Type of contribution:
Editorial
▶ Research Paper
Case Study
Review Paper
Scientific Data
Report of Tech. Application

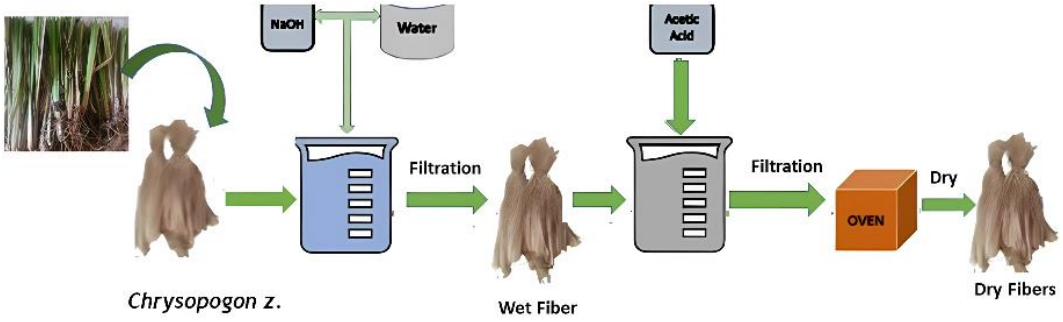
e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 5, No. 2 (2025) pp 385-398
https://doi.org/10.31603/mesi.14133

Characterization of alkali-activated *Chrysopogon zizanioides* natural fibers as reinforcement for energy-efficient biocomposite applications

Nasmi Herlina Sari[1]*, Sujita[1], Edi Syafri[2], Suteja[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, University of Mataram, Mataram 83125, **Indonesia**
[2] Department of Agricultural and Computer Engineering, Politeknik Pertanian Negeri Payakumbuh, Payakumbuh 26271, **Indonesia**
✉ n.herlinasari@unram.ac.id



Highlights:

- Alkali activation of *Chrysopogon zizanioides* fibers (CZF) studied for biocomposites.
- NaOH treatments (1–5%) enhanced crystallinity up to 65.74% and reduced impurities.
- Tensile strength increased from 252 MPa to 553 MPa with 5% NaOH treatment.
- Improved thermal resistance with 4.46% char residue at 600 °C was achieved.
- 5% NaOH-treated CZF showed optimal structural, mechanical, and interfacial properties.

Abstract

This study examines the characteristics of alkali-activated *Chrysopogon zizanioides* natural fibers (CZFs) to determine their applicability as reinforcements in energy-efficient biocomposite applications. Unlike earlier research, which has mostly focused on conventional natural fibers, this paper proposes CZFs as a fresh, sustainable reinforcing possibility. The study investigates the impact of different levels of NaOH (1%, 3%, and 5%) on fiber structure and functionality, offering new insights into optimizing alkali activation for improved interfacial bonding and strength in biocomposites. The results show that alkaline treatment significantly influenced the structural and functional properties of the fibers. X-ray diffraction (XRD) analysis revealed an increase in crystallinity index from 36.17% in untreated fibers to 65.74% in those treated with 5% NaOH, indicating significant removal of amorphous components. FTIR spectra confirmed the reduction of non-cellulosic functional groups, while TGA/DTA analysis demonstrated improved thermal resistance, with a maximum char residue of 4.46% at 600 °C. Mechanical tests showed tensile strength increased from 252 ± 25 MPa to 553 ± 26 MPa and elongation from 4.1% to 5.8%, while SEM analysis revealed cleaner, rougher surfaces that promote fiber–matrix bonding. Additionally, fiber density rose from from 410 ± 20 to 980 ± 20 Kg/m^3, and moisture content declined from 8.9% to 5.3%, reflecting improved dimensional stability. Among all treatments, the 5% NaOH-treated fibers offered the most optimal combination of structural, thermal, and interfacial performance. These results indicate that alkali-modified CZFs are promising candidates for use in energy-efficient biocomposites, particularly for lightweight structural components, automotive panels, and sustainable packaging requiring thermal durability and high stiffness.

Keywords: *Chrysopogon zizanioides*; Alkali treatment; Natural fiber; Thermal stability; Energy-efficient materials

Article info
Submitted: 2025-06-04
Revised: 2025-09-11
Accepted: 2025-10-18

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License

Publisher
Universitas Muhammadiyah Magelang

1. Introduction

Increased awareness of environmental challenges, as well as the limited availability of non-renewable resources, has fueled interest in the development of eco-friendly materials. Natural fiber-reinforced composites have emerged as a possible answer, particularly those based on lignocellulosic fibers, which offer an appealing combination of low density, mechanical strength, sustainability, and lower environmental impact when compared to synthetic alternatives [1], [2].

One potential yet underutilized natural fiber is generated from *Chrysopogon zizanioides* stems, also known as vetiver. This perennial grass species from the *Poaceae* family is gaining popularity worldwide due to its extraordinary resilience to harsh environmental conditions and wide range of industrial applications [3], [4]. *Chrysopogon zizanioides* is well-known for its essential oil produced from the roots, which has significant antibacterial and antioxidant qualities, making it particularly useful in the fields of medicine and skincare. However, this plant's fibrous stem is still neglected as a biological resource. Recent research has demonstrated that the stem fibers of *C. zizanioides* contain high quantities of cellulose and have a distinct structural shape, indicating that they have significant promise as reinforcement in sustainable biocomposites [5], [6]. Despite the plant's well-known environmental benefits, extensive research into the structural and functional performances of its stem fibers in composite applications is currently absent. One of the most significant issues is its intrinsic weaknesses, which include excessive water absorption, low heat stability, and weak interfacial interaction with the polymer matrix [7], [8], [9]. These issues are typically linked to the presence of non-cellulosic constituents including lignin, hemicellulose, and surface waxes, which impede effective stress transfer at the fiber-matrix interface. To address these constraints, alkali treatment with sodium hydroxide (NaOH) was developed as a dependable approach for improving fiber characteristics (**Figure 1**). This chemical treatment not only removes amorphous elements, but also enhances fiber crystallinity, surface roughness, and interface adhesion [10], [11], [12], [13]. In addition, the improved thermal resistance and interfacial compatibility attained by this alteration hold great promise for the creation of high-performance, energy-efficient biocomposites.

Several prior investigations looked into chemical treatments for natural fibers to increase their performance in composite materials. For example, Ren *et al*. [14] discovered that treating kenaf fibers with 1% NaOH can boost crystallinity and adherence to the epoxy matrix, hence increasing the composite's mechanical characteristics. Furthermore, Sari *et al*. [15] discovered that a 5% NaOH treatment on *Paederia foetida* fibers increased their tensile strength by up to 43.27% while maintaining good thermal stability. Meanwhile, Alsafran *et al*. [1] discovered that treating *Pulicaria undulata* fibers with NaOH and acetic acid can improve crystallinity and surface roughness, but it also reduces the fibers' innate antifungal and antioxidant characteristics. Furthermore, Djalal *et al*. [16] discovered that treating *Aster squamatus* fibers with 1.5% NaOH improved their mechanical characteristics and crystallinity, making them more competitive as composite reinforcements than synthetic fibers. However, research into *C. zizanioides* as a source of biofunctional fibers, particularly in terms of physicochemical modification via alkali (NaOH) treatment as well as its effects on thermal stability and reinforcement potential in composite materials, is still limited. This research gap demonstrates that the potential of *C. zizanioides* as an engineering fiber material has not been adequately explored, particularly in terms of generating sustainable materials based on natural fibers.

Therefore, this study aims to evaluate the effect of alkali evaluate the effect of alkali NaOH treatment on the structural, morphological, mechanical, and thermal properties of *Chrysopogon zizanioides* stem fibers. Surface morphology was analyzed using scanning electron microscopy (SEM), functional groups were identified using Fourier transform infrared spectroscopy (FTIR), thermal stability was assessed using thermogravimetric analysis (TGA), and fiber tensile strength was tested. The findings are expected to not only provide a thorough understanding of changes in fiber properties as a result of NaOH alteration, but also to help produce green and energy-efficient biocomposites for structural applications in the advanced materials industry.

2. Materials and Methods

2.1. Materials

Chrysopogon zizanioides grass plants were found in the Pagesangan area of Mataram, West Nusa Tenggara. Distilled water, pure sodium hydroxide (NaOH) in concentrations of 1%, 3%, and 5%, and glacial acetic acid.

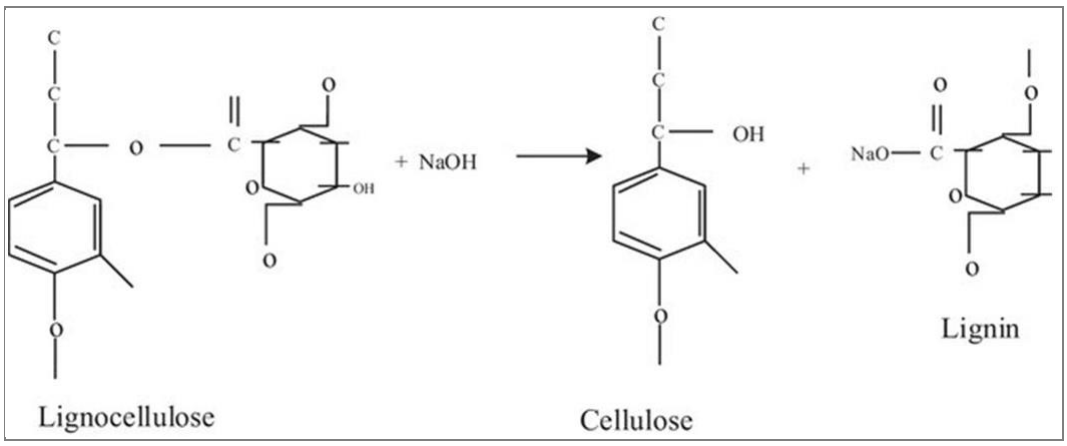


Figure 1. Mechanism of lignocellulose reacting with NaOH [17]

2.2. Fiber Extraction

Figure 2 depicting the extraction of *C. zizanioides* fibers. First, the grass stems were stripped of leaves. To aid fiber extraction, the grass stems were steeped in fresh water (water retting) for four days to allow microbial breakdown [18]. The fibers were carefully removed from the outer layer with a comb and rinsed under running water to eliminate any surface dirt. The fibers were then dried in an oven at 70 °C for 2 hours to yield fibers (hence referred to as CZFs raw).

2.3. Alkali Treatment of CZFs

CZFs were immersed in NaOH solution at several concentrations (1%, 3%, and 5%) at room temperature (31 ± 2 °C) for 2 hours. To maintain material uniformity, all fiber samples were collected from the same batch of *Chrysopogon zizanioides* fibers. To avoid bias, fibers from the batch were randomly picked for each treatment group before to alkali activation. They were rinsed with filtered water to remove any remaining NaOH solution, and then oven-dried for 60 min at 75 °C to eliminate the water content. They were then neutralized by soaking in an acetic acid solution for 60 min at room temperature [1], [16], [19], [20], and rinsing with distilled water until neutral pH. The fibers were then oven-dried at 65 °C for 2 hours. The treatment was conducted using a fiber-to-solution ratio of 1:20 (w/v) to ensure uniform chemical exposure. **Figure 3** depicts the alkali treatment of the fibers in detail, whereas **Table 1** shows the labeling of the generated test samples.



Figure 2. The extraction of *Chrysopogon zizanioides* fibers

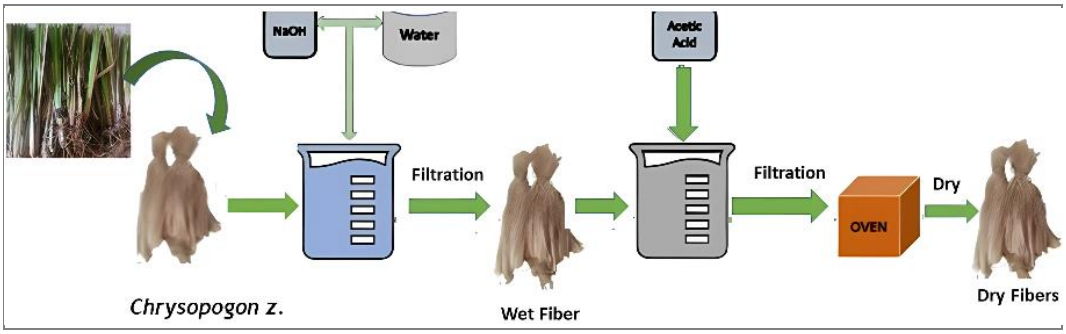


Figure 3. Schematic of alkali treatment of *Chrysopogon zizanioides* fiber

Table 1. Fibers sample codes before and after treatment with NaOH at varied concentrations for 2 hours

Samples	Description
CZFs raw	Untreated *C. zizanioides* fiber
CZFs-treated 1% NaOH	*C. zizanioides* fiber treated with 1% NaOH for 2 h.
CZFs-treated 3% NaOH	*C. zizanioides* fiber treated with 1% NaOH for 2 h.
CZFs-treated 5% NaOH	*C. zizanioides* fiber treated with 1% NaOH for 2 h.

2.4. Characterization

2.4.1. Chemical Composition

CZF's cellulose, hemicellulose, and lignin contents were determined using the TAPPI method. An 8-hour soxhlet extraction with alcohol and acetone was performed. TAPPI T203 om-93 was used to conduct the chemical analysis of CHF, while T222 om-88 was used to quantify the Klason lignin content (acid insoluble). The technique was followed to determine the hemicellulose content [21].

2.4.2. Moisture Content Test

The sample's water content was tested using a typical oven-drying procedure. To eliminate moisture, 5 g of CZFs samples were weighed and dried in a laboratory oven at 105 ± 2 °C for 24 hours. After drying, the samples were moved to a desiccator and cooled to ambient temperature to prevent moisture absorption from the surrounding environment. We used an analytical balance with a precision of 0.0001 g to record the beginning and final masses as W_{wet} and W_{dry}. The water content (*WC*) was estimated using Eq. (1) [11], [22].

$$Water\ Content\ (\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100\% \quad (1)$$

2.4.3. Density

The density of CZF samples was evaluated using a pycnometer and toluene as the displacement medium, in accordance with the ASTM D578-79 standard. Three independent measurements (n = 3) were conducted for each treatment group using approximately 1.0 g of oven-dried fibers. To decrease variability and assure consistent packing, samples were randomly picked from the same batch, trimmed to 10 mm length, and manually blended. The provided values are the mean ± standard deviation from three replicates. Prior to testing, the CZFs were dried in a desiccator using silica gel for 96 hours to remove residual moisture before being ground into roughly 5 mm particles. To remove trapped air, the samples were submerged in toluene in a borosilicate tank for 120 min. Eq. (2) was used to get the density (ρ_{CZFs}) [21], [23].

$$\rho_{sample} = \left(\frac{(m_2 - m_1)}{(m_3 - m_1) - (m_4 - m_2)}\right) \times \rho t \quad (2)$$

where: ρ_{sample} = density of CZFs (kg/m³); ρ_t = density of toluene (866 kg/m³); m_1 = mass of empty pycnometer (kg); m_2 = mass of pycnometer with CZFs (kg); m_3 = mass of pycnometer with toluene (kg); m_4 = mass of pycnometer with CZFs and toluene (kg).

2.4.4. Fourier Transform Infra-Red (FTIR) Analysis

The functional group of all examined samples was determined using FTIR on a Perkin-Elmer Frontier. All samples were made in a square film measuring 1 cm x 1 cm. The spectra were scanned from 4000-600 cm^{-1} with 4 cm^{-1} resolution.

2.4.5. Crystallinity Index

PANalytical used X-Ray Diffraction (XRD) to investigate the crystallinity index (*CI*) of the samples. A diffractometer equipped with a ray circuit captured the XRD profile. Radiation was *Cu-Kα* with a wavelength of 1.5406 Å. The current and voltage were set at 30 mA and 40 kV, respectively. The 2θ degree was scanned at a rate of 20°/min from 2-100°. The Segal method is used to calculate crystallinity, as shown in Eq. (3) [24].

$$CrI\ (\%) = \frac{I_{002} - I_{am}}{I_{002}} \times 100 \quad (3)$$

where, I_{002} represents the crystalline peak at 2θ = 22°, while I_{am} represents the amorphous zone at 2θ = 18°.

2.4.6. Morphology Test by Scanning Electronic Microscopy (SEM)

The surface morphologies of samples were examined using a JEOL JCM 7000 (USA Inc.) SEM operated at 10 kV. Before examination, the samples were coated with gold and sputtered for 5 min. A moving magnifier was used to collect images in order to investigate the structural properties of the CZFs in general.

2.4.7. Thermogravimetric Analysis (TGA)

Thermogravimetric and differential thermal analyses (TGA/DTA) were performed using a Shimadzu DTG-60H thermal analyzer (Shimadzu Corporation, Japan). Approximately 10 mg of each fiber sample was heated from room temperature to 600 °C at a rate of 10 °C/min under a nitrogen atmosphere.

2.4.8. Mechanical Tests

Tensile tests were carried out on a Universal Testing Machine (UTM, model RTG 1310 INSTRON) fitted with a 5 kN load cell and a crosshead speed of 2 mm/min. To assure data reliability, each measurement was taken in triplicate. The composite tensile strength was tested at 31.7 °C and 56% relative humidity. The dimensions of the tensile test specimens are in accordance with ASTM D3039.

3. Results and Discussion

3.1. FTIR Analysis

Figure 4 displays the FTIR spectra of various produced fiber samples. The FTIR spectra reveal a number of distinctive peaks for the produced fibers, each representing a distinct functional group. The band at 3465 – 3476 cm^{-1} represents the – OH (hydroxyl) stretching vibration, linked to water concentration and hydroxyl groups in cellulose, hemicellulose, and lignin. The strength of this band diminishes after NaOH treatment, showing that the elimination of hemicellulose and lignin reduces the number of free hydroxyl groups available. The band at 2869 – 2907 cm^{-1} corresponds to the asymmetric-CH stretching vibration of the methyl and methylene groups. After treatment, this band diminishes somewhat, indicating that the alkyl chain structure has changed. Then, carbonyl groups in hemicellulose or pectin exhibit a C=O stretching vibration at 1735 cm^{-1} [21]. These bands vanished after being treated with NaOH, showing that the alkalinization method was effective in eliminating hemicellulose. The bands at 1618 – 1640 cm^{-1} and 1400 –1419 cm^{-1} correspond to lignin's aromatic ring vibrations. Their intensities dramatically decreased following treatment, indicating a decrease in lignin content.

The band at 1017-1112 cm^{-1} corresponds to the C-O-C stretching vibration in cellulose structure. This band stays after treatment and even rises somewhat, showing that the relative concentration of cellulose is growing. Overall, the FTIR spectra demonstrate that alkali treatment effectively eliminates the majority of the hemicellulose, lignin, and other non-cellulosic substances, increasing the cellulose content of the fibers. These chemical alterations also affect the crystallinity and surface response of the fibers, which are critical for developing better chemical connections with the polymer matrix in composite materials. **Table 2** contains details on the specific band assignments.

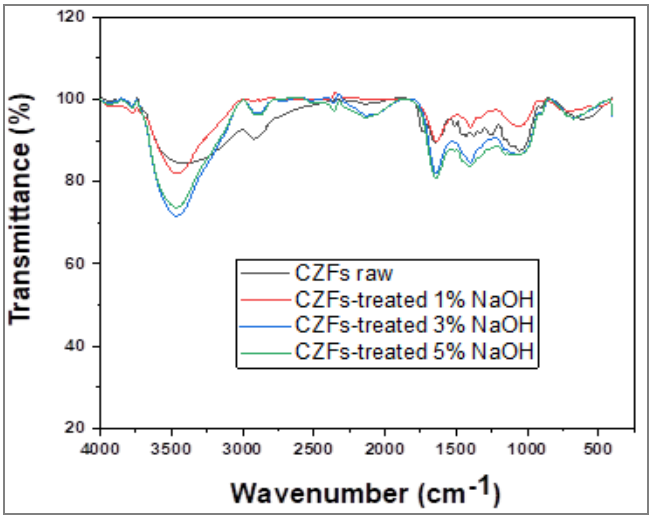


Figure 4. FTIR spectra of raw and alkali-treated *Chrysopogon zizanioides* fibers. Vertical guide lines indicate the major absorption bands corresponding to –OH (~3330 cm^{-1}), C–H (~2900 cm^{-1}), C=O (~1730 cm^{-1}), and C–O (~1050–1150 cm^{-1}) groups

3.2. Analysis of Fiber Morphology with SEM

Figure 5 depicts the fibers' surface morphology before and after NaOH treatment. **Figure 5a** depicts the uneven surface of raw CZFs that is still covered in non-cellulosic substances like hemi cellulose, lignin, and other impurities. The presence of these chemicals tends to blanket the cellulose surface and reduces the possibility of interfacial interaction with the matrix in composite materials. This effect is consistent with findings by Raghunathan *et al*. [25] and Sari *et al*. [15], who found that non-cellulosic lignocellulosic components lead the surface to become less chemically responsive and more hydrophobic. **Figure 5b** displays considerable modifications on the fiber surface

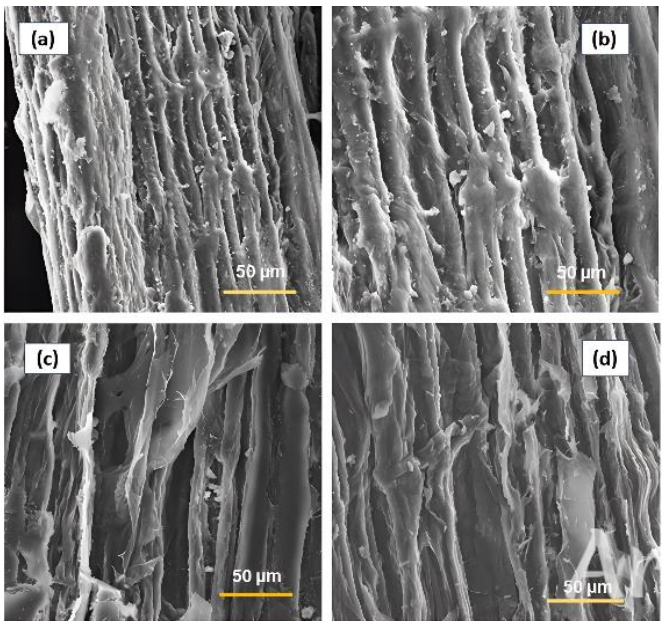


Figure 5. Fiber surface morphology using SEM: (a) Raw; (b) CZFs-treated 1% NaOH; (c) CZFs-treated 3% NaOH; (d) CZFs-treated 5% NaOH

surface (CZFs treated 1% NaOH sample). Most of the non-cellulosic surface layers were lifted. In comparison to raw CZFs, the surface seems cleaner, with certain individual fibers being more separated. This suggests that 1% NaOH treatment can eliminate some of the amorphous components, enhance roughness, and potentially increase contact area with the matrix. These findings are comparable with those of Dembri *et al*. [26], who discovered that mild alkali treatment eliminated surface contaminants while strengthening interfacial bonding in natural fiber composites.

Table 2. FTIR spectrum of *C. zizanioides* fibers (CZFs) before and after alkali treatment

Wave number (cm^{-1})				Assignments
CZFs Raw	CZFs-treated 1% NaOH	CZFs-treated 3% NaOH	CZFs-treated 5% NaOH	
3465	3465	3467	3476	O-H stretching of cellulose, lignin, and hemicellulose
2893	2907	2883	2869	C-H stretching of methyl and methylene groups
2088	2125	2132	2128	C≡O stretch
1735	-	-	-	C=O stretching of esters and carboxylic acids (hemicellulose)
1618	1640	1640	1635	Aromatic double bond vibrations (lignin).
1419	1401	1400	1400	Aromatic ring vibrations of lignin
1017	1061	1112	1044	C-O stretching in the cellulose structure.

Figure 5c depicts the surface of the CZFs-treated 3% NaOH sample, which is cleaner and has a more open cellulose fiber structure. Lignin and hemicellulose have mostly decomposed, leaving the surface rougher and more porous. This condition suggests an increase in the specific area and the possibility of stronger mechanical connections in the composite material, allowing this concentration a rather effective treatment. This treatment improves the composite's tensile properties, as demonstrated by Dembri *et al*. [26], who found that removing lignin and hemicellulose enhances the roughness and interfacial contact area, which promotes the composite's tensile strength. Meanwhile, the SEM image of the CZFs-treated 5% NaOH sample (**Figure 5d**) indicates the CZFs structure that has degraded further. The surface appears not only clean, but the roughness is becoming more visible, which has the ability to boost the fiber's mechanical strength. Alkali treatment was found to be efficient for enhancing the surface morphology of CZFs by removing non-cellulosic chemicals while increasing roughness. The optimum treatment condition for fiber surface alteration proved to be 5% NaOH, which enabled surface cleaning and fiber morphological alteration while producing no structural damage.

3.3. Density and Moisture Content Analysis

CZFs' physical properties are dramatically affected by alkaline treatment with NaOH, especially their density and moisture content. From **Table 3**, the results show that untreated fibers had a low density of 410 ± 20 kg/m³ and gradually grew with greater NaOH dosages, achieving a maximum of 980 ± 20 kg/m³ at 5% NaOH. This significant increase in density implies the removal of amorphous components including hemicellulose, and lignin, which occupy interfibrillar spaces and contribute to a porous, less compact structure. The removal of these components results in tighter packing of cellulose microfibrils, smaller diameters, and overall structural consolidation. A phenomena previously reported in similar investigations on alkali-treated natural fibers like kapok,

in which density increases by up to 211% at 10.5% NaOH due to the elimination of wax and amorphous components [27].

Interestingly, the densification process was followed by a continuous decrease in moisture content, from 8.9% in raw CZFs to 5.3% following 5% NaOH treatment (**Table 3**). The reduced hygroscopicity of the treated fibers is due to the elimination of hydroxyl-rich hemicellulose and pectin, which are principally responsible for moisture absorption in natural fibers. This trend is consistent with observations in *raffia* and *Paederia Foetida* fibers, where alkali-treated samples showed increased dimensional stability and decreased swelling behavior, enhancing compatibility with hydrophobic polymer matrix [15], [28]. These combined changes in density and moisture behavior indicate that 5% NaOH-treated CZFs have a more compact and hydrophobic structure, making them better suited for composite reinforcement, particularly in applications that need mechanical dependability and moisture resistance.

The substantially greater standard deviations found for raw and 5% NaOH-treated samples are most likely due to fiber heterogeneity. Raw fibers retained contaminants, resulting in uneven packing, whereas delignification with 5% NaOH promoted fibrillation. Nonetheless, the results are statistically significant (n = 3), and the overall density range is consistent with previously published values for natural lignocellulosic fibers like *Paederia foetida* and *Careya arborea* tree.

Table 3. Density and moisture content of CZFs before and after treatment with NaOH at various concentrations for 2 h

Samples	Density (kg/m³)	Moisture content (%)
CZFs raw	410 ± 20	8.9 ± 0.02
CZFs-treated 1% NaOH	530 ± 10	7.4 ± 0.01
CZFs-treated 3% NaOH	680 ± 10	6.6 ± 0.01
CZFs-treated 5% NaOH	980 ± 20	5.3 ± 0.02

3.4. Chemical Content Analysis

Table 4 show that the chemical composition of CZF fibers changed dramatically after alkali treatment. Cellulose content increased dramatically from 47.5% in raw fibers to 66.7% after 5% NaOH treatment, however hemicellulose and lignin reduced significantly—hemicellulose from 29.2% to 16.3% and lignin from 21.7% to 15.9%. The residual ash level also fell marginally, from 1.5% to 1.1%, indicating the elimination of inorganic pollutants. The primary mechanism underlying this phenomenon is alkali hydrolysis, in which NaOH breaks the ester bonds in hemicellulose and lignin, eliminates the amorphous part, and selectively leaves a denser and more crystalline cellulose microstructure. This cellulose increase is consistent with the XRD data, which show an increase in *CrI* of upwards of 65.7% at the same treatment level, and also supports the TGA/DTA-observed increases in tensile modulus and thermal stability. This phenomenon has also been confirmed in previous literature, such as in *Careya arborea* fibers, which increased cellulose from 71% to 79% after 5% NaOH treatment [29], [30] and *Himalayacalamus falconeri* bamboo fibers, which increased cellulose by +6% and density by +4% after a similar treatment [31]. The fiber's alkali purification increases mechanical adhesion and thermal endurance, making it suitable for biocomposite applications requiring lightweight and environmental resistance. The composition of 5% NaOH-treated CZFs, with 66.7% cellulose, 16.3% hemicellulose, and 15.9% lignin, represents an ideal combination of tensile strength, stiffness, and elevated temperature resistance, making it a promising reinforcing material for automotive panel applications, small paneling plates, structural components, and temperature-resistant biocomposites. More research is needed to assess fiber-matrix interactions, the effect of fiber ratios, the impact of other modifications (including silanes or maleates), and long-term characteristic stability under real-world settings.

Table 4. Chemical composition of CZFS fiber before and after NaOH treatment

Samples	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash content (%)
CZFs raw	47.5	29.2	21.7	1.5
CZFs-treated 1% NaOH	52.3	26.7	19.6	1.4
CZFs-treated 3% NaOH	59.7	21.8	17.2	1.2
CZFs-treated 5% NaOH	66.7	16.3	15.9	1.1

3.5. Crystallinity Analysis

Figure 6 shows the X-ray diffraction (XRD) patterns of raw and alkali-treated CZFs at different NaOH concentrations (1, 3, and 5%). The XRD patterns were presented in their raw form without smoothing to preserve signal integrity. Minor background noise was retained to maintain accurate peak intensity ratios for reliable crystallinity index (CrI) calculation. The XRD profiles of all samples showed characteristic cellulose I peaks at 2θ = 16° and 22°, indicating that the native crystalline structure was retained after alkali treatment. The absence of additional peaks associated with

cellulose II or amorphous breakdown products suggests that the cellulose crystalline lattice remained intact, even at greater alkali concentrations. This finding is consistent with prior studies on natural fibers such as jute and sisal, which show modest alkali-induced fibrillation without affecting the core cellulose I structure.

Table 5 shows the crystallinity index (*CrI*), which was calculated using the Segal method to quantify changes in crystallinity. This gradual rise in *CrI* can be attributed to the efficient removal of amorphous components—primarily hemicellulose and lignin—during alkali treatment, which enriches the crystalline cellulose content. The greatest *CrI* was obtained at 5% NaOH treatment, indicating an appropriate concentration for selectively removing non-crystalline elements while causing minimal disturbance to the cellulose crystalline areas. A similar trend has been observed in other natural fibers, such as *Ziziphus jujuba* (from 35.7% to 50.8%) [32], *Careya Arborea* bast fiber (85.5%) [30], and *Oil palm* fiber (64.07%) [33], and *ramie* fiber (66.3%) [34], *banyan aerial* roots (39% to 52%) [29], all of which demonstrate increased *CrI* with moderate alkali treatment.

Compared to these fibers, the CZFs show a higher relative increase in crystallinity (approximately 82% improvement from raw to 5% NaOH-treated), indicating a favorable structure for further development as reinforcement in biocomposites. Notably, *Careya arborea* bark fibers treated with 5% NaOH achieved a *CrI* of 83.3% [30]; however, the raw *CrI* was already higher, suggesting CZFs undergo a more significant structural refinement upon treatment. These results demonstrate that 5% NaOH is an effective pretreatment for enhancing the crystalline structure of CZFs, which is essential for improving their mechanical strength, thermal stability, and compatibility with polymer matrices. Higher crystallinity has been correlated with better fiber-matrix adhesion and stiffness in biocomposite applications [35], [36]. Therefore, CZFs treated with 5% NaOH offer a promising alternative to more established natural fibers for high-performance green composite materials.

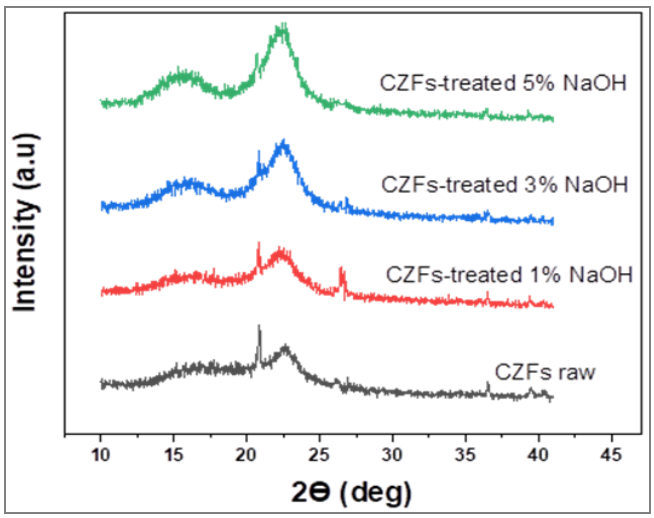


Figure 6. XRD patterns of CZFs before and after NaOH treatment at different concentrations (raw data shown to preserve signal integrity)

Table 5. Crystallinity index (*CrI*) of CZFs before and after treatment with different NaOH concentrations

Samples	I_{002}	*Iam*	Crystallinity Index (*CrI, %*)
CZFs raw	150	235	36.17
CZFs-treated 1% NaOH	138	256	46.09
CZFs-treated 3% NaOH	141	341	58.65
CZFs-treated 5% NaOH	136	397	65.74

3.6. Thermal Stability (TGA/DTA) Analysis

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were used to study the thermal degradation behavior of CZFs prior to and after alkali treatment with varied NaOH concentrations (1%, 3%, and 5%), as shown in Figure 7a and Figure 7b, respectively. All samples demonstrated the normal three-stage breakdown behavior found in lignocellulosic materials. During the first phase, below 150 °C, all samples experienced a slight weight loss due to the evaporation of adsorbed water and volatiles. This stage accounted for around 5 - 8% of the overall mass, with no notable variation between raw and processed samples. The second stage, occurring between 200 - 350 °C, predominantly degrades hemicellulose and amorphous cellulose. As demonstrated in Figure 7a, alkali-treated samples had a slightly higher initiation temperature of deterioration than raw CZFs, indicating increased thermal stability. This improvement is due to the partial elimination of hemicellulose and other thermally unstable constituents during alkaline treatment. The third stage (350 - 500 °C) involves the breakdown of crystalline cellulose and lignin components. Differential thermal analysis (Figure 7b) corroborated this stage by revealing strong exothermic peaks that increased in intensity and switched to higher temperatures as the NaOH concentration increased. These changes imply that alkali-treated fibers have a better level of thermal stability, particularly at 5% NaOH. The char residue is an important quantity in thermal analysis because it represents the thermally stable part that remains after full decomposition.

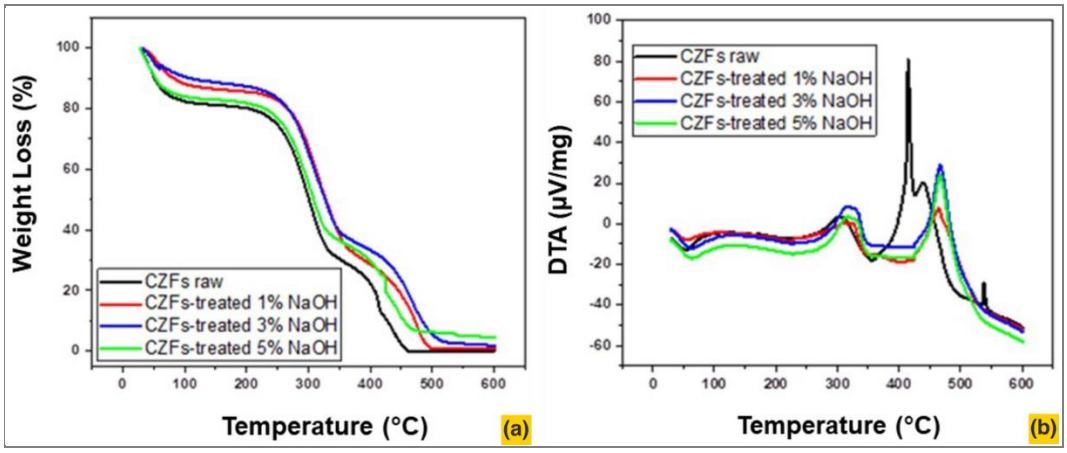


Figure 7. (a) TGA; (b) DTA of CZFs raw and after alkali treatment

Table 6 shows that greater NaOH concentrations resulted in significantly higher char residue at 600 °C, from 0.0021% in raw CZFs to 0.99%, 2.01%, and 4.46% for fibers treated with 1%, 3%, and 5% NaOH, respectively. This significant rise in residue shows that the fiber structure is changing to become more carbonaceous and thermally stable. The higher char concentration is also consistent with the rise in crystallinity reported in the XRD analysis (Section 3.5), confirming the conclusion that alkali treatment improves both thermal and structural stability.

These findings are consistent with trends reported in recent literature. For example, *Borassus flabellifer* fibers treated with NaOH exhibited increased residue content and improved thermal degradation profiles, with integral procedural decomposition temperatures (IPDT) reaching up to ~524 °C and char content around 8–11% [37]. Similarly, *Tinospora cordifolia* fibers treated with 5% NaOH showed a ~10 °C increase in onset degradation temperature and improved thermal resistance [38]. Collectively, the results of this study confirm that 5% NaOH is the most effective concentration among those tested for improving the thermal properties of CZFs. The combination of delayed degradation, intensified exothermic activity, and increased char yield highlights the suitability of treated CZFs for use in bio-based composite materials intended for thermally demanding applications.

Table 6. Char residue of CZFs at 600 °C

Samples	Char residue (%)
CZFs raw	0.0021
CZFs-treated 1% NaOH	0.99
CZFs-treated 3% NaOH	2.01
CZFs-treated 5% NaOH	4.46

3.7. Mechanical Properties Analysis

Figure 8a depicts *Chrysopogon zizanioides* fiber stress-strain curves before and after NaOH treatment. Raw fibers have a maximum stress of roughly 5 MPa at a strain of ~1.2%, whereas fibers treated with 5% NaOH have a comparable maximum stress but can resist somewhat higher strains. The most intriguing changes are observed in the initial modulus, which rises with NaOH concentration: the 5% NaOH fibers are stiffer, representing the increased stiffness caused by the removal of amorphous components. While the peak stress is slightly lower than in raw, this implies a trade-off between stiffness and elasticity. Alkali hydroxide is the primary cause of this phenomena, as it eliminates lignin, hemicellulose, and wax, enhancing the connections between cellulose microfibrils [39]. *Tinospora cordifolia* fibers showed a 30% increase in modulus following 5% NaOH treatment, but maximum stress fell by 8% [38].

This fiber behavior is especially essential in the production of lightweight composites like automotive overlay panels, sandwich panels, and vibration-resistant structural parts, where stiffness and energy dissipation are critical [39].

Figure 8b demonstrates that *C. zizanioides* fibers' tensile strength rose from 252 ± 24 MPa (raw fibers) to 553 ± 26 MPa after 5% NaOH treatment. This trend suggests that alkali activation with up to 5% NaOH significantly increases fiber strength by eliminating hemicellulose and surface contaminants, resulting in improved fibrillation and stress transfer. However, beyond this concentration, tensile strength is projected to decrease due to excessive degradation and partial dissolving of hemicellulose, which might disturb the cellulose microfibril structure. Such overtreatment can reduce the fiber's load-bearing capacity, implying that the ideal alkali concentration for fibers is around 5% NaOH. Other natural fibers like *Paederia foetida*, and careya arborea tree have been shown to exhibit similar degrading behavior above the optimal concentration level [15], [40]. The large standard variation in the tensile strength of raw CZFs (± 24 MPa) and CZFs treated with 5% NaOH (± 26 MPa) is mostly attributable to inherent variability in

fiber morphology, such as uneven diameters and surface defects. This intrinsic heterogeneity contributes to variations in load-bearing behavior between samples, which is consistent with findings from other lignocellulosic fiber investigations. This increase suggests that NaOH's elimination of amorphous components (lignin, hemicellulose) increases the integrity and interface of cellulose, resulting in fibers that are stronger to the optimal point at 5% NaOH. This finding is consistent with the rise in *CrI* reported in XRD analysis as well as the increase in modulus shown in **Figure 6**. **Table 7** summarizes the mechanical properties of CZFs. Meanwhile, elongation has an inverse connection with tensile strength (**Figure 8c**). The elongation improves from 4.1% (raw CZFs) to 5.8% at 3% NaOH, then drops to 4.7% at 5% NaOH. This suggests that fibers treated with 3% NaOH more ductile, showing an increase in microfibril cohesion and flexibility as stress is redistributed in a more homogenous fibril structure. When the concentration approaches 5%, the fibers become brittle, and elongation diminishes. This nonlinear behavior, in which the optimal modulus, elongation, and tensile strength occur at various alkali concentrations, can be attributable to the alkali treatment's competing microstructural effects. At low to high NaOH concentrations, partial elimination of hemicellulose and surface contaminants promotes fibrillation, improves surface roughness, and improves stress transfer between microfibrils, resulting in improved stiffness and tensile strength. However, as the alkali concentration exceeds the optimum for a certain characteristic, over-treatment can result in excessive delignification, partial dissolving of amorphous components, a reduction in effective surface area, and microstructural degradation. These degradation processes have the potential to lower load-bearing capacity and elongation while also shifting the property optimum to a different concentration. Furthermore, changes in microfibril angle and crystallization can have separate effects on stiffness (modulus) and ductility (elongation), thus peak values for both attributes do not always coincide. Taken together, the data show that each mechanical property is determined by a balance of surface change (beneficial) and structural degradation (detrimental), which explains the non-synchronous optima seen in **Table 7**. In addition, differences in microfibril angle and crystallinity may differentially influence stiffness and elongation, further contributing to this non-linear trend. These findings are similar with previous research on *Agave americana* fibers, which found that NaOH modification at moderate levels may improve fiber deformability to an ideal level [41].

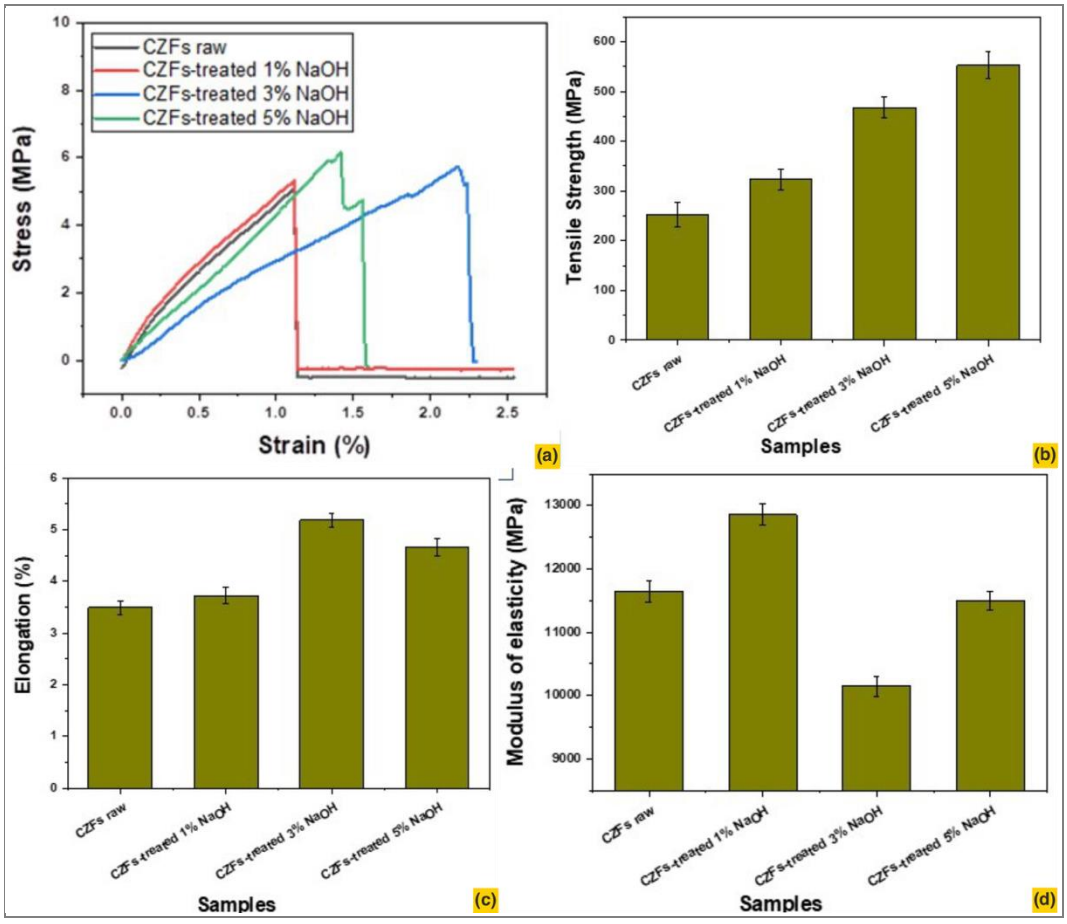


Figure 8. *C. zizanioides* fiber raw and after treated NaOH: (a) Stress vs strain; (b) Tensile strength; (c) Elongation; (d) Modulus of elasticity

In **Figure 8d**, the modulus of elasticity increased from 11643 ± 164 MPa to 12854 ± 170 MPa after 1% NaOH treatment, but decreased to 11498 ± 148 MPa after 5% NaOH treatment. This shows a stiffer material change due to higher crystallinity, which is also seen in XRD examination. These findings are consistent with the observed increase in modulus and hardness for *Tinospora cordifolia* fibers after alkali treatment [38]. CZF fibers treated with 5% NaOH have the best combination of high tensile strength and stiffness modulus, making them ideal for lightweight composite panels, automotive structures, and thermal resistance.

Although NaOH treatment improves the mechanical and interfacial properties of CZFs, industrial processing must be carefully handled to ensure sustainability. The usage of 5% NaOH can produce alkaline wastewater, which must be neutralized and treated before release. Process optimization with lower alkali concentrations, effluent recycling, and neutralization with mild acids (e.g., acetic acid) can all be used to lessen environmental impact. Furthermore, creating closed-loop systems and incorporating green alkali alternatives (including bio-based alkaline agents or enzymatic pretreatments) are interesting avenues for enhancing environmental compatibility. These concerns emphasize the importance of combining material performance optimization with prudent waste management in alkali activation process scaling.

The enhanced surface shape and exposed reactive hydroxyl groups on alkali-treated CZFs indicate good compatibility with polar polymer matrices. These treated fibers hold particular promise for usage in biodegradable polymer systems like polylactic acid (PLA), polyhydroxybutyrate, or starch-based biopolymers, wherein hydrogen bonds can improve interfacial adhesion. Alkali-treated CZFs could also be included into thermoset matrices like epoxy or polyester, which can benefit from enhanced surface roughness and better fiber-matrix interaction. These combinations may result in lightweight, energy-efficient, and environmentally friendly composite materials for structural and semi-structural applications.

Table 7. Mechanical properties of fibers before and after NaOH treatment. Values represent mean ± standard deviation (n= 3)

Samples	Tensile strength (MPa)	Elongation (%)	Modulus of elasticity (MPa)
CZFs raw	252±24	3.49±0.34	11643±164
CZFs-treated 1% NaOH	323±21	3.73±0.51	12854±170.3
CZFs-treated 3% NaOH	467±20	5.19±0.6	10148±155
CZFs-treated 5% NaOH	553±26	4.66±0.47	11498 ±148

4. Conclusion

This research has thoroughly assessed the influence of NaOH treatment on the structural, thermal, mechanical, and surface characteristics of *Chrysopogon zizanioides* fibers (CZFs). This study has demonstrated that alkali treatment using sodium hydroxide significantly modifies the physicochemical, thermal, and mechanical properties of CZFs. The crystallinity index increased markedly from 36.17% in raw fibers to 65.74% following 5% NaOH treatment, indicating substantial removal of amorphous components and a higher proportion of ordered cellulose. FTIR analysis confirmed the reduction of hemicellulose and lignin functional groups, while TGA/DTA data revealed improved thermal stability, with char residue increasing from 0.0021% to 4.46% at 600 °C after treatment. Tensile strength raised from 252 ± 25 MPa to 553 ± 26 MPa, whereas tensile modulus increased from 11643 ± 164 MPa to 11498 ± 148 MPa, indicating increased stiffness. Based on these findings, the 5% NaOH-treated CZFs exhibited the most favorable combination of crystallinity, thermal resistance, interfacial morphology, and modulus enhancement, making them the optimal candidate for reinforcing biodegradable composites. The treated fibers show strong potential for use in applications requiring dimensional and thermal stability, such as in automotive interior components, structural panels, and eco-friendly packaging. Future studies should focus on optimizing alkali concentration and treatment duration to improve the stiffness-toughness balance. Furthermore, assessing the interfacial bonding behavior of CZFs inside polymer matrices, and also their long-term durability under moisture, UV, and thermal aging, will be critical in determining their feasibility in real-world applications. Future comparison research with other natural fibers may also serve to assess CZF performance in the larger context of green composite design.

Acknowledgements

The authors gratefully acknowledge the support provided by the Ministry of Higher Education, Science, and Technology through the Competitive Grant under the Fundamental Research Program for the fiscal year 2025. (No. 079/C3/DT.05.00/PL/2025).

Authors' Declaration

Authors' contributions and responsibilities - Nasmi Herlina Sari: Conceptualization, Validation, Supervision, Methodology, Investigation, Writing – original draft, formal analysis.: Edi Syafri, Sujita: Methodology, Investigation, Data curation, Writing - Review & Editing. Suteja: Resources, Project administration, Visualization.

Funding – Ministry of Higher Education, Science, and Technology through the Competitive Grant under the Fundamental Research Program for the fiscal year 2025. (No. 079/C3/DT.05.00/PL/2025).

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

References

[1] M. Alsafran, K. K. Sadasivuni, J. M. Haneesh, M. M. Razavi, and D. M. Kasote, "Extraction and characterization of biofunctional lignocellulosic fibers from Pulicaria undulata plant and the effect of alkali treatment on their bio-physicochemical properties," *Carbohydrate Polymer Technologies and Applications*, vol. 8, p. 100542, Dec. 2024, doi: 10.1016/j.carpta.2024.100542.

[2] J. Tengsuthiwat, V. A, V. R, Y. G. T. G, S. M. Rangappa, and S. Siengchin, "Characterization of novel natural cellulose fiber from Ficus macrocarpa bark for lightweight structural composite application and its effect on chemical treatment," *Heliyon*, vol. 10, no. 9, p. e30442, May 2024, doi: 10.1016/j.heliyon.2024.e30442.

[3] D. Fontanel, "In vitro antimicrobial activity of vetiver root essential oil Chrysopogon zizanioides (L.) Roberty, and relationships with their major chemical compounds. A review," *American Journal of Essential Oils and Natural Products*, vol. 13, no. 1, pp. 45–55, Jan. 2025, doi: 10.22271/23219114.2025.v13.i1a.269.

[4] I. G. C. Barcellos-Silva *et al.*, "Vetiver, Vetiveria zizanioides (L.) Nash: Biotechnology, Biorefineries, and the Production of Volatile Phytochemicals," *Plants*, vol. 14, no. 10, p. 1435, May 2025, doi: 10.3390/plants14101435.

[5] A. Khan *et al.*, "Extraction and characterization of vetiver grass (Chrysopogon zizanioides) and kenaf fiber (Hibiscus cannabinus) as reinforcement materials for epoxy based composite structures," *Journal of Materials Research and Technology*, vol. 9, no. 1, pp. 773–778, Jan. 2020, doi: 10.1016/j.jmrt.2019.11.017.

[6] K. Harini and C. Chandra Mohan, "Isolation and characterization of micro and nanocrystalline cellulose fibers from the walnut shell, corncob and sugarcane bagasse," *International Journal of Biological Macromolecules*, vol. 163, pp. 1375–1383, Nov. 2020, doi: 10.1016/j.ijbiomac.2020.07.239.

[7] T. D. Tavares, J. C. Antunes, F. Ferreira, and H. P. Felgueiras, "Biofunctionalization of Natural Fiber-Reinforced Biocomposites for Biomedical Applications," *Biomolecules*, vol. 10, no. 1, p. 148, Jan. 2020, doi: 10.3390/biom10010148.

[8] A. Vinod *et al.*, "Extraction and Characterization of Natural Fiber from Stem of Cardiospermum Halicababum," *Journal of Natural Fibers*, vol. 18, no. 6, pp. 898–908, Jun. 2021, doi: 10.1080/15440478.2019.1669514.

[9] N. H. Sari *et al.*, "Morphology and mechanical properties of coconut shell powder-filled untreated cornhusk fibre-unsaturated polyester composites," *Polymer*, vol. 222, p. 123657, Apr. 2021, doi: 10.1016/j.polymer.2021.123657.

[10] R. Ilyas *et al.*, "Natural Fiber-Reinforced Polylactic Acid, Polylactic Acid Blends and Their Composites for Advanced Applications," *Polymers*, vol. 14, no. 1, p. 202, Jan. 2022, doi: 10.3390/polym14010202.

[11] F.-E.- Karim, M. R. Islam, R. Ahmed, A. B. Siddique, and H. A. Begum, "Extraction and characterization of a newly developed cellulose enriched sustainable natural fiber from the epidermis of Mikania micrantha," *Heliyon*, vol. 9, no. 9, p. e19360, Sep. 2023, doi: 10.1016/j.heliyon.2023.e19360.

[12] R. Raharjo, D. Bangun Darmadi, F. Gapsari, P. H. Setyarini, and T. D. Widodo, "Characterization of bromelain enzyme treated Bamboo petung fiber (BPF) for composite reinforcement," *Case Studies in Chemical and Environmental Engineering*, vol. 9, p. 100683, Jun. 2024, doi: 10.1016/j.cscee.2024.100683.

[13] N. H. Sari, Suteja, Y. A. Sutaryono, and M. A. Khan, "A Review: Fracture Structure of Natural Fiber after Treatment with Various Alkali Chemicals," *Journal of Fibers and Polymer Composites*, vol. 3, no. 2, pp. 158–180, 2024, doi: 10.55043/jfpc.v3i2.203.

[14] Z. Ren *et al.*, "Effect of Alkali Treatment on Interfacial and Mechanical Properties of Kenaf Fibre Reinforced Epoxy Unidirectional Composites," *Sains Malaysiana*, vol. 48, no. 1, pp. 173–181, Jan. 2019, doi: 10.17576/jsm-2019-4801-20.

[15] N. H. Sari, E. Syafri, Suteja, W. Fatriasari, and A. Karimah, "Comprehensive Characterization Of Novel Cellulose Fiber From Paederia Foetida and Its Modification For Sustainable Composites Application," *Journal of Applied Science and Engineering*, vol. 26, no. 10, pp. 1399–1408, 2023, doi: 10.6180/jase.202310_26(10).0005.

[16] M. Djalal, M. Nafissa, R. Mansour, M. Jawaid, M. Hocine, and B. Lamia, "Effect of alkali treatment on new lignocellulosic fibres from the stem of the Aster squamatus plant," *Journal of Materials Research and Technology*, vol. 32, pp. 2882–2890, Sep. 2024, doi: 10.1016/j.jmrt.2024.08.104.

[17] H. S. Kusuma, D. Permatasari, W. K. Umar, and S. K. Sharma, "Sugarcane bagasse as an environmentally friendly composite material to face the sustainable development era," *Biomass Conversion and Biorefinery*, no. January, pp. 1–16, 2023, doi: 10.1007/s13399-023-03764-2.

[18] S. Sathish *et al.*, "A review of natural fiber composites: Extraction methods, chemical treatments and applications," in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 8017–8023. doi: 10.1016/j.matpr.2020.12.1105.

[19] W. Jin, F. He, S. Song, M. Cao, Y. Zhai, and C. Han, "Study on the mechanical properties of fly ash cement mortar reinforced with alkali-treated sisal fiber and sodium sulfate," *Industrial Crops and Products*, vol. 224, no. December 2024, p. 120375, 2025, doi: 10.1016/j.indcrop.2024.120375.

[20] H. A. Begum, T. R. Tanni, and A. Shahid, "Analysis of Water Absorption of Different Natural Fibers," *Journal of Textile Science and Technology*, vol. 7, pp. 152–160, 2021, doi: 10.4236/jtst.2021.74013.

[21] N. Herlina Sari, I. N. G. Wardana, Y. S. Irawan, and E. Siswanto, "Characterization of the Chemical, Physical, and Mechanical Properties of NaOH-treated Natural Cellulosic Fibers from Corn Husks," *Journal of Natural Fibers*, vol. 15, no. 4, pp. 545–558, 2018, doi: 10.1080/15440478.2017.1349707.

[22] K. Sangeetha and M. Bhuvaneshwari, "Investigation of Physical, Chemical and Structural Characterization of Eichhornia crassipes Fiber," in *International Conference on Information Engineering, Management and Security 2016 (ICIEMS 2016)*, 1st ed., 2016, ch. Chapter: I, pp. 92–96.

[23] M. Pokhriyal and P. Kumar, "Mechanical and microstructural behaviour of NaOH treated Himalayacalamus falconeri fibers as biodegradable reinforcing material in polymer based composites Materials Today : Proceedings Mechanical and microstructural behaviour of NaOH treated Himalayacala," *Materials Today: Proceedings*, no. April, pp. 1–6, 2022, doi: 10.1016/j.matpr.2022.04.295.

[24] L. Segal, J. J. Creely, A. E. Martin, and C. M. Conrad, "An Empirical Method for Estimating the Degree of Crystallinity of Native Cellulose Using the X-Ray Diffractometer," *Textile Research Journal*, vol. 29, no. 10, pp. 786–794, Oct. 1959, doi: 10.1177/004051755902901003.

[25] V. Raghunathan *et al.*, "Influence of Chemical Treatment on the Physico-mechanical Characteristics of Natural Fibers Extracted from the Barks of Vachellia Farnesiana," *Journal of Natural Fibers*, vol. 00, no. 00, pp. 1–11, 2021, doi: 10.1080/15440478.2021.1875353.

[26] I. Dembri, A. Belaadi, A. Lekrine, M. Jawaid, A. S. Ismail, and D. Ghernaout, "Effect of alkaline treatment on the thermo-physicochemical and mechanical properties of biochar powder/Washingtonia robusta fibers/PLA hybrid biocomposites," *Journal of Materials Research and Technology*, vol. 33, no. December, pp. 9735–9751, 2024, doi: 10.1016/j.jmrt.2024.12.018.

[27] F. A. Rezeikinta, A. Kasim, E. Syafri, I. Chaniago, and F. Ridwan, "Reducing Water Absorption and Increasing the Density of Kapok (Ceiba pentandra, L.) Fibers from Kapok Production Center in Indonesia," *International Journal of Design and Nature and Ecodynamics*, vol. 18, no. 1, pp. 195–200, 2023, doi: 10.18280/ijdne.180124.

[28] R. G. Elenga, G. F. Dirras, J. Goma Maniongui, P. Djemia, and M. P. Biget, "On the microstructure and physical properties of untreated raffia textilis fiber," *Composites Part A: Applied Science and Manufacturing*, vol. 40, no. 4, pp. 418–422, 2009, doi: 10.1016/j.compositesa.2009.01.001.

[29] R. Thandavamoorthy, Y. Devarajan, and S. Thanappan, "Analysis of the characterization of NaOH-treated natural cellulose fibre extracted from banyan aerial roots," *Scientific Reports*, vol. 13, no. 1, pp. 1–8, 2023, doi: 10.1038/s41598-023-39229-9.

[30] H. J. Rao, S. Singh, and P. Janaki Ramulu, "Characterization of a Careya Arborea Bast Fiber as Potential Reinforcement for Light Weight Polymer Biodegradable Composites," *Journal of Natural Fibers*, vol. 20, no. 1, pp. 71–87, 2023, doi: 10.1080/15440478.2022.2128147.

[31] M. Pokhriyal, P. K. Rakesh, S. M. Rangappa, and S. Siengchin, "Effect of alkali treatment on novel natural fiber extracted from Himalayacalamus falconeri culms for polymer composite applications," *Biomass Conversion and Biorefinery*, vol. 14, no. 16, pp. 18481–18497, 2024, doi: 10.1007/s13399-023-03843-4.

[32] A. Amior, H. Satha, F. Laoutid, A. Toncheva, and P. Dubois, "Natural Cellulose from Ziziphus jujuba Fibers: Extraction and Characterization," *Materials*, vol. 16, no. 1, 2023, doi: 10.3390/ma16010385.

[33] X. Luo and X. Wang, "Preparation and characterization of nanocellulose fibers from NaOH/urea pretreatment of oil palm fibers," *BioResources*, vol. 12, no. 3, pp. 5826–5837, 2017, doi: 10.15376/biores.12.3.5826-5837.

[34] Jamasri and F. Yudhanto, "The Effect of Alkali Treatment and Addition of Microcrystalline Cellulose (MCC) on Physical and Tensile Properties of Ramie/Polyester Laminated Composites," *Revue des Composites et des Materiaux Avances*, vol. 32, no. 2, pp. 77–84, 2022, doi: 10.18280/rcma.320204.

[35] K. Büyükkaya, "Examining the Physical and Thermal Properties of Nettle Fibers Obtained from Different Genetic Sources and Determining Their Usability as Reinforcement Materials in Composites," *Journal of Natural Fibers*, vol. 22, no. 1, pp. 1–24, Dec. 2025, doi: 10.1080/15440478.2025.2519609.

[36] Y. Subagyo *et al.*, "Development of magnesium biocomposites with hydroxyapatite or carbonate apatite reinforcement as implant candidates: A review," *Mechanical Engineering for Society and Industry*, vol. 3, no. 3, pp. 152–165, 2023, doi: 10.31603/mesi.10389.

[37] M. A. Rahman, M. Ndiaye, B. Weclawski, and P. Farrell, "Alkali-treated Borassus Husk Fibre Reinforced High-heat Resistant Epoxy Composites: Insights into Their Thermal, Dynamic Mechanical and Outgassing Properties," Apr. 21, 2025. doi: 10.22541/au.174526773.38930625/v1.

[38] J. Hindi, M. K, K. S. Bhat, G. B M, A. Ibrahim, and S. Y M, "Physical, Morphological, Tensile, and Thermal Stability Characteristics of Novel Tinospora Cordifolia Natural Fiber," *Journal of Natural Fibers*, vol. 22, no. 1, pp. 1–12, 2025, doi: 10.1080/15440478.2024.2437539.

[39] I. G. N. N. Santhiarsa, I. G. B. W. Kusuma, I. P. Lokantara, N. M. Dwidiani, S. P. G. G. Tista, and I. G. A. Negara, "The influence of NaOH concentration on the mechanical properties of Corypha gebanga fiber-reinforced composites," *Archive of Mechanical Engineering*, vol. 71, no. 4, 2024, doi: 10.24425/ame.2024.152616.

[40] J. R. H *et al.*, "Effect of chemical treatment on physio-mechanical properties of lignocellulose natural fiber extracted from the bark of careya arborea tree," *Heliyon*, vol. 10, no. 5, p. e26706, Mar. 2024, doi: 10.1016/j.heliyon.2024.e26706.

[41] P. Sathiamurthi, K. S. Karthi Vinith, T. P. Sathishkumar, S. Arunkumar, and A. S. Anaamalaai, "Fiber extraction and mechanical properties of Agave Americana/Kenaf fiber reinforced hybrid epoxy composite," *Materials Today: Proceedings*, vol. 46, pp. 8594–8601, 2021, doi: 10.1016/j.matpr.2021.03.571.