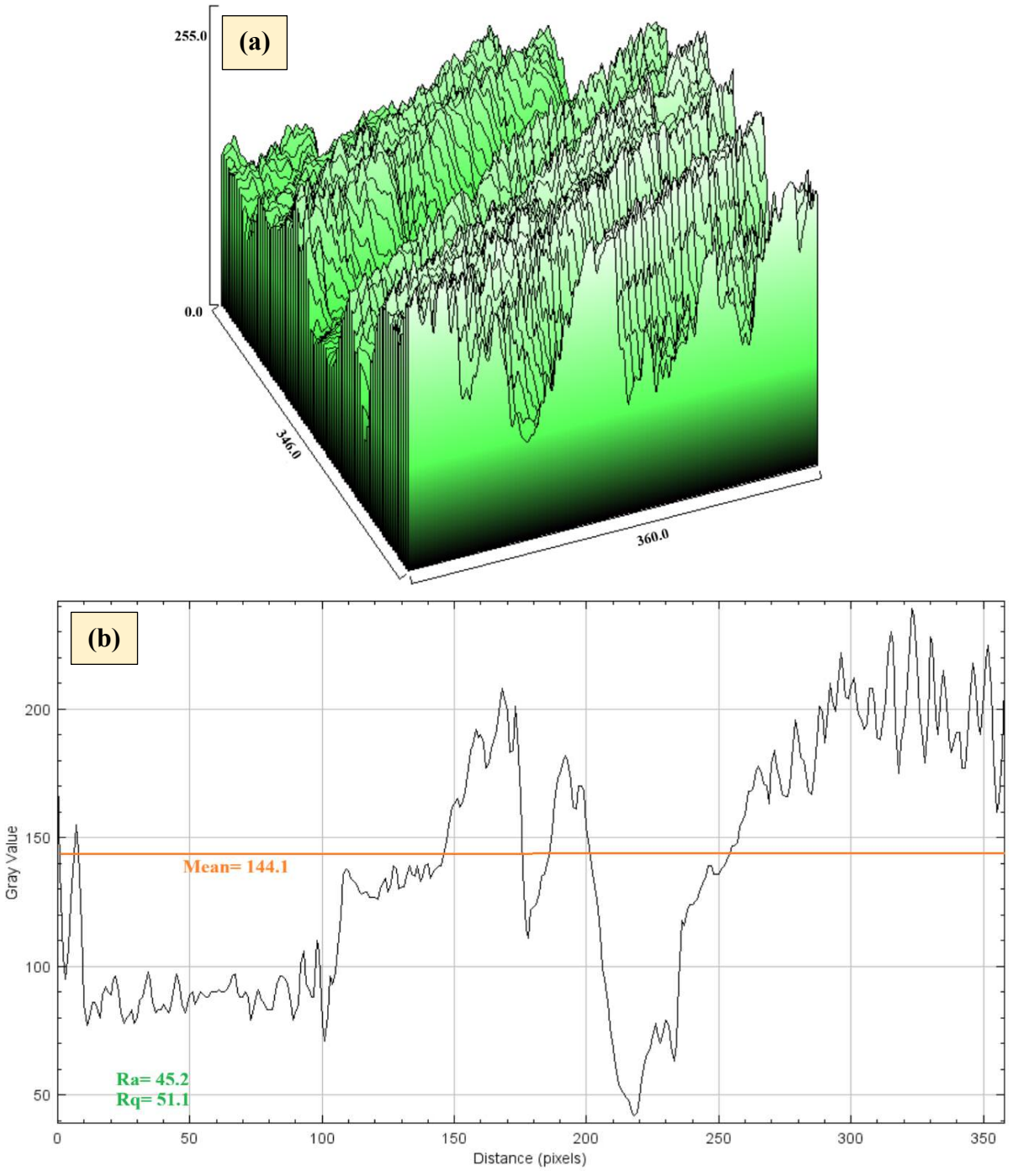


Fig. 7 Surface roughness analysis (a) 3D structure and (b) 2D structure of bamboo sheath fiber surface roughness picks.

Fig. 7 shows the 3D surface plot (a) and its corresponding 2D gray-value line profile (b), generated in ImageJ, together characterize the surface texture of the fiber by mapping pixel intensity (0–255) as a proxy for topographic height across the scanned area (346 × 360 pixels). The 3D rendering reveals a markedly heterogeneous, ridge-like surface with irregular peak-to-valley transitions running roughly parallel to the fiber axis, while the 2D profile shows the gray value fluctuating around a mean of 144.1, punctuated by a pronounced localized trough (near pixel 210–220) likely corresponding to a surface defect or lumen exposure. The derived roughness parameters Ra = 45.2 and Rq = 51.1 (with Rq slightly exceeding Ra, indicating a mildly skewed, non-uniform texture distribution) point to a moderately-to-highly textured surface. This is qualitatively consistent with reported surface characteristics of jute and hemp bast fibers in the literature, which are similarly dominated by irregular, wax/pectin/lignin-coated topographies that promote mechanical interlocking with a polymer matrix; treated (e.g., alkali-treated) jute and hemp fibers typically show even greater roughness than untreated ones due to removal of the waxy outer layer(Mwaikambo & Ansell, 2002; Rahman et al., 2023).

Chemical Composition analysis:

Fig. 8 presents Bamboo sheath fiber's composition (71.27% cellulose, 15.01% hemicellulose, 11.30% lignin, 2.42% wax/impurities) places it in a favorable middle ground between jute and hemp bast fiber. Its cellulose content is comparable to or slightly higher than hemp's typical 70–74% and clearly exceeds jute's usual 58–65%, suggesting tensile strength and stiffness competitive with hemp, one of the strongest natural fibers. Its hemicellulose fraction is close to hemp's range but notably lower than jute's characteristic 20–24%, implying better moisture stability and less swelling than jute. Its lignin content, however, mirrors jute's roughly 11–14% far more than hemp's low 3.5–6%, meaning bamboo sheath fiber retains a stiffer, more rigid "cementing" phase that gives it good microbial and structural resistance but likely requires similar delignification treatment to jute for finer, more flexible processing, unlike the naturally softer hemp bast fiber. Overall, bamboo sheath fiber combines hemp-like cellulose strength with jute-like lignin rigidity, making it a promising candidate for natural-fiber composites, though exact values across all three fibers vary with species, maturity, and extraction method(Aliasgharlou et al., 2026).

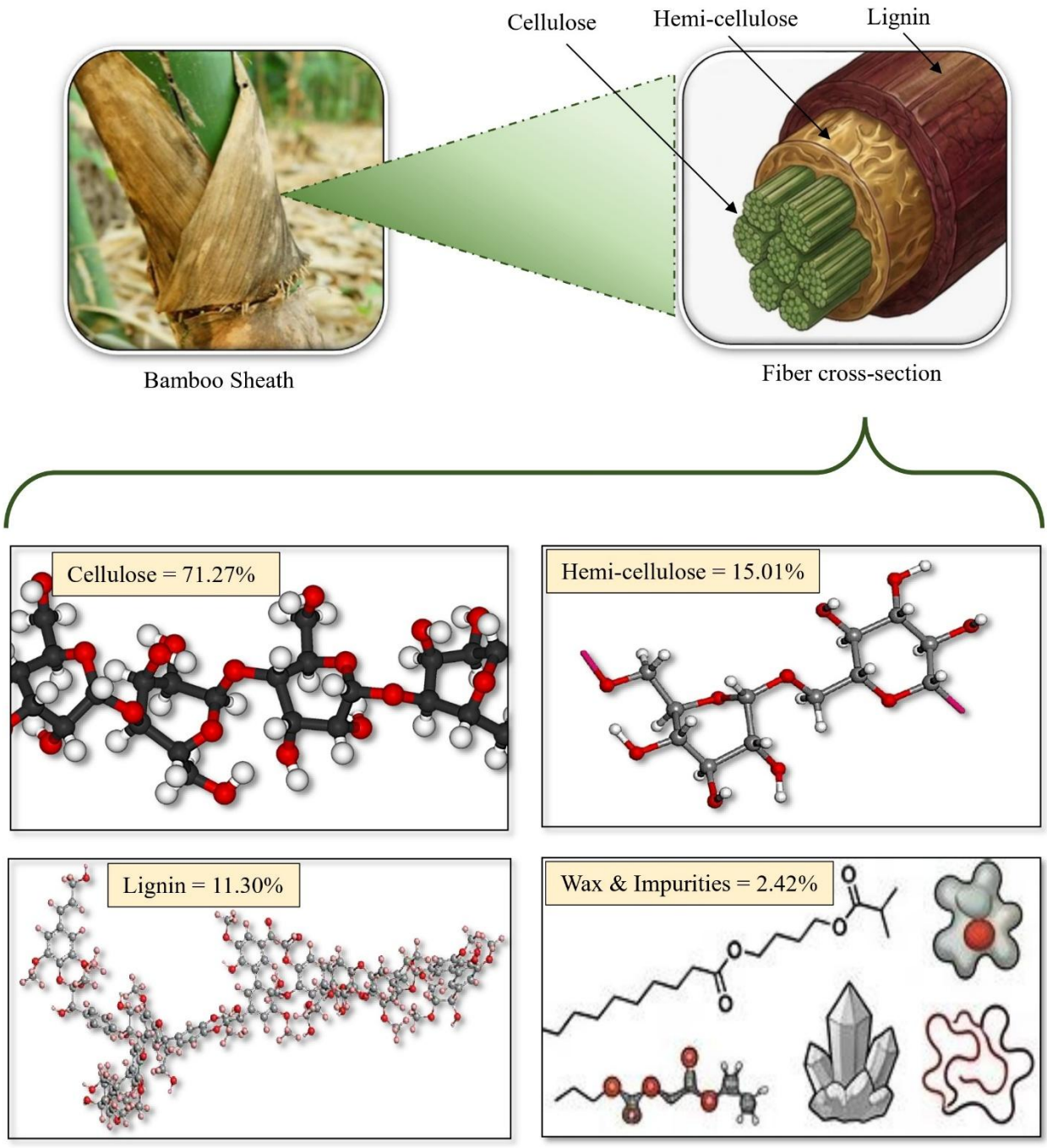


Fig. 8 Chemical composition of bamboo sheath fiber

Water absorbency analysis:

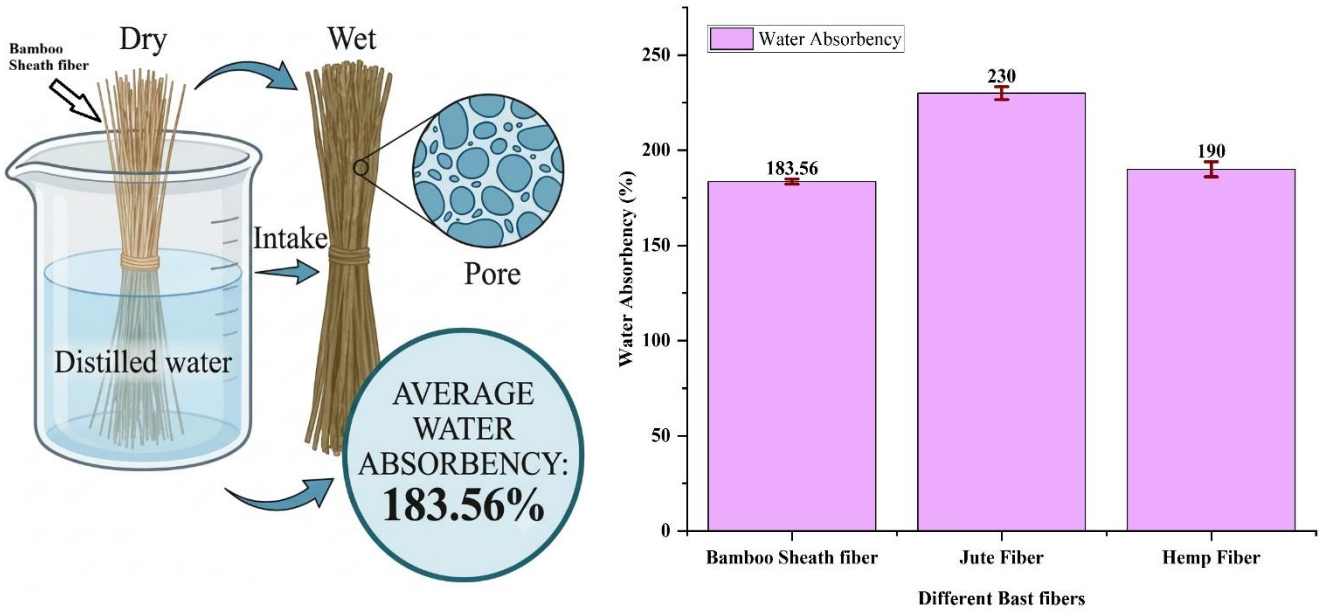


Fig. 9 Water absorbency analysis

Fig. 9 describes bamboo sheath fiber exhibited an average water absorbency of 183.56%, the lowest among the three bast-type fibers tested, followed by hemp fiber at 190% and jute fiber at 230%, the highest. This water uptake occurs primarily through capillary action within the fiber's lumen and inter-fibrillar spaces, combined with hydrogen bonding between water molecules and the abundant hydroxyl groups in cellulose, hemicellulose, and residual lignin/pectin, with the internal pore structure (visible in the micrograph inset) governing the extent of moisture retention. The comparatively lower absorbency of bamboo sheath fiber likely reflects tighter fibrillar packing, higher cellulose crystallinity, and/or a protective waxy cuticle layer that limits water penetration relative to the looser, more hemicellulose-rich structure of jute and the denser but more permeable structure of hemp. The small error bar for bamboo sheath fiber indicates high reproducibility across replicate measurements, and its lower, more stable water absorption makes it a promising candidate over jute and hemp for applications like natural-fiber composites, where excessive moisture uptake can compromise interfacial bonding, dimensional stability, and mechanical performance(Dev et al., 2025; Roy et al., 2026; Zolfakkar et al., 2024).

Conclusion:

Characterization of bamboo sheath fiber alongside jute and hemp using tensile testing, FTIR, XRD, SEM, surface roughness, chemical composition, and water absorbency analyses reveals that bamboo sheath fiber, despite having lower crystallinity index (40%) than the bast fibers,

achieves nearly three times higher tensile strength (23.14 N) owing to its bundled fibrillar architecture, which fails progressively and provides greater toughness than the brittle, single-stage fracture seen in jute and hemp. Its chemical composition (71.27% cellulose, 15.01% hemi-cellulose, 11.30% lignin) blends hemp-like cellulose strength with jute-like structural rigidity, while SEM and surface roughness analysis show a fibrillar, moderately rough morphology favorable for polymer matrix adhesion. Notably, bamboo sheath fiber recorded the lowest water absorbency (183.56%) among the three fibers, indicating better dimensional stability for composite applications. Collectively, these results position bamboo sheath fiber as a mechanically strong, moisture-resistant and structurally promising alternative to conventional bast fibers. Future work should focus on evaluating its performance in actual polymer composites, optimizing surface treatments such as alkali or silane modification to improve fiber–matrix bonding, enhancing crystallinity through refined extraction methods, and assessing long-term durability and scalable processing to establish bamboo sheath fiber as a viable industrial reinforcement material.

Author contributions:

Md. Redwanul Islam and Fahmida-E-Karim: writing—preparation and editing of the original draft, formal analysis, resources, figures and tables; Md. Reajul Islam, Amit Chakrabortty and Md. Zawad Ibna Jalil: conceptualization, visualization, supervision, review and editing; Samio Hossain, Atiq Shahriar, Md. Nakib Hossen: data curation, supervision, review and editing.

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Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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