Fibers and Polymers (2024) 25:1765–1777
https://doi.org/10.1007/s12221-024-00542-3

Online ISSN 1875-0052
Print ISSN 1229-9197

REGULAR ARTICLE

Impact of NaOH Treatment on the Chemical, Structural, Physico-mechanical, and Thermal Characteristics of Jute Species

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Received: 21 November 2023 / Revised: 28 February 2024 / Accepted: 22 March 2024 / Published online: 15 April 2024
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Abstract

Fiber extracted from two species of jute, *Corchorus olitorius* (tossa) and *Corchorus capsularis* (white), is chemically treated with different concentrations (1–6 wt%) of NaOH. Chemical composition, crystallinity, fineness, whiteness, surface morphology, mechanical strength, and thermal stability of both untreated and treated fibers from both jute species are studied. The effects of alkali treatments on the two jute species are characterized using chemical composition analysis, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), digital fiber fineness tester, photovoltmeter, universal testing machine (UTM), and thermogravimetric analyzer (TGA). Based on the comprehensive findings, the optimal NaOH treatment concentration was determined to be 5%. The 5% NaOH treatment on both species showed improvements in cellulose content (tossa 13.08%, white 12.88%), crystallinity (tossa 7.81%, white 8.09%), and single fiber strength (tossa 58.61%, white 72.22%). The higher mechanical strength of tossa fiber compared to white jute fiber indicates its potential for composite preparation. On the other hand, the comparatively thinner white jute fiber, when compared to tossa jute fiber, is suitable for blending with cotton or man-made fibers.

Keywords Tossa and white jute · Chemical treatment · FTIR · XRD · Single fiber strength · Fineness

1 Introduction

The significance of utilizing natural fibers has become more widely acknowledged as environmental and ecological concerns have grown [54]. Right after cotton, jute ranks as the second-largest natural fiber in the world [6]. Due to their remarkable qualities, such as low health risks, cost-effectiveness, favorable mechanical properties, low density, excellent insulation, thermal qualities, widespread availability, potential sustainability, and biodegradability, jute fibers are being widely used for a variety of purposes. These purposes include reinforcement in composite materials, blending with cotton fibers, applications in geotextiles, technical textiles, agro textiles, and more [2, 12, 53]. According to Cottrell et al., jute is a herbaceous shrub that grows quickly and belongs to the family Tiliaceae. Its genus name is Corchorus [9]. Most of the world's best fiber comes from tossa (*Corchorus olitorius*) and white (*Corchorus Capsularis*), which are the most valuable natural fiber sources [13]. These two types of jute fiber are known for having different fiber properties and yields [23, 33]. According to Ronald Aseer et al. [41], the distinctive physical and mechanical characteristics of jute fibers are mainly due to the presence of cellulose, hemicellulose, and lignin. Jute fibers possess excellent mechanical properties because of their high cellulose content and a minimal microfibrillar angle (J. A. [5, 26]. Another essential factor connected to the tensile strength of jute fibers is their diameter [4, 56].

For the future of sustainable engineering, structural materials composed of composite materials reinforced with jute fibers are currently seen as holding great promise [48]. However, the matrix is hydrophobic, while the cellulosic jute fiber is hydrophilic and contains the –OH group [17, 28].

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Jute fibers cannot adhere to the non-polar matrix due to the presence of the polar group. As a result, they are susceptible to moisture, which negatively impacts the qualities of jute composites, especially their strength and dimensional stability [8, 19, 21]. Another application of jute–cotton blended yarn in the textile sector faces a major challenge as jute fibers are coarse and contain non-cellulosic components [3]. The three structural components that bind jute fibers together are pectin, hemicellulose, and lignin. It is possible to improve fiber fineness/diameter as well as fiber softness by removing non-cellulosic elements [32, 44]. Jute yarn quality also depends on fiber diameter because fiber diameter determines means how many fibers are present in the cross section of a yarn of given thickness. The fiber diameter is also correlated with the tensile strength [43].

To address this issue, jute fibers need to undergo chemical processing to meet the demands of various applications [47, 54]. Alkali, silane, acrylation, acetylation, maleated coupling agents, benzoylation, permanganate, isocyanates, and various other chemical approaches have all been extensively studied [1, 16, 24, 29, 30, 52]. Among these, alkali (NaOH) treatment is the most popular and successful technique for enhancing the qualities of jute fibers when used as reinforcing materials [45, 49]. The textile industry commonly employs alkali treatment for mercerization and degumming. Additionally, this treatment not only removes impurities, especially hemicellulose and lignin, but also enhances qualities, such as absorbency, strength, structural integrity, and smoothness [27, 35, 36].

Research reveals that applying a 1–5% NaOH surface treatment increases the strength of jute fiber [37]. According to Zafar, Maiti, and Ghosh [58], jute fiber recently demonstrated the highest levels of tensile strength, crystallinity, and thermal stability after being treated with 5wt% NaOH for one hour. Sayeed (2019) conducted a study that examined the effects of NaOH on treated tossa jute fiber at different concentrations (4wt%, 0.5wt%, and 25wt%) and durations (30 min, 24 h, and 20 min). The findings indicated a 0.5wt% increase in tensile strength after a 24-h period.

This study aimed to subject tossa and white jute fibers to a 30-min treatment with NaOH at temperatures between 30 ± 20 ℃ and concentrations ranging from 1 to 6%. No prior research has compared these two species after they have been treated with NaOH. This study's main goal was to optimize the alkali treatment process for both species by subjecting them to varying amounts of NaOH, followed by a comparison of their distinct characteristics. By investigating the alkali treatment process, we aim to understand how it alters physical, structural, mechanical, thermal, and chemical properties of these two species. This knowledge will enable us to explore new applications for them in the textile, geotextile, composites, packaging, and other fields. After alkali treatment, jute fibers could play a crucial role in future of eco-friendly materials as people seek alternatives to synthetic fibers.

2 Materials and Methods

2.1 Material

Tossa (*Corchorus olitorius*) grade BTB (Bangla Tossa B) and white (*Corchorus capsularis*) grade BWB (Bangla White B) jute samples were obtained from the Farm management unit of the Bangladesh jute Research Institute (BJRI), Bangladesh. Sodium hydroxide (NaOH) pellets and acetic acid were used for chemical treatment and sourced from Merck, Germany. Sodium chloride salt and sulfuric acid, used for the chemical composition analysis of jute fiber, were sourced from Merck, Germany.

3 Methods

3.1 Modification of Raw Jute Fiber

Tossa and white jute fibers were alkali-treated by cutting them into 30 cm lengths, washing them in distilled water, and then oven-drying them to achieve a consistent weight. The solution was prepared by adding (1–6)% NaOH (by weight) to water. It was stirred at ambient temperature (30 ± 2 ℃) for a duration of 30 min while maintaining a fiber weight-to-liquor ratio of 1:30 (w/v). Afterward, the fibers were repeatedly rinsed with distilled water to remove alkali residues. Subsequently, the fibers were neutralized using 5 wt% acetic acid and washed thoroughly with distilled water. After washing, the fibers were left to air-dry for 24 h at room temperature and then underwent additional oven-drying at 80 ℃ for 6 h. Prior to conducting structural, mechanical, and thermal investigations, the dried fibers were stored in sealed plastic bags to protect them from moisture and contamination. Both untreated and alkali-treated single fibers were subjected to tensile tests following ASTM D3822.

3.2 Chemical Composition

The sample (tossa and white jute) was ground into a powder. A 0.7% sodium chlorite solution was used to treat three grams of fiber powder, maintaining a pH of 4.5 at a temperature of 70–80 ℃ for 3 h. The residue was dried and weighted (W1), and then it was mixed with 35 ml of a 17.5% NaOH solution. An additional 40 ml of NaOH was gradually added over a period of 10 min. The mixture was then left to stand overnight and filtered through a sintered crucible-1. The residues were dried, and their weight (W2) was measured.

Equations (1 and 2) were employed to calculate the percentages of cellulose and hemicellulose.

$$\text{Cellulose}(\%) = \frac{w2}{\text{Weight of dried fiber power}} \times 100 \quad (1)$$

$$\text{Hemicellulose}(\%) = \frac{w1 - w2}{\text{Weight of dried fiber power}} \times 100 \quad (2)$$

One gram of fiber powder was placed in a round-bottom flask, and 10 ml of 72% (V/V) sulfuric acid was added. The flask was cooled in an ice bath and left to dissolve for 2 h with intermittent stirring. Afterward, the mixture was diluted with 200 ml of distilled water and refluxed for 6 h. After cooling, the mixture was filtered through a sintered crucible-2 and thoroughly washed with distilled water. The lignin residue was subsequently dried at 100–105 ℃ until a constant weight was achieved. The lignin percentage was determined using Eq. (3).

$$\text{Lignin}(\%) = \frac{\text{Weight of dried lignin}}{\text{Weight of dried fiber power}} \times 100 \quad (3)$$

3.3 X-Ray Diffraction Analysis

The X-ray diffraction (XRD) technique was employed to identify and measure the crystalline phases of jute fibers by tracking the diffraction of X-rays following their interaction with the sample. Cu-kα radiation (incident ray wavelength, λ = 1.544 A) was directed at the sample. The scattered radiation was then detected within a 2θ range (10–80°) along the axis, with the detector rotating at a rate of 2° per minute. The Rigaku Smart lab SE Lab XRD system was utilized to determine the crystallinity of treated and untreated jute fibers, with a voltage of 40 kV and a current of 30 mA.

3.4 Fourier-Transform Infrared (FTIR) Spectroscopy Analysis

The structural characterization of the compositional bond properties for both untreated and treated tossa and white jute fibers was conducted using Fourier-Transform Infrared (FTIR) spectroscopy. A digital FTIR spectrophotometer (JASCO) employing the Attenuated Total Reflectance (ATR) technique was used at the Textile Physics Division of BJRI, Bangladesh. The transmittance range of the scan was 4000–500 cm^{-1}, and 60 scans were performed.

3.5 Measurement of Fiber Fineness

Fineness is an important property of any fiber, defined as the weight of fiber per unit length. The fineness of jute fiber was measured using the ISO-137 compliant YGOO2C fiber fineness analysis system. Initially, jute fibers were combed and individual fibers were prepared as slides. These slides were then placed on the microscope's sample holder, and the fiber diameter or fineness (in micrometers, μm) was measured using specialized software.

3.6 Whiteness (%)

Whiteness (%) was measured as a percentage compared to MgO, which is considered a hundred percent white, using a Photovolt reflectance meter Model 577.

3.7 Tensile Strength Measurement

The tensile strength of single fibers was measured at room temperature using H10KS-UTM Hounsfield test equipment from Tinius Olsen Ltd., England. The test was conducted under standard atmospheric conditions at (21 ± 2) and relative humidity of (65 ± 2)%, following ASTM D3822 guidelines. To mitigate the influence of diameter irregularities in the test, fibers within a diameter range of 30–40 mm were meticulously chosen under a microscope. Single fibers were chosen randomly by hand. In the testing process, samples with fiber misalignment at the center of the holes were omitted. The specimens were uniaxially pulled with a 10 N load range, a test speed of 2 mm/min, and a gage length of 37 mm.

3.8 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was employed to assess the surface characteristics of the fibers. SEM utilizes a focused electron beam that scans the surface of the sample to generate high-quality images of the surface topography. Surface morphologies of both untreated and alkali (NaOH)-treated jute fibers were examined using SEM.

3.9 Thermo-Gravimetric (TGA) Analysis

TGA was conducted on 400 mg of both untreated and treated tossa and white jute fibers at a heating rate of 5 ℃/mm in a nitrogen atmosphere. This analysis was carried out using a thermos-gravimetric Analyzer (ELTRA THERMOSTEP) at the textile physics division, BJRI, Bangladesh. The chemically treated/untreated jute fibers underwent TGA in high-purity nitrogen with a constant rate of 5 ml/min, a sample purge flow of 60 ml/mm and a balance purge flow of 40 ml/mm. Thermal decomposition of each sample occurred within a temperature range of 30–550 ℃, monitored by a programmable heating system.

4 Results and Discussion

4.1 Chemical Composition

The major chemical components of jute fiber are cellulose, hemicellulose, and lignin, which have a significant impact on the material's mechanical, structural, and physical characteristics [55]. Alkalization of the surface of the jute species alters their inherent chemical compositions. Alkali treatment alters hemicellulose, lignin, and other impurities in jute fiber by breaking down its molecular structure through hydrolysis and solubilization, resulting in its removal from the fiber matrix, which enhances the fiber's overall properties and performance [40]. Cellulose exhibits greater resistance to hydrolysis and solubilization due to its complex polysaccharide structure and strong intermolecular hydrogen bonds, unlike hemicellulose and lignin [14]. Table 1 presents the chemical composition of untreated and NaOH-treated tossa and white jute fiber (see Figs. 1, 2).

It is evident from Table 1 that NaOH treatment reduces hemicellulose, lignin, cellulose, and other components (such as fats, waxes, pectin, impurities). Notably, hemicellulose is reduced to a greater extent than other substances. Consequently, the percentage calculations

Table 1 Chemical composition of NaOH-treated Tossa and White jute fiber

Sample ID	Tossa Jute Fiber (Composition %)				White Jute Fiber (Composition %)			
	Cellulose	Hemicellulose	Lignin	Others	Cellulose	Hemicellulose	Lignin	Others
Untreated	63.50	21.30	13.00	2.20	60.70	23.00	14.00	2.30
2% NaOH-Treated	74.34	10.81	13.43	1.42	70.32	14.00	14.21	1.46
4% NaOH-Treated	75.66	9.59	13.38	1.37	71.78	12.45	14.35	1.42
5% NaOH-Treated	76.58	8.77	13.34	1.31	73.58	10.92	14.14	1.35
6% NaOH-Treated	76.33	9.04	13.30	1.33	73.30	10.91	14.45	1.34

Fig. 1 Tossa and white jute varieties plant, fiber, flower, fruit, and seed

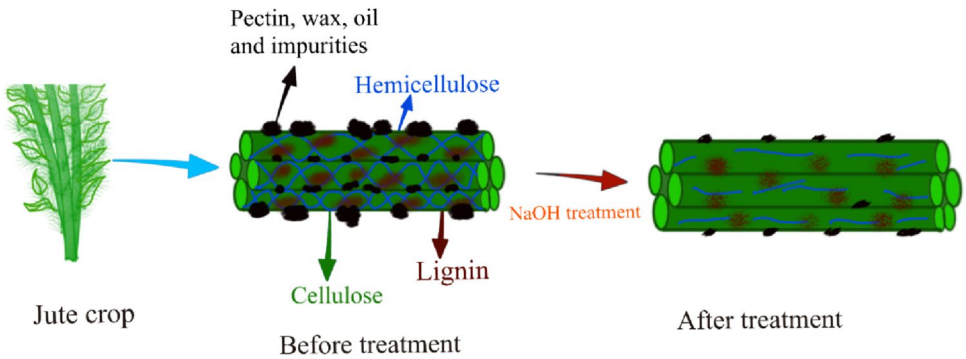

Fig. 2 Alkali treatment of jute fiber

following NaOH treatment for both varieties indicate an increase in cellulose and lignin relative to the sample's overall weight. The NaOH treatment resulted in a notable increase of 13.08% in cellulose content for tossa jute fibers, compared to a slightly smaller increase of 12.88% for white jute fibers. In the treated state, tossa jute fibers exhibited a slightly higher cellulose content (76.58%) compared to white jute fibers (73.58%), indicating a difference of 3%. Consequently, the single fiber strength, the whiteness (%), and the crystallinity moderately improve, while the diameter or fineness decreases [25, 57].

4.2 Changes in Chemical Compositions (FTIR)

The chemical structure of tossa and white jute species was examined using FTIR-ATR. Key absorption peaks of interest in this study have been identified and are depicted in Fig. 3a and b to observe compositional changes. The three main constituents of jute fiber, including cellulose, hemicellulose, and lignin, are tabulated in the Tables 2 and 3 [15].

The peaks in the range 3200–3600 cm^{-1} arise due to hydrogen-bonded O–H groups, representing cellulose and absorbed water [10]. The peaks at 2900 cm^{-1} are responsible for the C–H stretching vibration of cellulose and hemicellulose [39]. The band at 1733 cm^{-1} is characteristic of the C=O stretching vibration of carboxylic acid and ester groups in hemicellulose [39]. The reduction in

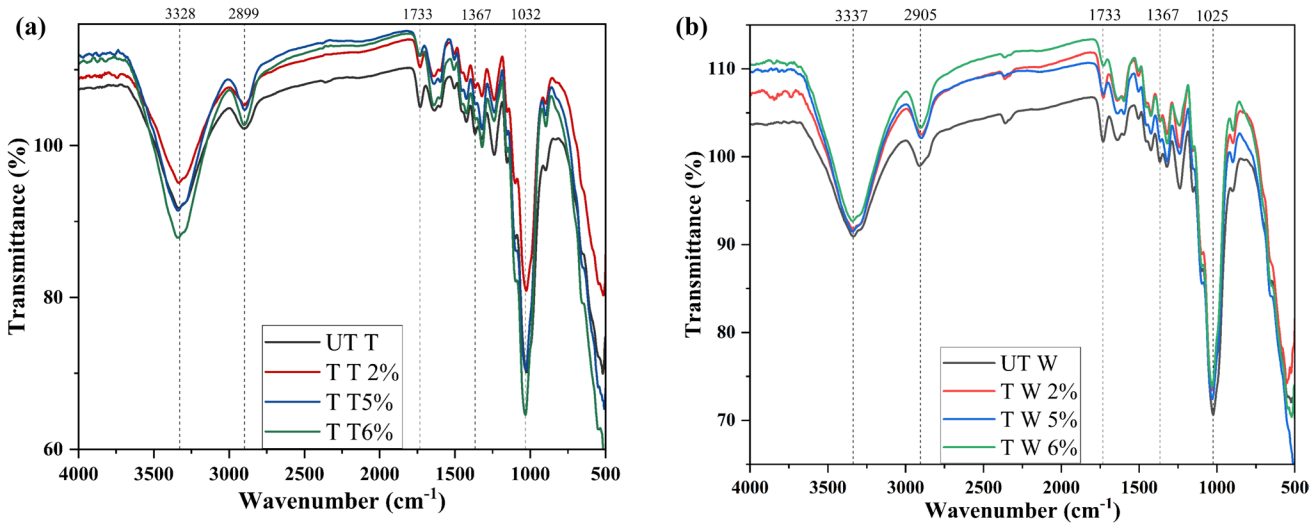

Fig. 3 FTIR of **a** untreated and treated tossa fiber, **b** untreated and treated white fiber

Table 2 FTIR peaks for raw, untreated, and treated tossa jute fiber

Possible assignment	Wavelength (cm^{-1})			
	UT T	2% T T	5% T T	6% T T
O–H stretching	3200–3600	3200–3600	3200–3600	3200–3600
C–H stretching vibration of cellulose and hemicellulose	2900	2899	2896.8	2096
C = O stretching of carboxylic acid or ester	1733	1732	1731	1730.9
Aromatic ring in lignin (exclusively in jute spectrum)	1601	1600	1599	1598.90
Aromatic ring in lignin (exclusively in jute spectrum)	1504	1505	1504	1506
Carboxylic acid and COO- vibration	1425	1425	1425	1425
C–H bending	1366	1365	1363	1362
O–H in plane bending	1321	1321	1321	1321
C–O stretching of acetyl (lignin)	1245	1245	1245	1245
v(C–C) ring breathing, asymmetric	1151	1151	1152	1153
v(C–O–C) glycosidic	1098	1100	1094	1094
v(C–OH) 10 alcohol	1026	1028	1029	1034

Table 3 FTIR peaks for raw, untreated, and treated white jute fiber

Possible assignment	Wavelength (cm^{-1})			
	UT W	2% T W	5% T W	6% T W
O–H stretching	3200–3600	3200–3600	3200–3600	3200–3600
C–H stretching vibration of cellulose and hemicellulose	2900	2898.5	2896.6	2995
C = O stretching of carboxylic acid or ester	1732	1731	1730	1729
Aromatic ring in lignin (exclusively in jute spectrum)	1600	1601	1600	1599
Aromatic ring in lignin (exclusively in jute spectrum)	1503	1503	1503	1503
Carboxylic acid and COO- vibration	1425	1425	1425	1425
C–H bending	1365	1365	1365	1365
O–H in plane bending	1322	1322	1322	1322
C–O stretching of acetyl (lignin)	1242	1242	1242	1242
v(C–C) ring breathing, asymmetric	1150	1150	1150	1150
v(C–O–C) glycosidic	1096	1096	1096	1096
v(C–OH) 10 alcohol	1025	1031	1031	1031

peak intensity found at 1733 cm^{-1} indicated the partial removal of hemicellulose, confirming the alkali treatment. The peaks at 1424 cm^{-1} and 1419 cm^{-1} are due to CH_2 symmetric bending, which is associated with cellulose and lignin [10]. The band at 1367 cm^{-1} is attributed to the C–H stretching vibration, associated with cellulose and hemicellulose [10]. The band at 1240 cm^{-1} is present in raw jute but removed due to the acetyl group in hemicelluloses via alkali treatment [39]. The C=O and O–H stretching vibration, connected to polysaccharides in cellulose, is responsible for the prominent peaks at 1032 cm^{-1} and 1025 cm^{-1}, respectively [42]. As a result, alkali treatment partially removes lignin, hemicellulose, pectin, oil, and fat, improving the surface functionality of the jute fibers compared to untreated jute fibers.

4.3 Crystallinity Property

The crystallinity of jute fibers is indicative of their strength and rigidity. Figure 4a and b displays the XRD patterns of both untreated/treated tossa and white fibers.

The major crystallinity peaks at 2θ = 23° and 16° represent the cellulose crystallographic planes (002) and (101), respectively. White and tossa fibers have somewhat distinct chemical compositions, which is reflected in the crystallinities of the fibers as well. Clearly, treated fibers from both species display narrower and heightened peaks when compared to untreated jute fibers. Following treatment, tossa jute fibers exhibited a growth of 7.81%, with white jute fibers displaying a similar increase of 8.09%. Regarding the comparison between tossa and white, prior to treatment,

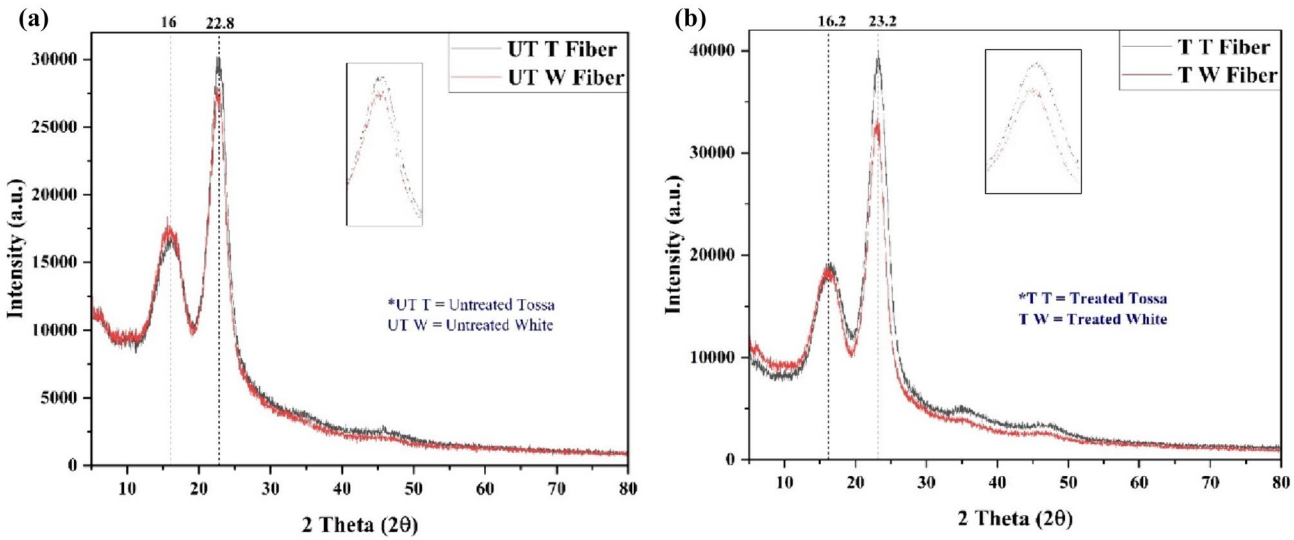

Fig. 4 XRD pattern of **a** Untreated Tossa and White fiber, **b** Treated Tossa and White fiber

untreated tossa jute fibers boasted a crystallinity approximately 1.14% higher than untreated white jute fibers. Post-treatment, this distinction marginally decreased to around 0.86%. Similar results were reported by [31, 58]. Table 4 represents the crystallinity index (CIs) of fibers.

4.4 Fineness/Diameter Property

The fineness of jute fibers is an important characteristic, typically measured by their weight per unit of length. Tensile strength and fiber diameter are interrelated. The fineness of tossa and white jute fibers is depicted Fig. 5a and b, respectively. The effect of NaOH treatment on jute fibers involves the removal of hemicellulose, lignin, waxes, and other impurities from the fiber surface, resulting in a decrease in fiber fineness. The fineness of single tossa jute fibers ranges from 36.42 µm to 33.24 µm, while white jute fiber fineness ranges from 33.45 µm to 29.72 µm for untreated and treated fibers, respectively. Treated tossa jute fibers exhibit an 8.73% reduction in fineness, and white jute fibers show an 11.15% reduction compared to untreated fibers. Initially, tossa jute fibers were 2.97 µm larger in diameter than white jute fibers. After treatment, this difference increased to approximately 3.52 µm. This is because white jute carries a higher content of hemicellulose and also loosens more compared to tossa. As a result, white jute fibers are finer than tossa jute fibers. This is important for blending with cotton or man-made fiber. [20] noted that altering the concentrations of alkali treatment on natural fiber kenaf resulted in differing levels of reduction in fiber diameter.

Table 4 The crystallinity index of untreated, 5% NaOH-treated Tossa, and White fiber

Sample Name	Untreated Tossa Fiber	Treated Tossa Fiber	Untreated White Fiber	Treated White Fiber
Crystallinity	64.37	72.18	63.23	71.32

4.5 Whiteness (%) Property

Whiteness (%) is an important factor when evaluating a fiber's quality. Figure 6a, and b shows the whiteness (%) of untreated and treated tossa, and white fiber. It is observed that the whiteness or color (%) increases with NaOH treatment as shown in Table 5. The whiteness (%) of tossa, whether treated or untreated jute fiber, is higher than that of white jute fiber, and both treated tossa and white fiber whiteness (%) gradually increase. This is due to NaOH treatment, which removes hemicellulose, fat, waxes, dirt, and other impurities from the fiber. Chakrabarti et al. [7] reported that treated fiber color (%) is higher than untreated fiber.

4.6 Tensile Strength Measurement

The stress–strain curve and the average single fiber tensile strength of untreated/alkali-treated tossa and white jute fiber are shown in Figs. 7a, b and 8, respectively. It is observed that treated/untreated tossa single jute fibers have higher strength compared to the white jute fibers. Tossa jute fibers contain more cellulose than white jute fibers [11, 43].

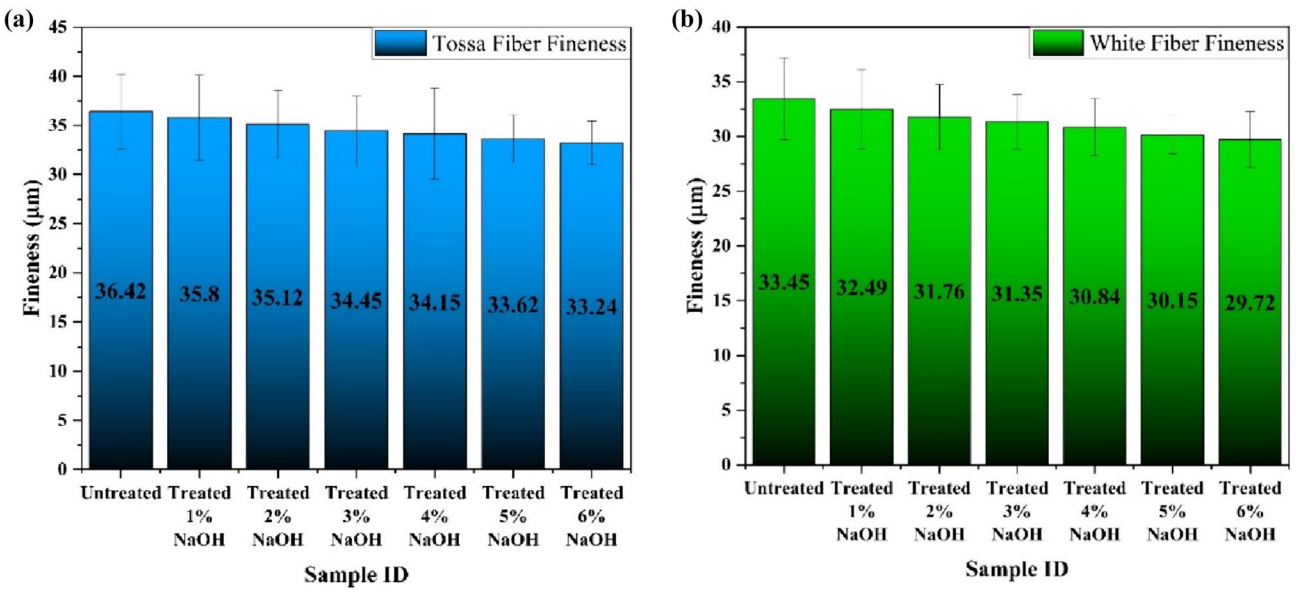

Fig. 5 Fineness of **a** tossa jute fiber, **b** white jute fiber

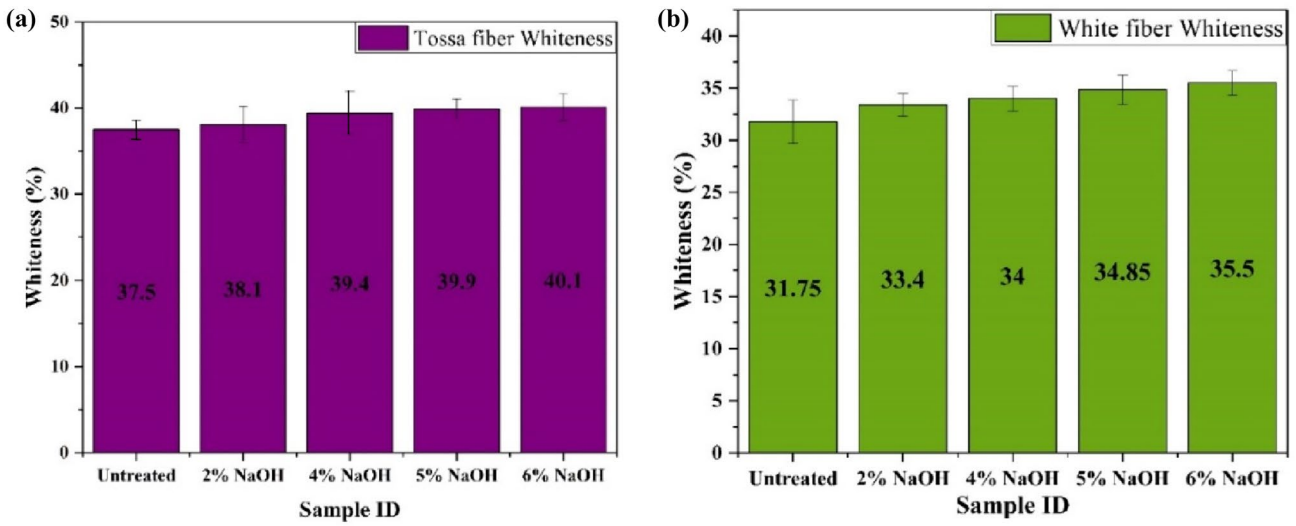

Fig. 6 Whiteness % of **a** untreated and treated tossa fiber, **b** untreated and treated white fiber

Table 5 Whiteness (%) of tossa and white (Treated/Untreated) jute fiber

Variety	Untreated	2% NaOH	4% NaOH	5% NaOH	6% NaOH
Tossa	37.5	38.1	39.4	39.9	40.1
White	31.75	33.4	34.0	34.85	35.5

The linear region of the stress–strain curve indicates the elastic properties of jute fiber. When comparing untreated and treated fibers for both species, the slope of the stress–strain curve increases. For tossa fiber, the slope increases by 24.91%, and for white jute fiber, it increases by 41.10%. This indicates that the treated fiber is stiffer than the untreated fiber. When compared with tossa and white fibers, the slope is higher by 55% and 65% for untreated and treated fiber, respectively.

Both treated fibers exhibit greater tensile strength than untreated jute fibers. The strength of white jute fiber improved by 72.22% and that of toss by 58.61% after the 5% NaOH treatment. Initially, untreated tossa jute fibers showed roughly 11.08% higher tensile strength than untreated white jute fibers. Post-treatment, this difference narrowed to about 2.22%. Further additional NaOH% resulted in a decline in strength. Zafar, Maiti, and Ghosh [58] demonstrated that an improvement in the packing of cellulose chains following

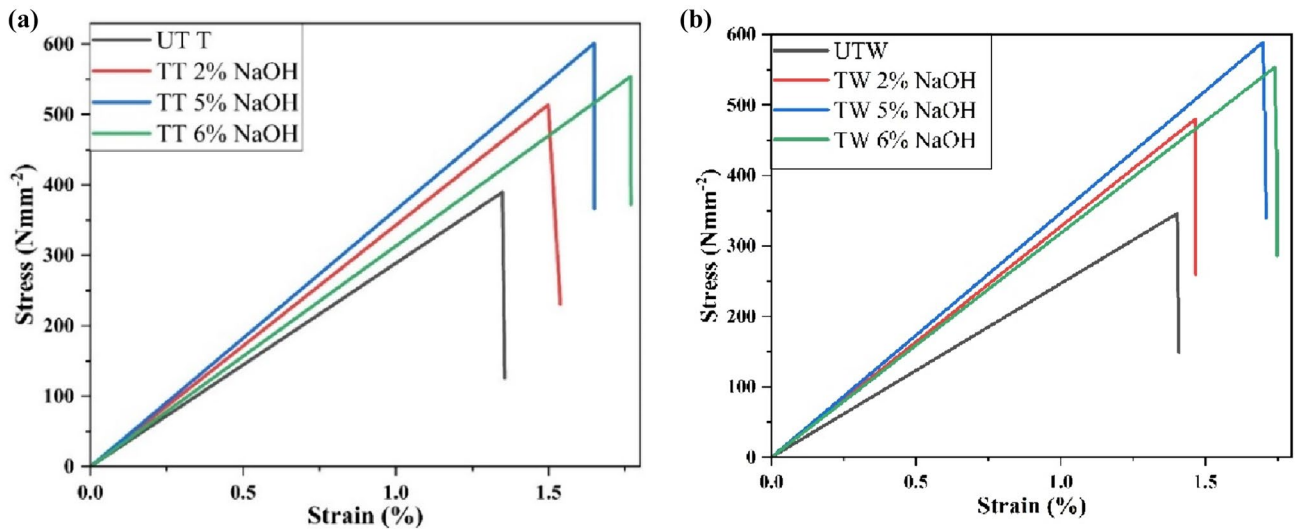

Fig. 7 Stress–strain graph of **a** untreated and treated tossa fiber **b** Stress–strain graph of untreated and treated white fiber

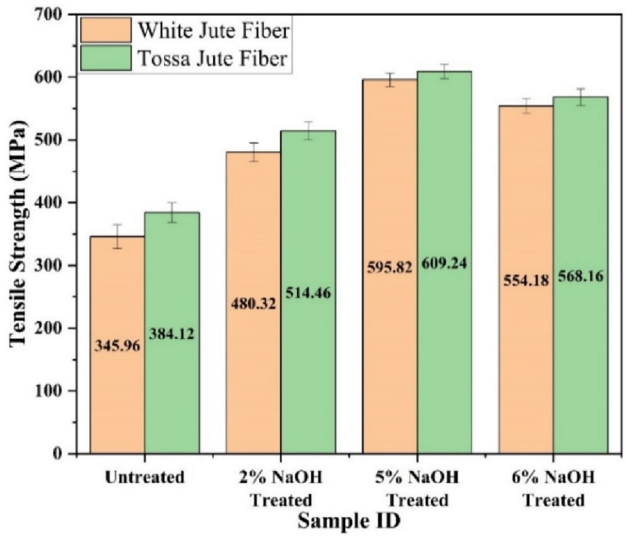

Fig. 8 Tensile strength of untreated and treated tossa and white fiber

the elimination of the non-cellulosic-like hemicellulose substances due to treatment may be the reason for an increase in the average single fiber strength of alkali-treated jute fiber compared to the untreated jute fiber.

In prior work, Taha, Steuernagel, and Ziegmann [51] discovered that treating natural fibers with alkali causes the cellulose micro-fibrils' spiral angle to decrease, allowing the cellulosic chains to be restructured and increasing tensile strength [18, 34]. Hemicellulose frequently remains dispersed in the inter-fibrillary space that separates the cellulose chains from one another in untreated jute fibers. Because the internal strain is released during the removal of the hemicellulose by NaOH, the cellulose chains are packed closer together [45]. As a result, tensile strength of jute fibers treated with NaOH increases as the fibrils organize themselves more compactly over time.

4.7 Surface Morphology

The surface morphology of untreated and treated tossa and white jute fibers is effectively examined through scanning electron microscopy. The surface morphology, specifically the smoothness and roughness, of untreated jute fibers is anticipated to differ from that of fibers treated with alkali.

The presence of hemicelluloses, lignin, gummy materials (waxes, pectin, and oil substance), and other impurities in the interfibrillar network of jute fibers increases irregularity. These gummy materials and impurities cover the cellulosic hydroxyl groups, inhibiting their interactions with the polymer matrices in jute fiber-reinforced composites and during blending with cotton fiber [50, 58]. The changes induced by alkali treatment in surface morphology and linear density of jute fibers significantly improve the adhesion of jute fibers with polyester matrices in jute fiber-reinforced composites [20]. Figures 9a, b, 10a, and b show a comparison of the surface morphology of jute fibers before and after alkali treatment using SEM. It is observed that untreated jute fibers carry hemicellulose, gummy materials (waxes, pectin, oil substance), impurities, and other cementing materials, such as lignin, on the surface. In contrast, treated fibers exhibit a reduction in hemicellulose, pectin, contaminants, and delignification on the fiber surface due to the improvements in cleanness and roughness. This enhancement contributes to increased tensile strength and crystallinity, as evidenced by their finer size.

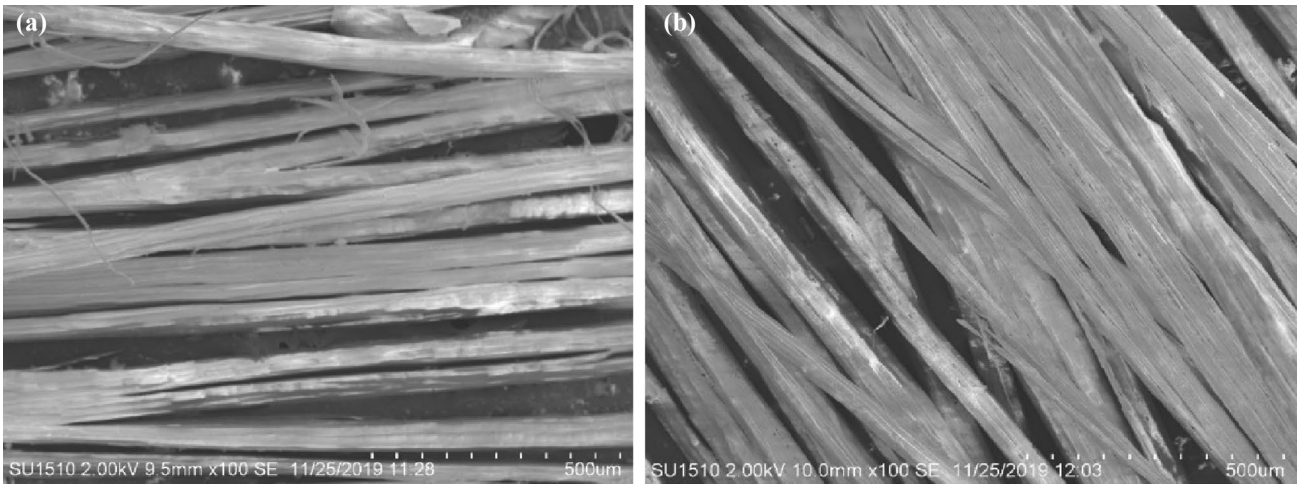

Fig. 9 SEM (500μm scale) of **a** untreated and **b** treated jute fiber

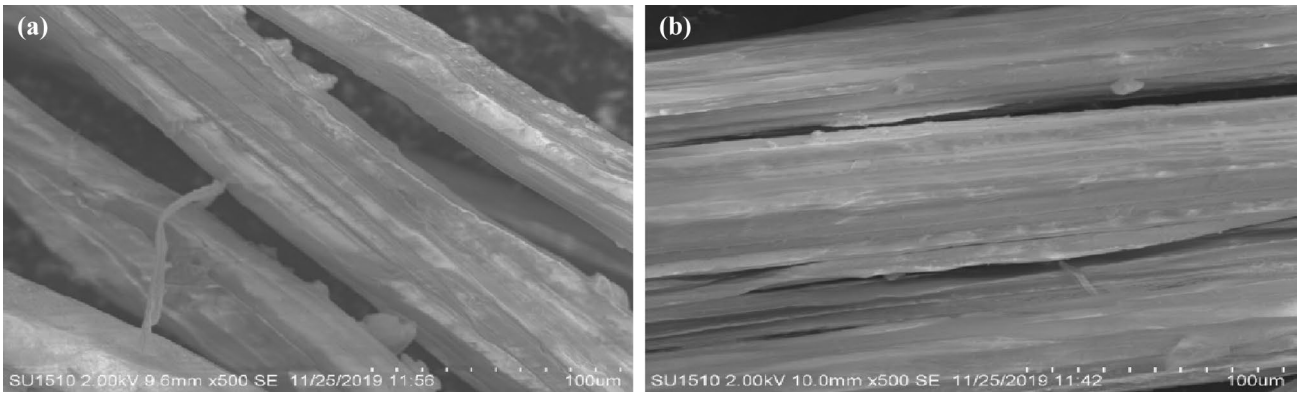

Fig. 10 SEM (100μm scale) of **a** untreated and **b** treated jute fiber

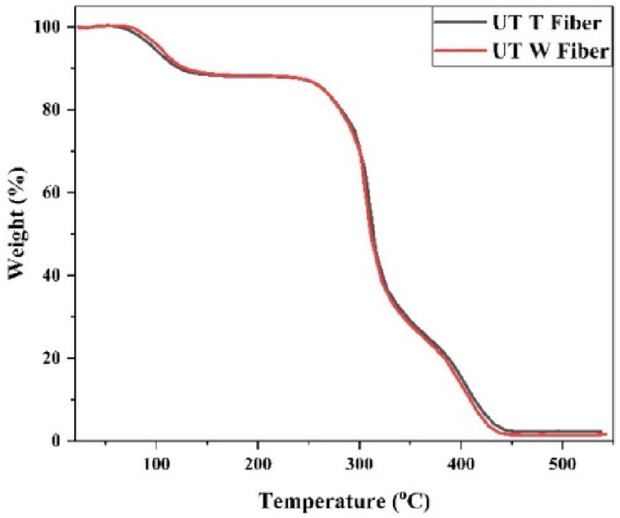

Fig. 11 a TGA of Untreated tossa/white jute fiber

4.8 Thermal Property

Figure 11a, b and c illustrates the changes in weight loss and thermal stability of tossa and white jute fibers over time at various temperature stages. Thermal stability of tossa and white (both treated and untreated) jute fibers was measured using TGA and is presented in Tables 6 and 7, respectively.

Overall, the thermal decomposition of jute fibers occurs in four phases. It begins with the decomposition of hemicellulose followed by cellulose, lignin, and finally the ash content. Both treated tossa and white jute fibers exhibit enhanced thermal stability compared to untreated fibers. In comparison between two jute varieties, tossa jute fiber demonstrates superior stability to white jute fiber. This observation is consistent with the findings of Ray et al. [38], who reported that alkali-treated jute fiber exhibits greater stability than untreated jute fiber. Huda et al. [22] also made similar observations for the surface treatment of pineapple leaf fiber (See Figs. 12, 13).

5 Conclusions

This study presents a detailed examination of the impact of NaOH treatment on tossa and white jute fibers, focusing on their chemical composition, structural properties (crystallinity, FTIR), fineness, whiteness (%), single fiber strength, surface morphology, and thermal characteristics.

Table 6 TGA of tossa jute fiber

Sample	Temperature (°C)			
	5% Weight loss	10% Weight loss	20% Weight loss	Maximum Weight loss
Untreated Tossa	97.2	125.7	282.5	310.2
1% NaOH-Treated	98.3	128.1	283.8	313.2
2% NaOH-Treated	100.2	134.1	282.1	314.1
3% NaOH-Treated	100.7	136.2	283.9	314.2
4% NaOH-Treated	102.4	137.2	285.4	315.2
5% NaOH-Treated	105.1	147.1	286.2	316.3
6% NaOH-Treated	106.3	141.7	288.6	318.2

Table 7 TGA of white jute fiber

Sample	Temperature (°C)			
	5% Weight loss	10% Weight loss	20% Weight loss	Maximum Weight loss
Untreated White	103.4	129.5	283.1	305.2
1% NaOH-Treated	104.3	142	283.7	306.5
2% NaOH-Treated	107.2	154.1	284.3	307.2
3% NaOH-Treated	117.1	149.1	284.4	308.5
4% NaOH-Treated	110.2	147.2	285.6	311.2
5% NaOH-Treated	108.5	140.1	286.2	310.2
6% NaOH-Treated	107.4	139.2	285.1	305.3

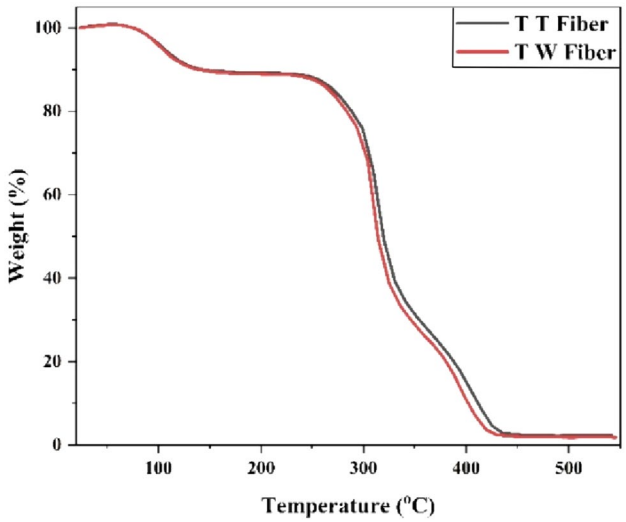

Fig. 12 a TGA of Treated tossa/white jute fiber

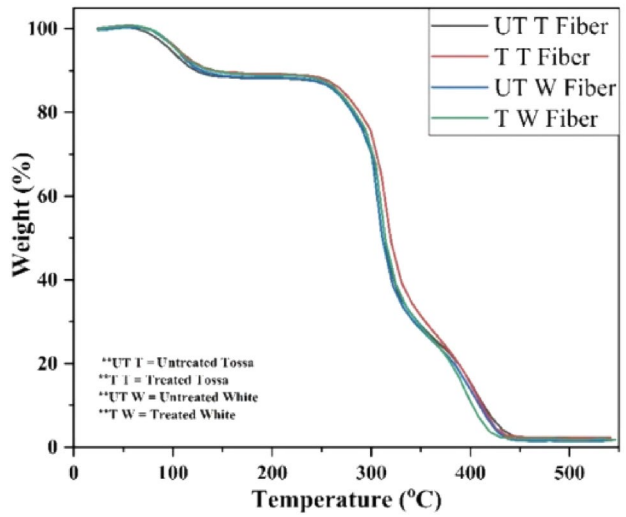

Fig. 13 c TGA of Untreated/Treated both jute fiber

In our comparative analysis, white jute exhibited a notably higher content of amorphous hemicellulose compared to tossa, influencing percentage-based outcomes across all examined aspects post-treatment. The NaOH treatment led to the disintegration of amorphous hemicellulose, a reduction in lignin, fat, and waxes, resulting in significant chemical changes. These alterations manifested in increased cellulose content, crystallinity, strength, whiteness (%), and fineness.

After NaOH treatment, compared to untreated tossa jute, tossa jute showed an increase in cellulose content by 20.60% and crystallinity by 12.13%, contributing to an enhanced single fiber strength of 58.61%. Similarly, white jute exhibited improved cellulose content (21.22%), crystallinity (12.79%), and a notable increase in single fiber strength (72.22%). However, both varieties experienced a decrease in fineness after treatment, for tossa, it is 8.73% and for white, it is 11.15%.

These quantitative findings provide valuable insights into the specific enhancements brought about by NaOH treatment. The results suggest that tossa jute, particularly after NaOH treatment, is well-suited for reinforcing composites in structural applications, showcasing significant improvements in mechanical properties. On the other hand, white jute, whether untreated or treated, proves to be suitable for blending with cotton or man-made fibers to achieve finer properties. These outcomes contribute to a nuanced understanding of the implications of NaOH treatment on different jute species, offering practical applications in diverse industries.

Data Availability Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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