

Extraction and characterization of natural fibers from Tamban variety pineapple leaves using a variable frequency drive for sustainable biocomposite reinforcement

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ABSTRACT

The transition toward a circular economy has encouraged the utilization of natural fibers as alternatives to synthetic fibers. This study aimed to characterize pineapple leaf fibers of the Tamban variety (*Ananas comosus* (L.) Merr.) extracted using a variable frequency drive (VFD) system at frequencies of 15 Hz (V15), 20 Hz (V20), and manual press (MP) for potential use as reinforcement in biocomposites. The testing methods included determination of fiber yield, evaluation of mechanical properties through analysis of variance (ANOVA) using a randomized complete block design (RCBD) with IBM SPSS Statistics Version 25, and microstructural characterization using x-ray diffraction (XRD) and Scanning Electron Microscopy coupled with energy-dispersive x-ray spectroscopy (SEM-EDX) on selected fibers. The fiber yield ranged from 2.605% to 3.260%. The RCBD ANOVA indicated that the variation in extraction methods did not have a statistically significant effect ($p > 0.05$) on the mechanical property parameters. Descriptively, the V15-K2 specimen exhibited the highest observed tensile strength of 85.77 MPa and tensile toughness of 4.842 MJ/m³. XRD analysis of the V15-K2 sample confirmed a Cellulose I β crystalline structure at $2\theta = 22.4207^\circ$, with a crystallinity index of 52.44% and a crystallite size of 8.52 nm. Furthermore, SEM observations revealed a well-organized longitudinal fiber morphology, while EDX analysis detected the major organic elements C and O, along with minor elements including Al, Si, Cl, and Ca. Overall, the use of a controlled extraction system provides comprehensive data supporting the potential of Tamban pineapple leaf fibers as reinforcement materials for sustainable polymer composites.

Keywords: biocomposite, microstructural characterization, Tamban pineapple leaf fiber, mechanical properties, variable frequency drive.

INTRODUCTION

The growing demand for more environmentally friendly production processes has accelerated the use of locally available and renewable materials in the composite industry. Agricultural production systems are increasingly required to adopt sustainable resource management strategies that minimize environmental burdens while

improving biomass utilization efficiency (Ouedraogo, 2026). Synthetic fibers, particularly carbon and glass fibers, have been widely used in the production of composite structures. Although these fibers exhibit excellent mechanical properties, their non-biodegradable and non-renewable nature poses a significant environmental concern (Khan et al., 2022). To address these challenges, ongoing research has explored the potential of

agricultural feedstocks and agro-industrial waste through waste valorization, particularly natural fibers, as sustainable alternatives to synthetic fibers (Bichang'a et al., 2022; Boumane et al., 2026).

Natural fibers have been investigated as reinforcement materials from diverse plant sources (Daramola et al., 2021), as well as through the utilization of organic biofillers, including spent coffee grounds (Boumane et al., 2026). Recent studies in environmental engineering have emphasized the importance of converting renewable biomass resources into value-added products as part of sustainable resource management strategies. Life-cycle-based approaches have demonstrated that replacing fossil-based materials with alternatives derived from renewable biomass can contribute to reducing environmental burdens and supporting the transition toward a circular economy (Abah et al., 2025).

Natural fibers are obtained from various parts of plants, particularly bark, stems, seeds, fruits, and leaves, using a range of extraction techniques, including manual peeling, mechanical decortication, and retting (Oladele et al., 2021). The value-added utilization of locally available biological resources has become an important direction in sustainable engineering, with plant-derived materials increasingly being investigated as alternatives for reducing the environmental impacts associated with conventional technologies (Sikder and Mumit, 2024). The conversion of agricultural by-products, such as rice husk ash waste, into reinforcement materials for thermoplastic composites has been demonstrated to be effective in supporting green manufacturing and reducing dependence on conventional synthetic reinforcements (Ginting et al., 2023).

Recently, emerging fiber sources such as pineapple leaves (*Ananas comosus* (L.) Merr.) have shown potential as reinforcement for thermoplastic polymer matrices, including low-density polyethylene (LDPE) and polypropylene (PP) (Gadzama et al., 2020; Rahman et al., 2021). In the textile sector, pineapple leaf fibers have been processed into knitted fabrics (Jalil et al., 2024), woven fabrics (Surjit et al., 2022), and nonwoven fabrics (Thilagavathi et al., 2020). Meanwhile, in the fiber-reinforced composite industry, the high cellulose content of pineapple leaf fibers has been utilized as a natural reinforcement for polymer matrices (Vu et al., 2022). Their porous structure has also enabled their application as sound-absorbing materials (Qian et al., 2023), as well as

raw materials for paper pulp and environmentally friendly food packaging (Praveen Kumar, 2020). Furthermore, the integration of nanotechnology with natural biopolymer matrices in bionanocomposite structures has been shown to improve thermal stability and morphological compactness while providing active and intelligent functional properties, such as UV radiation protection and real-time freshness monitoring (Hasan et al., 2024). Pineapple leaf biomass residues can also be further utilized as livestock feed and mushroom cultivation substrates or converted into renewable energy sources such as biofuel. Collectively, these applications demonstrate the important role of pineapple leaf fibers in supporting the circular economy by converting agricultural waste into high-value products across various industries (Rallabandi et al., 2025). In addition, cellulose-derived materials are increasingly being developed as functional materials for passive daytime radiative cooling using agricultural and agro-industrial waste as feedstocks (Gliti et al., 2026).

This substantial potential creates an opportunity for the utilization of the Tamban pineapple variety, a leading agricultural commodity of Barito Kuala Regency, South Kalimantan Province, as recognized by the Decree of the Minister of Agriculture No. 2088/Kpts/S.R.120/5/2009, with an average fruit production of approximately 13,000 tons in 2025. Following pineapple fruit harvesting, the leaves constitute the largest wet biomass residue generated per hectare, reaching approximately 250 metric tons (Saini et al., 2022). Nevertheless, this leaf waste contains a high proportion of natural cellulose, ranging from 70% to 82%. The microstructural characteristics of crystalline cellulose provide the primary basis for its superior mechanical properties, particularly durability and tensile strength, making it promising for green manufacturing applications (Sethupathi et al., 2024).

Fresh pineapple leaves contain approximately 2–3.5% fiber by total leaf weight (Jalil et al., 2021). The resulting extracted fibers have considerable potential as reinforcement materials for green biocomposites (Giri et al., 2024). However, a major challenge in the downstream utilization of natural fibers lies in optimizing the extraction method to ensure that the release of cellulose microfibrils from the amorphous phase does not induce physical defects that compromise the mechanical performance of the material (Lalhruaitluangi and Mandal, 2024). Manual extraction is time-consuming and relatively unproductive and generates more than

50% additional waste, although the resulting fibers tend to be finer (Jalil et al., 2021). Meanwhile, the retting method using 0.5% urea is constrained by an excessively long processing time for industrial-scale applications (Rukundo et al., 2024). As an alternative, mechanical extraction using a decorator machine has been proposed as an effective solution for increasing production capacity while reducing processing time (Nayak et al., 2024). However, conventional mechanical methods are associated with a high risk of technical failure when the number, dimensions, and blade angles are not precisely controlled, potentially causing the leaves to break or rupture during the scraping process (Lalhruitluangi and Mandal, 2024).

Although the development of pineapple leaf fiber extraction techniques has continued to advance, the effects of controlled mechanical extraction parameters on the relationships among processing conditions, fiber structural characteristics, and mechanical performance remain insufficiently understood. Most previous studies have focused on manual, chemical, or conventional mechanical fiber extraction, with limited attention given to how controlled mechanical energy input simultaneously affects cellulose organization, surface morphology, and tensile properties. Therefore, the existing knowledge gap concerns not only the utilization of different pineapple varieties but also the lack of a systematic understanding of the extraction–structure–property relationship in pineapple leaf fibers. It is hypothesized that controlling the extraction process using a VFD-based mechanical system can regulate fiber separation efficiency and minimize structural damage, thereby producing improved fiber characteristics suitable for sustainable biocomposite reinforcement.

The scientific novelty of this study lies not merely in the use of a variable frequency drive (VFD) system or the utilization of a specific local pineapple variety, but in examining the relationship between controlled mechanical extraction conditions, fiber microstructural characteristics, and observed mechanical performance. In contrast to the general assumption that higher fiber yield necessarily indicates more successful extraction, this study investigates whether controlled VFD operation is associated with differences in fiber yield, microstructural characteristics, and observed mechanical performance. Precise control of the VFD frequency is expected to prevent the destructive shear forces commonly encountered during conventional constant-speed extraction. Through this

approach, the study evaluates whether the extraction process contributes to variations in the degree of crystallinity and crystallite size, as well as how these characteristics are associated with the tensile resistance profile and static tensile energy absorption capacity of the fibers.

Therefore, this study aimed to evaluate the characteristics of mechanically extracted fibers from Tamban pineapple leaf waste using a VFD-controlled extraction system. The raw materials were obtained from Barito Kuala Regency, South Kalimantan Province, Indonesia. Information regarding the physical, mechanical, and microstructural properties of fibers derived from this local pineapple variety remains limited. Accordingly, this study is expected to provide scientific evidence for evaluating the extraction process and determining appropriate operating conditions for producing environmentally friendly pineapple leaf fibers as reinforcement materials for biocomposite applications.

MATERIALS AND METHODS

Materials

Tamban pineapple leaves were collected from a pineapple plantation after harvesting and field clearing in Barito Kuala Regency, South Kalimantan Province, Indonesia. The collected Tamban pineapple leaves were subsequently divided into three batches based on the raw-material sacks, namely Sack 1 (K1), Sack 2 (K2), and Sack 3 (K3), prior to the fiber separation process.

Experimental design and replication

The experiment was designed using a randomized complete block design (RCBD), with three groups (raw-material sack blocks) serving as independent replicates ($n = 3$) to control for initial variation in the fiber material. The treatment factor consisted of three levels of fiber extraction from Tamban pineapple leaves: extraction using a VFD inverter-based fiber-separation machine at frequencies of 15 Hz (V15 Hz) and 20 Hz (V20 Hz), and manual press (MP) as the control. This experimental design resulted in a total of nine experimental units ($N = 3 \times 3$), as presented in Table 1. All quantitative test data were reported as mean $\pm$ standard deviation (Mean $\pm$ SD) based on $n = 3$ independent replicates.

Table 1. Treatment arrangement based on the randomized complete block design

Block	Treatment		
	V15 Hz	V20 Hz	Manual press (MP)
Sack 1	V15-K1	V20-K1	MP-K1
Sack 2	V15-K2	V20-K2	MP-K2
Sack 3	V15-K3	V20-K3	MP-K3

Tamban pineapple leaf fiber extraction

The initial preparation stage involved sorting the leaves to remove dirt, spines, and decayed portions, followed by rinsing under running water. Fiber extraction was then performed mechanically without soaking or water addition using a VFD inverter-based fiber extraction and separation machine to control the driving motor speed while maintaining a constant roller gap (Figure 1). The main structure of the machine was constructed from angle-iron steel framing and driven by a 0.75 kW AC induction motor connected to a VFD control panel. Power was transmitted through a V-belt and pulley system and a side reduction gear with a 3:1 ratio to a pair of precision cylindrical steel rollers with a diameter of 180 mm and a length of 480 mm. The VFD frequency setting of 15 Hz (V15) resulted in a motor rotational speed of 450 rpm, whereas 20 Hz (V20)

resulted in a motor speed of 600 rpm. Through the 3:1 reduction gear, these speeds were converted to extraction roller speeds of 150 rpm and 200 rpm, respectively. The gap between the rollers was maintained at a constant 1 mm using a dual-screw adjustment mechanism mounted on the upper part of the frame. During extraction, the pair of smooth-surfaced steel rollers directly compressed the pineapple leaf material at a controlled feed rate of $0.1 \text{ kg} \cdot \text{min}^{-1}$. For the MP treatment, the pineapple leaves were manually fed and clamped between the rollers using a lever. The extracted fibers were subsequently washed thoroughly and naturally dried by hanging them for 1–2 days until a moisture content of 10–12% was reached. The technical specifications and operating parameters of the VFD-based fiber extraction machine used in this study are presented in Table 2. The extraction yield was subsequently determined based on the percentage of fiber yield using Equation 1:

$$R = \frac{Wf}{Wl} \times 100\% \quad (1)$$

where: R – the percentage of extracted fiber yield (%), Wf – the weight of the extracted dry fiber, (kg), Wl – the initial weight of the fresh pineapple leaves (kg).

Fiber characterization

Tensile strength test

The tensile strength of the natural fiber bundles was evaluated in accordance with the ASTM D3822 standard (Kumar et al., 2024) (Figure 2). The tensile strength of the fiber bundles was calculated as the maximum load at failure divided by the average cross-sectional area, following Equations 2 and 3:

$$A = \frac{\pi \times d1 \times d2}{4} \quad (2)$$

$$\sigma = \frac{Fmax}{A} \quad (3)$$

where: σ – the tensile strength (MPa), $Fmax$ – the maximum load at failure (N), A – the cross-sectional area of the fiber bundle (mm^2), $d1$ – the average major diameter of the fiber bundle (mm), $d2$ – the average minor diameter of the fiber bundle (mm).

Determination of tensile toughness

Tensile toughness was determined from the data obtained through quasi-static tensile testing using a UTM. The stress–strain curve obtained during

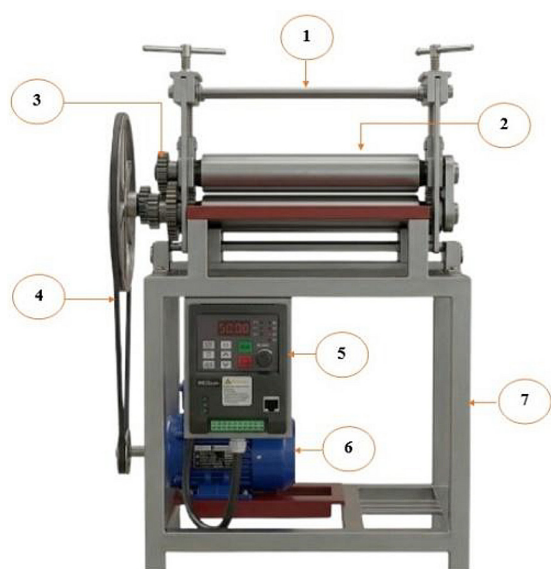


Figure 1. VFD-based pineapple leaf fiber extraction machine: (1) dual-screw gap adjustment mechanism, (2) pair of cylindrical steel rollers, (3) reduction gear, (4) V-belt transmission, (5) VFD inverter, (6) 0.75 kW AC induction motor, and (7) main frame

Table 2. Technical specifications and operating parameters of the VFD-based fiber extraction machine

Category	Parameter	Specification
Technical specifications	Machine dimensions	750 × 450 × 1000 mm (angle-iron steel frame)
Control system	Speed controller	9600 Series VFD (<i>Variable Frequency Drive</i>)
Drive system	Driving motor	0.75 kW AC induction motor (1 HP, 4-pole)
Power transmission	Transmission system	V-belt and side reduction gear (3:1 ratio)
Roller geometry	Extraction element	Pair of precision cylindrical steel rollers (smooth surface, without blades)
Roller dimensions	Roller size	Diameter: 180 mm; Length: 480 mm
Pressing system	Gap/pressure adjustment	Dual-screw mechanism
	Roller gap	1 mm (constant)
Raw material and method	Raw material condition	Fresh Tamban pineapple leaves
	Processing condition	Direct mechanical extraction without water addition or prior soaking treatment
	Feed rate	1 leaf per process (0.1 kg·min ⁻¹)
Operating speed	Roller speed at 15 Hz (V15)	Motor: 450 rpm; extraction rollers: 150 rpm
	Roller speed at 20 Hz (V20)	Motor: 600 rpm; extraction rollers: 200 rpm
Electrical parameters	VFD operating voltage	122 V
	VFD load current	0.7 A
	Power consumption	Manual Press (MP): 0 W; V15 Hz: 651.2–651.4 W; V20 Hz: 650.1–650.6 W

the test represents the deformation response of the specimen under loading up to the point of fracture. Tensile toughness was calculated from the area under the stress–strain curve and expressed as the energy absorbed per unit volume of material (MJ/m³).

**Figure 2.** Tensile testing of Tamban pineapple leaf fiber bundles using a Universal Testing Machine (UTM)

This parameter was used to describe the ability of the specimen to absorb energy during quasi-static tensile loading (Figure 2). The test did not employ a dynamic pendulum impact instrument; therefore, the tensile toughness values obtained should not be interpreted as direct measurements of the material's dynamic impact resistance. The UTM software used in this study exports the raw acquisition data for the complete testing batch as a single *raw data.xls* file rather than separate specimen-level files. Therefore, the original *raw data.xls* file is provided as the primary raw acquisition record, together with the original instrument-generated reports for all nine specimens. No raw measurements or stress–strain curves were reconstructed retrospectively. Analytically, the total static energy absorption capacity (U_t) was defined as the total deformation energy per unit volume of material (MJ/m³) up to specimen failure. This value was determined by calculating the area under the engineering stress–strain curve through numerical integration, as expressed in Equation 4 (Bai et al., 2020):

$$U_t = \int_0^{\epsilon^f} \sigma d\epsilon \quad (4)$$

where: U_t – the tensile toughness or total static energy absorption capacity (MJ/m³), ϵ^f – the strain at failure (decimal), σ and ϵ – the axial stress (MPa) and strain (decimal), respectively.

Because the discrete data obtained from the UTM exhibited an approximately *bilinear* stress–strain response, the area under the curve was numerically approximated by separating the total strain energy density into two principal geometric components based on standard mechanical behavior: the elastic deformation component (U_e), represented by a triangle, and the plastic deformation component (U_p), represented by a trapezoid (Hibbeler, 2018). The yield strain (ε_y) was calculated from the ratio of the yield strength (σ_y) to Young's Modulus (E) according to Equation 5:

$$\varepsilon_y = \frac{\sigma_y}{E} \quad (5)$$

The elastic strain energy density was calculated using Equation 6:

$$U_e = \frac{1}{2} \sigma_y \cdot \varepsilon_y \quad (6)$$

The plastic strain energy density from the yield point to the maximum tensile strength (σ_{max}) and failure strain (ε_f) was subsequently calculated using Equation 7:

$$U_p = \left(\frac{\sigma_y + \sigma_{max}}{2} \right) \cdot (\varepsilon_f - \varepsilon_y) \quad (7)$$

Thus, the total static energy absorption capacity was obtained by summing the two components according to Equation 8, providing a mechanically valid and transparent equivalent consistent with the principles of mechanics of materials for analyzing quasi-static tensile test data:

$$U_t = U_e + U_p \quad (8)$$

where: U_t – the total static energy absorption capacity or tensile toughness (MJ/m^3), U_e – the elastic strain energy density (MJ/m^3), U_p – the plastic strain energy density (MJ/m^3), σ_y – the yield strength (MPa), σ_{max} – the maximum tensile strength (MPa), E – Young's Modulus (MPa), ε_y – the strain at the yield point (decimal), and ε_f – the total strain at specimen failure or fracture (decimal).

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics Version 25. All quantitative data obtained from the mechanical property tests of Tam-ban pineapple leaf fibers were expressed as mean $\pm$ standard deviation (Mean $\pm$ SD), based on $n = 3$ independent replicates for each treatment group (N

= 9 experimental units in total). The study was designed using a randomized complete block design (RCBD) to evaluate the effects of different fiber extraction treatments (V15 Hz, V20 Hz, and MP).

The assumptions required for parametric analysis were evaluated prior to hypothesis testing, including error normality using the Shapiro–Wilk test and homogeneity of variance using Levene's test, both at a significance level of $\alpha = 0.05$. Hypothesis testing was performed using a two-way analysis of variance (ANOVA) without interaction, corresponding to the RCBD model, at a 95% confidence level ($\alpha = 0.05$). When $p < 0.05$, post-hoc mean comparisons were performed using Duncan's multiple range test (DMRT). When $p > 0.05$, no post-hoc mean comparison was conducted. The hypotheses tested were that the extraction treatment had no statistically significant effect on the mechanical properties of the fibers (H_0), whereas H_1 stated that at least one extraction treatment produced a statistically significant effect.

X-ray diffraction (XRD) analysis

The crystalline structure of the fibers was characterized using a PANalytical X'Pert Pro XRD instrument over a 2θ range of 10° – 90° (Yanti et al., 2019). The crystallinity index (CI) was calculated using the peak-height method (Segal method) according to Equation 9 (Liao et al., 2025):

$$CI = \frac{I_{200} - I_{AM}}{I_{200}} \times 100\% \quad (9)$$

where: CI (%) – the crystallinity index, I_{200} – the integrated intensity of the crystalline (200) plane of cellulose I at approximately 22° (2θ), I_{AM} – the intensity of the amorphous phase of cellulose $I\beta$ at approximately 18° (2θ).

The crystallite size (τ) of the cellulose I (200) lattice plane was calculated using the Scherrer equation according to Equation 10 (Liao et al., 2025), based on the full width at half maximum (FWHM) of the diffraction peak at $2\theta = 22^\circ$:

$$\tau = \frac{K\lambda}{\beta \cos(\theta)} \quad (10)$$

where: τ – the crystallite size (nm), K – the shape factor (0.9) (a commonly used value for cellulose and biomass materials), λ – the X-ray radiation wavelength (0.154056 nm), β – the full width at half maximum (FWHM) of the (200) diffraction peak

at approximately 22° , and θ – the Bragg diffraction angle corresponding to the selected diffraction peak.

Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) morphological analysis

The morphology and elemental composition of the fibers were analyzed using a Quanta FEG 650 FE-SEM/EDX system. Fiber specimens measuring approximately 5 mm were gold-coated and examined at an accelerating voltage of 20 kV and a magnification of $1.000\times$. EDX spectroscopy was used to identify the elemental composition of the fiber surface and detect minor elements associated with inorganic residues (Heryani et al., 2022).

Study limitations

This study has several limitations that should be considered when interpreting the findings. First, the study was limited to a single local pineapple variety (*Tamban*) cultivated in South Kalimantan, Indonesia. Although this provides valuable baseline data for the valorization of regional agricultural waste, further testing of other pineapple varieties and cultivation conditions is necessary to evaluate the generalizability of the proposed extraction approach.

Second, only three extraction conditions—manual extraction, 15 Hz, and 20 Hz—were investigated. The gap between the cylindrical steel rollers was adjusted manually using a dual-screw mechanism. Consequently, variations in pineapple leaf thickness could not be dynamically accommodated using a precision sensor-based system. This limitation may affect the consistency of the extraction process and should be addressed and optimized in future studies.

Third, the tensile toughness analysis did not employ a dynamic pendulum impact-testing instrument. Therefore, the tensile toughness values reported in this study represent quasi-static energy absorption capacity and should not be interpreted as direct measurements of dynamic impact resistance. Accordingly, primary impact-test data from a dedicated impact-testing instrument were not generated or included.

Fourth, this study focused on the physical and mechanical characterization of extracted fiber bundles for potential composite reinforcement

applications. The direct effects of VFD-extracted fibers on the mechanical, thermal, and durability properties of the resulting biocomposites remain to be experimentally verified.

Finally, the experiments were conducted under laboratory conditions using a prototype VFD-based extraction system. Further validation at pilot and industrial scales is required to assess process stability, productivity, economic feasibility, and long-term operational performance under sustainable manufacturing conditions.

Despite these limitations, the study establishes reproducible relationships among extraction parameters, fiber microstructure, and mechanical performance, providing a scientific basis for the further development of sustainable pineapple leaf fiber reinforcement for biomass-based composite materials.

RESULTS AND DISCUSSION

Fiber yield of tamban pineapple leaves

To evaluate the effect of the extraction method on fiber quality, the initial analysis focused on the fiber yield obtained from mechanical extraction using a VFD at frequencies of 15 Hz (V15 Hz) and 20 Hz (V20 Hz), as well as MP extraction, as shown in Figure 3.

Figure 3 shows that the fiber extraction yield of Tamban pineapple leaves ranged from 2.605% to 3.260%. Increasing the driving motor frequency through the VFD system from 15 Hz to 20 Hz consistently increased the yield percentage across all raw-material clusters. The V15 treatment produced yields of 3.043% (V15-K1), 2.933% (V15-K2), and 2.888% (V15-K3), whereas the highest yields were obtained under the V20 treatment, reaching 3.260% (V20-K1), 3.210% (V20-K2), and 3.233% (V20-K3).

From a mechanical perspective, increasing the frequency of the 9600 Series VFD inverter increased the rotational speed of the extraction rollers and consequently intensified fiber scraping. The higher mechanical action at 20 Hz more aggressively disrupted the non-cellulosic cell-wall components, resulting in a greater volume of fibers being separated and collected. In contrast, the MP treatment produced the lowest yields, namely 2.605% (MP-K1), 2.670% (MP-K2), and 2.808% (MP-K3). The lower fiber yield under the MP treatment was attributed to the

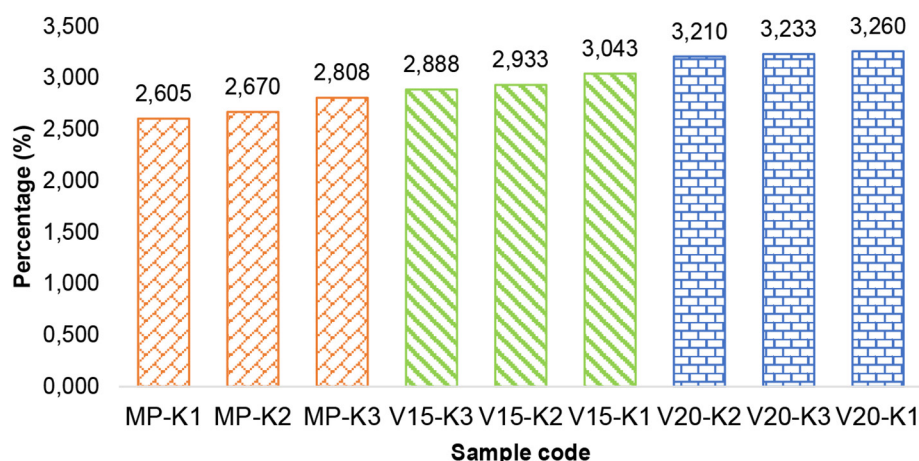


Figure 3. Fiber yield of Tamban pineapple leaves (primary data, processed in 2026)

instability of the manually applied compressive force during fiber separation from the leaf tissue, resulting in suboptimal separation and the loss of potentially recoverable fibers along with the residual biomass.

These findings suggest that the 9600 Series VFD inverter system provided more stable and consistent roller engagement during the extraction process. At a frequency of 15 Hz (V15 Hz), the pineapple leaves remained in contact with the machine for a longer period, allowing gradual scraping by the roller surfaces. This condition facilitated finer fiber separation while reducing the likelihood of fiber breakage. According to (Nayak et al., 2024), stable speed control in mechanical extraction equipment can produce a more uniform stripping force across variations in pineapple leaf thickness, enabling consistent fiber separation without damaging the primary fiber bundles.

The fibers obtained from the MP treatment in Figure 4 exhibited a dull color and a stiff, coarse appearance. This condition was attributed to the limited ability of manual operation to maintain stable roller pressure despite variations

in pineapple leaf size and thickness, resulting in fluctuations in fiber yield. According to (Mohd Amin et al., 2023), the appearance of yellowish to brownish coloration is a strong visual indicator of accumulated lignin and residual dried parenchymal sap following extraction. The remaining sap may harden and encapsulate the fibers, causing the fiber strands to become considerably stiffer and their surfaces to appear rough (Santulli et al., 2022). These observations indicate that the pressure generated during the MP process was insufficient to produce adequately clean fibers.

In contrast, the fibers obtained from the V15 Hz treatment in Figure 5 exhibited a bright creamy-white color and finely separated strands. The clean appearance of the V15-K1, V15-K2, and V15-K3 samples indicates that sap, mucilage, and residual leaf tissue had been effectively removed. The constant operating frequency of 15 Hz provided an appropriate contact time between the leaves and the roller surfaces, allowing the contaminating matrix to be gradually removed without substantially damaging the primary fiber strands. These findings indicate that fiber yield

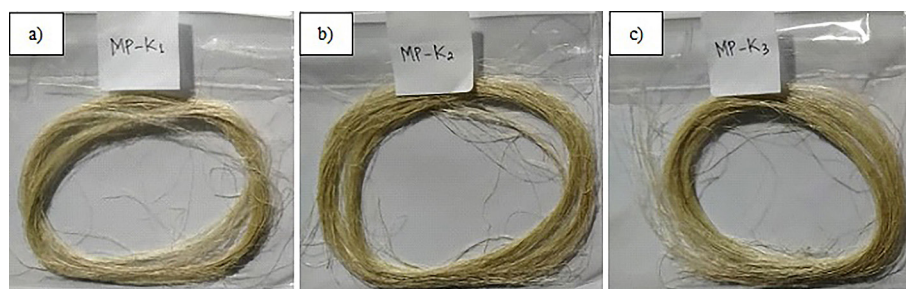


Figure 4. Tamban pineapple leaf fibers obtained from the Manual Press treatment: (a) MP-K1, (b) MP-K2, and (c) MP-K3

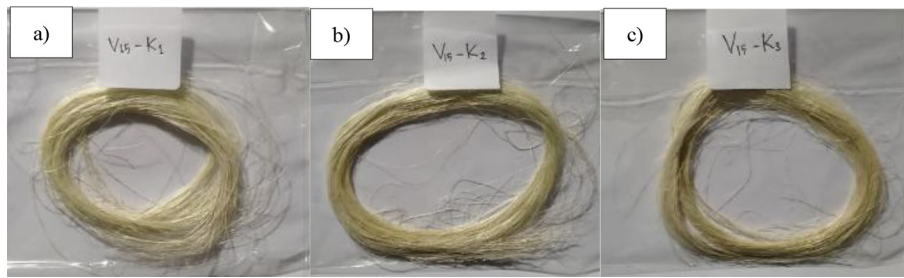


Figure 5. Tamba pineapple leaf fibers obtained from the V15 Hz treatment: (a) V15-K1, (b) V15-K2, and (c) V15-K3

alone may not be sufficient to determine the effectiveness of the extraction process, as the extraction conditions may affect fiber recovery and fiber cleanliness differently.

Meanwhile, the fibers obtained from the V20 Hz treatment exhibited a dull, yellowish, and coarsely agglomerated appearance, as shown in Figure 6. Although the V20 treatment produced the highest fiber yield, the visual characteristics indicated that the higher extraction speed did not necessarily result in better fiber cleanliness. The higher roller speed increased the mechanical stripping intensity and promoted the release of a greater amount of fibrous material. However, the shorter contact time between the pineapple leaves and the roller surfaces may have limited the effective removal of residual mucilage, sap, and non-fibrous tissue. Consequently, some of these components remained attached to the fiber bundles, resulting in a duller color and coarser, more agglomerated morphology. This observation suggests that a higher extraction frequency may improve fiber recovery but does not necessarily optimize fiber quality. Similar findings have been reported by (Nayak et al., 2024), who indicated that excessive mechanical speed can reduce the effective contact time between plant material and extraction surfaces, thereby limiting the uniform removal of non-fibrous components.

Macro-scale mechanical properties of tamban pineapple leaf fibers

Mechanical testing was conducted to compare the mechanical responses of the MP, V15 Hz, and V20 Hz treatments across the three raw-material groups (K1, K2, and K3), with the aim of evaluating the mechanical performance of the fibers as potential reinforcement materials for biocomposites.

Tensile strength characteristics

The VFD-based mechanical extraction method produced descriptively higher tensile strength values than the manual extraction method, as shown in Figure 7. The manual press (MP) treatment resulted in relatively low and highly variable tensile strength values of 28.628 MPa (MP-K1), 51.197 MPa (MP-K2), and 43.209 MPa (MP-K3).

Among the V15 Hz treatments, specimen V15-K2 exhibited the highest observed tensile strength among the nine experimental units, reaching 85.772 MPa, followed by V15-K3 (69.394 MPa) and V15-K1 (53.522 MPa). The mean tensile strength at 15 Hz reached 69.560 MPa, indicating the considerable structural potential of these fibers as reinforcement for sustainable polymer matrices. For comparison, untreated PALF-PP

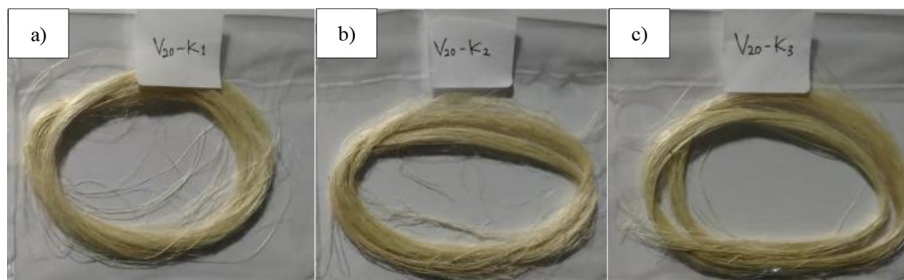


Figure 6. Tamba pineapple leaf fibers obtained from the V20 Hz treatment: (a) V20-K1, (b) V20-K2, and (c) V20-K3

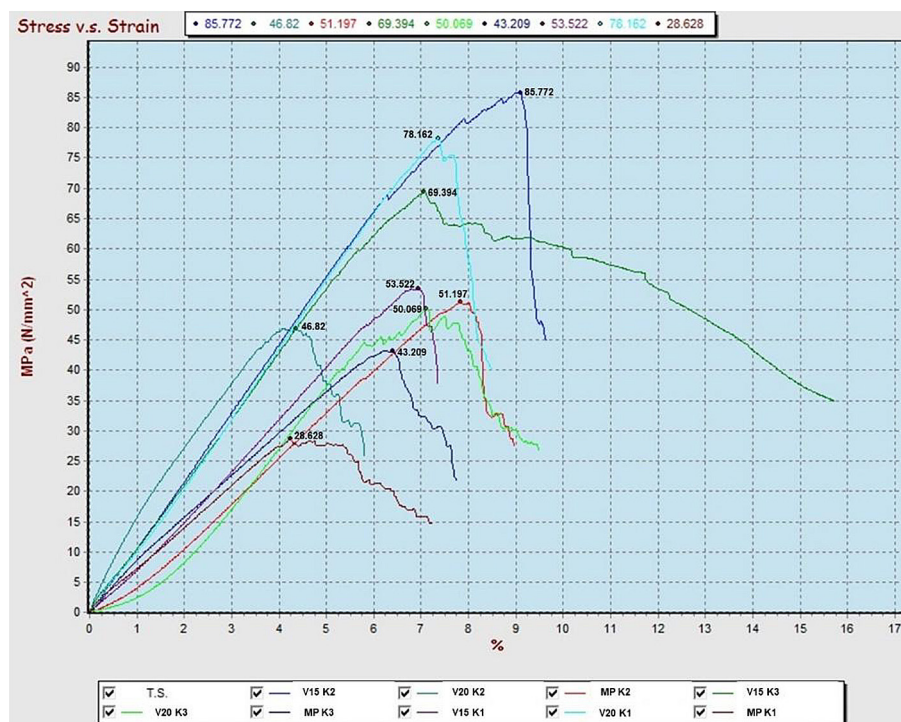


Figure 7. Stress–strain curves of the nine experimental units

composites have been reported to exhibit a tensile strength of 42.2 MPa (Gadzama et al., 2020) while NaOH-treated PALF-PP/LDPE composites have shown tensile strengths of 37–40 MPa (Rahman et al., 2021). The observed tensile strength of the V15 treatment was also within the range reported for PALF-PP composites subjected to intensive chemical modification, which reached approximately 87 MPa (Motaleb et al., 2018).

However, when the driving motor frequency was increased to 20 Hz, the fiber tensile strength showed a declining trend, with the lowest value of 46.82 MPa observed for V20-K2. Excessively high roller speed may generate greater mechanical energy input, potentially resulting in excessive fibrillation (Berzin et al., 2019) and the formation of microcracks within the fiber cell walls. These structural defects can act as stress concentrators and accelerate premature fiber failure (Sayeed et al., 2023).

The roller shear forces at V15 Hz appeared to effectively remove epidermal impurities while maintaining the integrity of the cellulose microfibril arrangement. The relatively clean fiber surface and absence of apparent structural defects may contribute to the potential of V15-extracted fibers as reinforcement materials for Polypropylene (PP) (Saber and Abdelnaby, 2022) and Low-Density Polyethylene (LDPE) matrices (Mylsamy et al., 2024).

In contrast, both the MP and V20 Hz treatments showed indications of limitations in maintaining fiber structural integrity, which may promote premature failure in composite applications due to increased susceptibility to fiber fracture.

Tensile toughness characteristics

The static tensile energy absorption capacity (modulus of toughness) of Tamban pineapple leaf fibers was evaluated by integrating the area under the engineering stress–strain curve obtained from quasi-static tensile testing using a universal testing machine (UTM). The energy absorption capacity was divided into elastic (U_e) and plastic (U_p), strain energy components, with the resulting tensile toughness ($U_t = U_e + U_p$) presented in Table 3.

Based on Table 3, the mechanical testing revealed variations in static energy absorption capacity and tensile toughness among specimens subjected to different extraction treatments using the VFD and manual extraction methods. The highest energy absorption capacity was recorded for specimen V15-K2, with a tensile toughness of 4.842 MJ/m³, consisting of 2.777 MJ/m³ of plastic energy and 2.065 MJ/m³ of elastic energy. High tensile toughness values were also observed in the V20 treatment, particularly for V20-K1, which reached 4.491 MJ/m³, and V15-K3, which reached 4.336 MJ/m³. In contrast, the lowest

Table 3. Static tensile energy absorption capacity and tensile toughness of Tamban pineapple leaf fiber bundles

Specimen code	Yield strength (σ_y) [MPa]	Tensile strength (σ_{max}) [MPa]	Young's modulus (E) [MPa]	Elongation (ϵ_f) [mm/mm]	Elastic energy (U_e) [MJ/m ³]	Plastic energy (U_p) [MJ/m ³]	Tensile toughness (U_t) [MJ/m ³]
V15-K1	47.01	53.52	851.93	0.0966	1.297	2.082	3.379
V15-K2	68.22	85.77	1127.10	0.0966	2.065	2.777	4.842
V15-K3	59.26	69.39	1095.17	0.0966	1.603	2.733	4.336
V20-K1	74.51	78.16	1009.98	0.0966	2.748	1.742	4.491
V20-K2	46.63	46.82	1153.07	0.0966	0.943	2.624	3.567
V20-K3	45.60	50.07	1008.01	0.0966	1.031	2.457	3.488
MP-K1	27.74	28.63	759.39	0.0966	0.507	1.693	2.200
MP-K2	38.18	51.20	758.55	0.0966	0.961	2.068	3.029
MP-K3	34.60	43.21	693.59	0.0966	0.863	1.817	2.680

energy absorption capacity was recorded for the manual extraction group, particularly MP-K1, with a tensile toughness of 2.200 MJ/m³, comprising 0.507 MJ/m³ of elastic energy and 1.693 MJ/m³ of plastic energy.

Overall, the higher tensile toughness observed in the VFD-based mechanical extraction treatments, particularly V15 and V20, suggests that controlled mechanical extraction may help preserve the integrity of cellulose microfibril structures and minimize microcracking within the fiber bundles. This structural integrity may allow the material to absorb a substantial amount of mechanical energy through permanent plastic deformation before ultimately undergoing failure or complete fracture under tensile loading.

Mechanical properties of tamban pineapple leaf fibers

Based on the analysis of variance using the randomized complete block design (RCBD), presented in Table 4, the variation in extraction treatment (V15 Hz, V20 Hz, and Manual Press) did not produce statistically significant differences ($p > 0.05$) in any of the evaluated mechanical properties

of Tamban pineapple leaf fibers. This lack of statistical significance was indicated by the tensile strength result ($F = 1.9630$, $p = 0.2547$), tensile toughness ($F = 4.563$, $p = 0.093$), yield strength ($F = 2.7953$, $p = 0.174$), maximum force ($F = 1.8939$, $p = 0.2638$), and Young's modulus ($F = 1.1150$, $p = 0.4122$). Because all p -values were greater than 0.05, the null hypothesis (H_0) was not rejected, and no post-hoc mean comparison was performed.

Although no statistically significant differences were observed among the extraction methods at the population level, descriptive evaluation based on the highest observed mean values showed that the V15 Hz treatment produced the highest tensile strength (69.560 ± 16.126 MPa), tensile toughness (4.186 ± 0.743 MJ/m³), yield strength (58.163 ± 10.647 MPa), and maximum force (218.567 ± 36.099 N).

X-ray diffraction patterns and crystallinity index of the fibers

XRD analysis and microscopic characterization were focused on all specimens from the V15 Hz treatment group (V15-K1, V15-K2, and

Table 4. Mechanical properties of Tamban pineapple leaf fibers under different extraction treatments

Parameter	V15 Hz	V20 Hz	MP	F-value	p-value
Tensile strength (MPa)	69.560 $\pm$ 16.126	58.350 $\pm$ 17.233	41.013 $\pm$ 11.444	1.9630	0.2547
Tensile toughness (MJ/m ³)	4.186 $\pm$ 0.743	3.849 $\pm$ 0.556	2.636 $\pm$ 0.416	4.563	0.093
Yield strength (MPa)	58.163 $\pm$ 10.647	55.580 $\pm$ 16.402	33.507 $\pm$ 5.305	2.7953	0.174
Maximum force (N)	218.567 $\pm$ 36.099	187.133 $\pm$ 65.250	129.673 $\pm$ 29.697	1.8939	0.2638
Young's modulus (N/mm ²)	1024.733 $\pm$ 150.501	1057.02 $\pm$ 83.19	737.177 $\pm$ 37.749	1.1150	0.4122

Note: values are presented as mean $\pm$ standard deviation ($n = 3$). RCBD ANOVA showed no statistically significant differences ($p > 0.05$) among treatments for any of the evaluated parameters; therefore, no post-hoc test was performed. Treatments were V15 Hz (15 Hz extraction frequency), V20 Hz (20 Hz extraction frequency), and MP (Manual Press).

V15-K3). The selection of this group was not based on a claim that V15 was the superior extraction method, as the ANOVA results showed no statistically significant differences among the extraction treatments ($p > 0.05$). Instead, the V15 Hz group was selected based on two objective technical considerations: (1) visually, V15 Hz produced a cleaner fiber morphology, with epidermal impurities appearing to be removed more effectively; and (2) this group included the experimental unit with the highest observed tensile strength, namely V15-K2, with a tensile strength of 85.77 MPa. This approach was specifically intended to evaluate the crystallographic profile and microstructural integrity of the material under the specimen condition that was descriptively the most favorable, without assuming a statistically superior treatment effect of V15 at the population level. As shown in Figure 8, all specimens from the V15 Hz treatment group (V15-K1, V15-K2, and V15-K3) exhibited diffraction patterns consistent with a Cellulose I β crystalline structure, in agreement with the JCPDS No. 03-0289 reference pattern.

The crystalline cellulose phase was identified through three characteristic diffraction peaks. A broad (110) reflection appeared at $2\theta = 15.9023^\circ$ for V15-K2 and at 16.2471° for both V15-K1 and V15-K3, indicating lateral ordering of the cellulose chains within the crystalline structure. The dominant (200) reflection, representing the crystalline cellulose phase, exhibited the highest diffraction intensity at $2\theta = 22.4207^\circ$ (V15-K2), 22.5685° (V15-K3), and 22.8814° (V15-K1), confirming the presence of crystalline regions in all specimens. In addition, an axial (004) reflection was observed at $2\theta = 33.9470^\circ$ for V15-K3

and at 34.1768° for V15-K1 and V15-K2, indicating longitudinal structural ordering within the cellulose microfibrils, which may contribute to tensile load transfer within the fibers. The appearance of the principal crystalline diffraction peak at $2\theta = 22.4207^\circ$ in specimen V15-K2 confirms the presence of a Cellulose I β crystalline structure in Tamban pineapple leaf fibers. The sharp peak in the $2\theta = 22^\circ$ – 23° region indicates a relatively high degree of crystalline cellulose lattice ordering, consistent with the crystalline characteristics reported for kenaf-derived lignocellulosic material (Saeed et al., 2021). Such crystalline ordering plays an important role in supporting mechanical resistance and axial stiffness in cellulose-based fiber structures.

A comparison of the tensile strength, crystallinity index, and crystallite size of the fiber samples investigated in this study with values reported in the literature is presented in Table 5.

As shown in Table 5, V15-K2 recorded the highest individual observed tensile strength among the samples examined in this study, at 85.77 MPa, with a crystallinity index of 52.44% and a crystallite size of 8.52 nm. In contrast, V15-K3 exhibited the highest crystallinity index (76.00%) but also showed a substantially larger calculated crystallite size of 89.99 nm, whereas V15-K1 exhibited a tensile strength of 53.52 MPa, a crystallinity index of 31.67%, and a crystallite size of 15.35 nm. The relatively large calculated crystallite size may reflect differences in the dimensions of coherent crystalline domains and/or peak-broadening characteristics; however, the present XRD data alone do not establish the presence of agglomeration or specific residual chemical components.

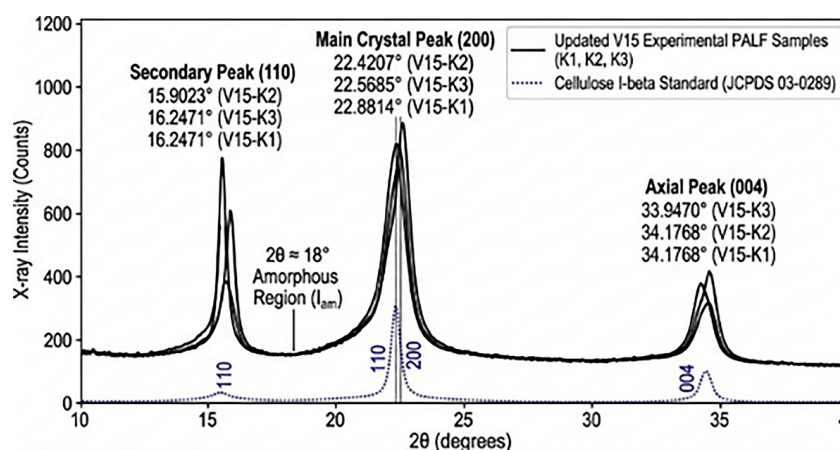


Figure 8. X-ray diffraction patterns of standard Cellulose I β (JCPDS No. 03-0289) and Tamban pineapple leaf fibers

Table 5. Comparison of tensile strength, crystallinity index, and crystallite size of the fibers with relevant literature

Fiber sample	Tensile strength (MPa)	Crystallinity index (%)	Crystallite size (nm)	Reference
V15-K1	53.52	31.67	15.35	This study
V15-K2	85.77	52.44	8.52	This study
V15-K3	69.39	76.00	89.99	This study
PALF (Untreated)	630 ± 50	62.2	18.53	Gaba et al., 2021
Raw PALF	616.8 (5.14 cN/dtex)	62.78	2.86	Liao et al., 2025
PALF (Untreated)	390.1	72	Not reported	Akarapoowadol et al., 2026
PALF (Untreated)	22.8	66	Not reported	Arumugam et al., 2025

According to Liao et al. (2025), the isolation of relatively pure cellulose is associated with nanoscale crystalline domains with reduced amorphous contributions. Such compact and relatively homogeneous structures may facilitate more uniform tensile load distribution along the fiber and reduce the likelihood of premature failure (de Sá Barros et al., 2021). In the present study, the crystallite size of 8.52 nm observed for V15-K2 may support effective load transfer within the cellulose structure. In contrast, the substantially larger calculated crystallite size of 89.99 nm for V15-K3 indicates differences in the characteristics of the crystalline domains that should be interpreted cautiously and may be associated with structural heterogeneity or residual amorphous material.

Compared with the literature, the tensile strength values obtained in the present study were generally lower. Gaba et al. (2021) and Liao et al. (2025) reported PALF tensile strengths exceeding 600 MPa, with crystallinity indices ranging from approximately 62% to 63%. Other studies by Akarapoowadol et al. (2026) and Arumugam et al. (2025) also reported a relatively wide range of tensile strength values, from 22.8 to 390.1 MPa, with crystallinity indices ranging from 66% to 72%.

The observed differences in characteristics indicate variations in the degree of microfibril disintegration and crystalline-domain characteristics that may be associated with the mechanical extraction conditions. The V15 Hz treatment appeared to expose cellulose-rich microfibrillar domains on the fiber surface. The XRD patterns remained consistent with a Cellulose I β structure in agreement with JCPDS No. 03-0289. These microstructural characteristics support the potential of V15 Hz as an environmentally friendly physical processing alternative for the production of pineapple leaf fibers.

Surface morphology and elemental composition analysis of pineapple leaf fibers

The crystallinity analysis was further complemented by characterization of the surface morphology and elemental composition using SEM–EDX. This complementary analysis was performed to assess the effectiveness of the mechanical extraction process in removing amorphous components and exposing the cellulose microfibrillar structure.

SEM–EDX characterization showed that the V15-K2 specimen exhibited the most favorable observed microstructural characteristics, with cellulose microfibrils well separated and aligned along the longitudinal axis of the fiber, as illustrated in Figure 9. This morphology indicates a reduction in the amorphous material covering the microfibril surfaces. The EDX spectrum showed that the observed surface was dominated by carbon and oxygen, consistent with the elemental composition expected for cellulose-rich lignocellulosic fibers. The removal of the amorphous layer also exposed naturally occurring mineral elements, including Al (3.48 wt%), Si (1.13 wt%), Cl (1.26 wt%), and Ca (0.94 wt%), indicating a relatively cleaner and more accessible fiber surface.

A different microstructural condition was observed in V15-K1, which retained a thin residual amorphous layer despite showing partially exposed cellulose microfibrils, as illustrated in Figure 10. EDX analysis revealed relatively high concentrations of carbon (52.09 wt%) and oxygen (45.80 wt%), along with the presence of titanium (Ti, 2.11 wt%). These findings indicate that although mechanical extraction successfully removed most of the non-cellulosic matrix, a small amount of amorphous material remained attached to the fiber surface, suggesting that portions of the

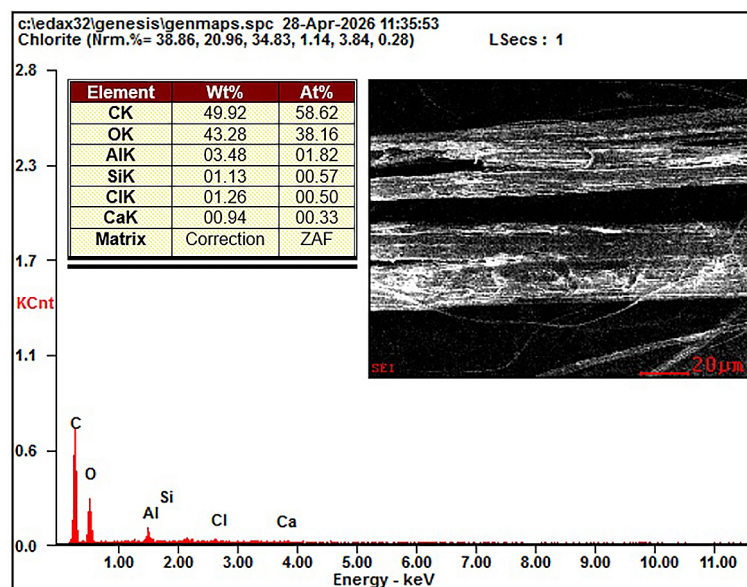


Figure 9. Surface morphology and EDX spectrum of Tamban pineapple leaf fiber from the V15-K2 sample

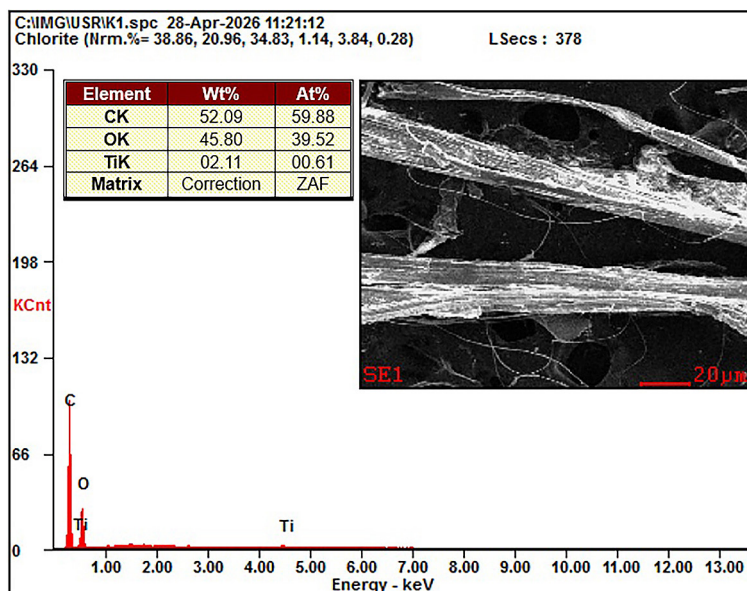


Figure 10. Surface morphology and EDX spectrum of Tamban pineapple leaf fiber from the V15-K1 sample

microfibrillar surface were still covered by residual amorphous components.

Furthermore, the predominance of carbon and oxygen detected by EDX is consistent with the elemental composition generally reported for plant-based natural fibers (Alzarieni et al., 2025; N. P. Kumar et al., 2022). Such longitudinally oriented surface features may be advantageous for sustainable textile biocomposites because they can reduce internal structural defects while enhancing mechanical interlocking between the fibers and polymer matrix, thereby improving interfacial adhesion and load-transfer efficiency (Figure 11).

CONCLUSIONS

This study demonstrated that operation of the VFD-based extraction system resulted in descriptive variations in the yield, mechanical properties, and microstructural characteristics of Tamban pineapple leaf fibers. The analysis of variance using a RCBD showed that the variation in extraction treatment did not have a statistically significant effect ($p > 0.05$) on the mechanical property parameters under the experimental conditions of this study.

No statistically significant differences were detected among the extraction treatments under

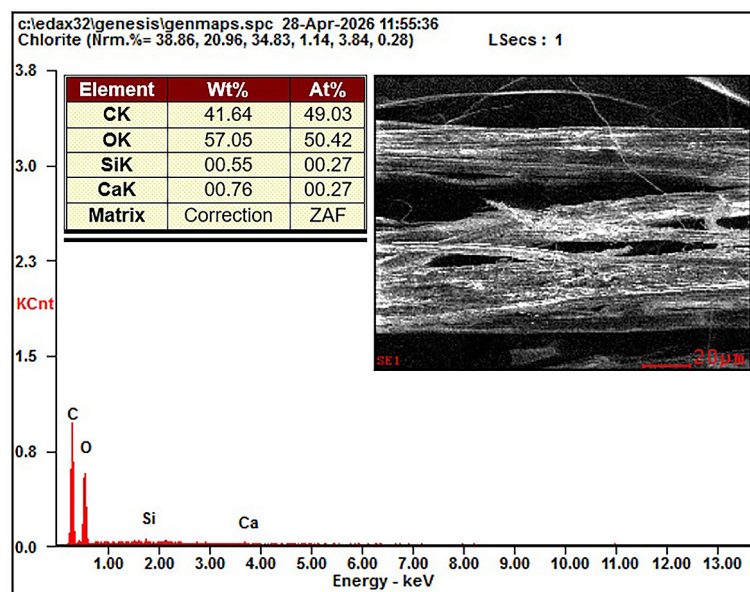


Figure 11. Surface morphology and EDX spectrum of Tamban pineapple leaf fiber from the V15-K3 sample

the present experimental conditions, although microstructural analysis revealed differences in the physical characteristics of the resulting fibers. The 20 Hz treatment produced the highest fiber yield but was associated with a duller and more coarsely agglomerated fiber appearance. In contrast, the V15-K2 specimen exhibited microstructural characteristics associated with reduced amorphous material covering the Cellulose I β microfibrillar domains associated, with a crystallinity index of 52.44% and a crystallite size of 8.52 nm.

These findings address the existing data gap regarding the characteristics of Tamban pineapple leaf fibers as a locally specific agricultural waste material that has not previously been comprehensively characterized in the scientific literature. Overall, this study provides a measurable engineering and methodological basis for conditioning local agricultural waste into renewable reinforcement materials for sustainable polymer composites, while contributing to agricultural waste valorization within a circular bioeconomy framework.

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