Research Paper

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CHARACTERIZATION OF TAMBAN VARIETY PINEAPPLE LEAF FIBER USING MECHANICAL EXTRACTION AS A SUSTAINABLE COMPOSITE REINFORCEMENT MATERIAL

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Article Info

Received: February 21, 2026
Revised: March 28, 2026
Accepted: April 16, 2026
Published: August 2026

Keywords:

biomass, crystallinity index, tensile and impact performance, fiber separation, natural fiber reinforcement

ABSTRACT. Pineapple leaf fiber (PALF) is one of the most promising natural fibers derived from agricultural waste. Utilization of abundant pineapple leaf waste is a strategic solution in the development of sustainable environmentally friendly materials. This study aimed at characterizing the microstructure and assessing the mechanical properties of PALF of the Tamban variety from Barito Kuala Regency extracted using a mechanical separation method. The characterization methods used include X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and Scanning Electron Microscopy-Energy Dispersive X-ray (SEM-EDX). Mechanical performance was evaluated through tensile tests (modified ASTM D638) and Izod impact tests on technical fiber bundles. The results showed that the mechanical extraction process produced a yield of 4.09% while maintaining the type I cellulose structure. XRD analysis showed a crystallinity index of 23.68% at $2\theta = 22.2675°$ with a nanoscale crystallite size (17.15 nm). XRF data showed the dominance of K (41.4%), Ca (26.6%), and Si (12.4%) elements contributing to the thermal resistance of the fiber and SEM-EDX observations showed a rough and porous surface morphology, which supported strong mechanical bonds. The mechanical advantages were shown by an average tensile strength of 509.29 MPa and a shock resistance of 33.33 kJ/m². This study proves the high potential of PALF Tamban variety as a tough structural composite reinforcement and supports the independence of sustainable local resource-based materials.

INTRODUCTION

The manufacturing industry is encouraged to shift from synthetic to nature-based materials to implement the Sustainable Development Goals (SDGs), specifically SDG 12 on Responsible Consumption and Production and SDG 9 on Industry, Innovation, and Infrastructure (Heryani *et al.*, 2022); (Dabet *et al.*, 2023). In line with this perspective, collaborating on the development of the creative industry provides opportunities for product innovation, supported by skilled, trained, and knowledgeable human resources, as well as the creativity and uniqueness of local natural potential (Heryani *et al.*, 2020). Synthetic glass fiber has become the gold standard because of its high strength; however, this material is non-biodegradable (Kar and Saikia, 2023).

The development of biodegradable plastics is one promising alternative for addressing these issues. Cellulose, derived from biomass, acts as a reinforcing agent owing to its crystalline structure. The strong mechanical properties of cellulose make it highly suitable for use as a reinforcing material in polymer composites (Kurniati *et al.*, 2019).

Natural fibers are renewable sources of raw materials with favorable physical and mechanical properties. They are environmentally friendly because of their biodegradability and significant CO_2 absorption capacity. The utilization of natural fibers extends beyond conventional applications, demonstrating their strong potential for further development as raw materials in various industrial sectors. This development could help meet domestic demand, reduce import dependency, and increase the added value and utilization of sustainable resources (Suparno, 2020).

Indonesia has abundant natural fiber potential, including pineapple leaves (*Ananas comosus (L.)* Merr.). However, post-harvest pineapple leaf utilization remains an environmental challenge due to underutilization and high tannin content, which makes the fiber difficult to decompose naturally. Tannins play a vital role in various fields, from the clothing (textile) industry to food processing and pharmaceutical manufacturing. This versatile ingredient can be used as wood glue, a leather preservative, and even as a health booster (antioxidants). As more people shift to a healthy and environmentally friendly lifestyle, the demand for natural ingredients such as tannins is increasing (Jannah *et al.*, 2021). The high tannin content in pineapple fiber is a polyphenol compound with antimicrobial properties that can inhibit the action of cellulose-degrading enzymes. This makes pineapple leaf waste difficult to decompose naturally on agricultural land and often accumulates as solid waste. Therefore, converting pineapple leaf waste into composite reinforcement fibers aligns with circular economy principles because it is environmentally friendly, lightweight, and renewable.

The inhibition of decomposition in pineapple leaf waste is advantageous when the fiber is extracted and used as a composite reinforcement. Resistance to fungal and microbial attack by polyphenolic and lignocellulosic compounds, particularly cellulose, hemicellulose, and lignin, indicates that the fiber has good durability as a composite material (Todkar and Patil, 2019);(Romruen *et al.*, 2022). Lignin has significant potential as a sustainable raw material because of its abundant availability and role as a structural component of lignocellulosic biomass. In addition to being sustainable, lignin is highly economical as it is a byproduct of the paper and natural fiber processing industries (Adriana *et al.*, 2024).

Pineapple leaf waste has chemical properties that can be optimized as a byproduct in the production of heterogeneous catalysts, an alternative to the use of homogeneous catalysts in the biodiesel industrial process (Heryani *et al.*, 2022). Pineapple leaf fibers contain 68–85% cellulose, 16–19% hemicellulose, and 5–12% lignin (Nath *et al.*, 2023). Currently, pineapple leaf waste is utilized as a cellulose fiber in the textile industry (Lalhruaitluangi and Mandal, 2024), as a raw material for paper with a smooth surface, and as a producer of biodegradable fiber as a leather substitute (Saini *et al.*, 2023).

South Kalimantan Province, particularly Barito Kuala Regency, is renowned for its superior pineapple variety, Tamban pineapple, according to Decree of the Minister of Agriculture No. 2088/Kpts/S. R.120/5/2009, with an average fruit production of 13,000 tons by 2025. Post-harvest, one hectare of pineapple plantation yields 1.5 tons of leaf waste. To date, Tamban pineapple leaves have not been optimally utilized.

Previous research has reported that pineapple leaf fibers from Queen, Smooth Cayenne, and Red Spanish PALF varieties, when bundled, exhibit stiffness or flexural strength (37–86 GPa) comparable to that of E-glass fibers commonly used as industrial materials (30–70 GPa) (Manaia *et al.,* 2019; Liao *et al.*, 2025). Many previous studies have suggested the use of chemicals to clean the surface of natural fibers to increase their strength when bonded to plastics or resins. This is because natural fibers are typically hydrophilic, whereas resins are hydrophobic, making it difficult to achieve a strong bond between them. Researchers have tried various methods, such as using alkaline solutions (NaOH), to reduce water absorption and increase fiber stiffness. However, the resulting strength is highly dependent on the type and chemicals used (Asim *et al.*, 2018; Gaba *et al.,* 2021).

Although pineapple leaf fibers have been extensively studied, most studies have focused on common pineapple varieties. In this study, we attempted to provide information on the microstructure and mechanical properties of pineapple leaf fibers of the Tamban variety, particularly those extracted using mechanical separation methods, which are still very limited. By avoiding chemical processes such as the use of NaOH, this mechanical extraction method is much more environmentally friendly and supports the sustainability of locally sourced materials. This study aimed to characterize the microstructure and assess the mechanical properties of Tamban variety PALF from Barito Kuala Regency extracted using the mechanical separation method.

MATERIALS AND METHODS

Materials

Pineapple leaf waste was collected from the post-harvest results of 11- and 18-month-old pineapple plants in the Jelapat II Farmers Group, Mekarsari District, Barito Kuala Regency, South Kalimantan Province.

Mechanical Extraction of Fiber

Old pineapple leaf waste with a minimum length of 55 cm was collected for the study. The leaves were then separated from dirt, thorns, and rotten parts and subsequently washed with running water. Next, mechanical extraction with a fiber separator was performed by inserting pineapple leaves one by one at a rotation speed of 800 rpm. The fibers that came out of the tool were immediately washed with clean water to remove mucus and any remaining leaf flesh. Then, the fibers were naturally dried by hanging them for 1-2 days (fiber moisture content was approximately 10-12%). Direct sunlight was avoided to prevent the fibers from becoming too brittle. The efficiency of the mechanical extraction process on Tamban pineapple leaves was determined by calculating the percentage of the fiber yield. The yield was calculated by comparing the mass of the dry fiber obtained after the extraction process through mechanical separation to the total mass of the fresh leaves used. The percentage of fiber was calculated using equation (1) as follows:

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

Descriptions:
Wf = Weight of dry fiber (kg)
Wl = Weight of fresh pineapple leaves (kg)

Microstructural Characterization of Materials

The characterization process began with the preparation of pineapple leaf fiber samples of the Tamban variety as a fine powder. The fiber powder was then placed in a porcelain dish and calcined in a furnace at 800°C for 4 h. Calcination at 800°C removed organic components (cellulose, hemicellulose, and lignin), but the resulting mineral profile provided important information regarding the thermal stability of the fiber and its potential interaction with the polymer matrix. After cooling, the sample was filtered using a sieve until it passed through an 80 mesh size to ensure particle homogeneity. Next, X-ray Fluorescence (XRF) analysis was performed using a PANalytical MiniPal 4 X-ray fluorescence spectrometer. XRF analysis was used to identify the inorganic elemental composition (mineral content) of the fiber, which remained stable even after the removal of organic matter. A calcination process at 800°C was carried out to produce a concentrated ash sample, thus allowing accurate measurements of mineral oxides such as K, Ca, and Si. Although calcination caused the loss of organic fractions, this method was chosen to evaluate the mineral content (such as Si, Ca, and Mg), which played a role in the thermal stability and interfacial interactions of the fiber. Measurements were carried out with a voltage of 20 kV and a current of 76 µA, which were automatically adjusted to optimize the composition of the detected elements (Na–U range) in the fiber with a high degree of accuracy (Heryani and Yanti, 2020).

The crystal structure of the fibers was analyzed using X-ray diffraction (XRD) with a PANalytical XPert Pro diffractometer using Cu-Kα radiation (λ=1.5406 Å). Data were collected over a 2q range of 10° to 90° with a step size of 0.02° and a scanning speed (time per step) of 0.7 s. The generator was operated at a voltage of 40 kV and a current of 30 mA (Yanti *et al.,* 2019). The crystallinity index (CI) was calculated using the peak height ratio (Segal Method), as shown in equation (2):

$$\text{CI (\%)} = \frac{I200 - IAM}{I200} \times 100\% \quad (2)$$

Descriptions:
I200 = Integrated peak intensity of the (200) crystal plane of cellulose I at 22° (2θ)
IAM = The amorphous intensity obtained from the Iβ cellulose phase is 18° (2θ)

The crystallite size, τ perpendicular to the (200) lattice plane of cellulose I, was determined using equation (3) (Scherrer equation) based on the full width at half maximum of the (200) diffraction peak at 22° (2θ).

$$\tau = \frac{K\lambda}{\beta \cos(\theta)} \quad (3)$$

Descriptions:
τ = Crystallite size (nm)
K = Correction factor (0.9) (Standard for cellulose/biomass)
λ = wavelength of X-ray radiation (0.154056 nm)
β = full width at half maximum (FWHM) of the diffraction peak (200) at 22°
θ = peak diffraction angle

The surface morphology and elemental composition of the Tamban pineapple leaf fibers were analyzed using Field Emission Scanning Electron Microscopy (FE-SEM) equipped with a Quanta FEG 650 energy-dispersive X-ray spectrometer (EDX). The SEM images were captured at an acceleration voltage of 20 kV with a magnification range of 500x to 2,500x. Before observation, the samples were coated with a thin layer of gold through a sputtering process to increase conductivity (Heryani *et al.,* 2022).

Physical Properties Testing of Materials

Physical property tests were conducted to determine the performance of Tamban pineapple leaf fibers as a sustainable composite reinforcement material through tensile strength and shock resistance tests. Tensile strength is the maximum stress a fiber material can withstand when stretched or pulled before breaking. In contrast, shock resistance is the ability of a natural fiber or composite material to absorb sudden impact energy without breaking. (Sayeed *et al.,* 2023);(Srinag *et al.,* 2024). In this study, physical property testing was conducted on a single-fiber bundle specimen consisting of hundreds of naturally interconnected cellulose filaments. A fiber bundle was selected as the test unit to obtain more stable data on material performance compared to single-fiber testing. To ensure accuracy, the testing procedure was tightened using a paper frame and low tensile speed (2 mm/min) to ensure even stress distribution and minimize measurement uncertainty.

The tensile strength test was performed using a Universal Testing Machine (UTM) in accordance with the ASTM D638 standard. In this test, the fiber specimen was subjected to a straight tensile load along its length at a constant speed until it reached its breaking point to determine the maximum tensile strength and elasticity of the material (Sayeed *et al.,* 2023). The use of the ASTM D638 procedure in this study was chosen with specimen modifications on fiber bundles to describe the overall mechanical behavior of the Tamban variety. The crosshead speed test was adjusted to a very low speed of 2 mm/min to approximate the natural fiber test conditions and obtain macroscopic tensile strength values. The tensile strength value (s) was then calculated based on the maximum load (Fmax) recorded on the tensile tester divided by the average cross-sectional area (α), according to Equations (4) and (5), respectively:

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

$$\sigma = \frac{Fmax}{A} \quad (5)$$

Descriptions:

σ	=	Tensile strength (MPa)
F_{max}	=	Maximum load at break (N)
A	=	Cross-sectional area of fiber bundle (mm^2)
d_1	=	Average major diameter of fiber bundle (mm)
d_2	=	Average minor diameter of fiber bundle (mm)

Fiber bundle specimens were prepared with a total length of 150 mm, and a test length of 50 mm was maintained in accordance with the best practices for natural fibers. Inset A' highlights the elliptical cross-section of the fiber bundle with an average major diameter of 0.45 mm and a minor diameter of 0.35 mm. Based on these dimensional data, the cross-sectional area was calculated to be 0.1237 mm2 (Inset B), which sustained a maximum load of 63.00 N during the test, as shown in Figure 1.

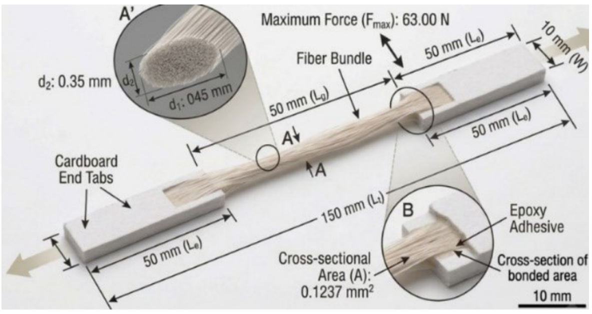


Figure 1. Schematic of fine fiber bundle specimen (d1=0.45 mm, d2=0.35 mm, Fmax =63.00 N)

Furthermore, shock resistance testing was conducted using the Izod Impact method, according to the ASTM D256 standard. The test specimens were prepared in the form of natural fiber bundles (fine microfilaments) arranged unidirectionally in a supporting resin matrix into standard dimensions of 80 mm × 15 mm × 8 mm. In the center of the specimen, there was a standard V-notch (V-notch) with a depth of 2.5 mm and an angle of 45°, which functioned as a stress concentration point to initiate fracture. Inset A' provides a detailed visualization of the fiber distribution in the resin matrix in the notch area. Inset B illustrates the Izod test mechanism, where the specimen was clamped vertically in a fixed specimen holder and struck by a pendulum hammer (hammer strike point) on the notched side to measure the energy absorption of the material at fracture. The test was carried out by placing the specimen in a vertical position and impacting it with a certain load energy to assess the material's shock resistance level, as shown in Figure 2. (Srinag *et al.,* 2024). This was done to measure the macro-shock energy absorption capacity of the Tamban variety fiber collection in a certain volume, which provided an overview of the material resistance before being processed into a composite. The shock resistance value (IS) was calculated based on the ratio of the absorbed energy to the cross-sectional area of the specimen using equation (6) as follows:

$$IS = \frac{E}{b \times h} \quad (6)$$

Descriptions:

IS = shock resistance (kJ/m²)
E = energy absorbed during fracture (Joule)
b = specimen width (15 mm)
h = specimen thickness (8 mm)

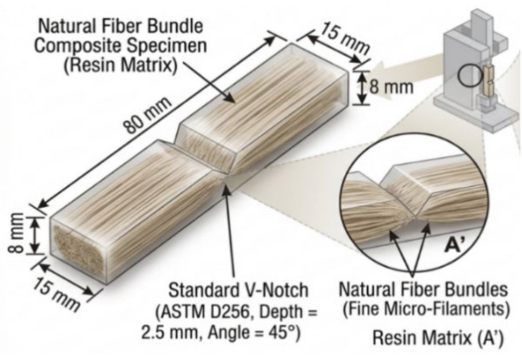


Figure 2. Schematic of a natural fiber bundle composite specimen for shock resistance testing (Izod Impact).

The tensile strength and shock resistance test results served as physical property parameters for determining the suitability of Tamban pineapple leaf fibers as an environmentally friendly composite reinforcement.

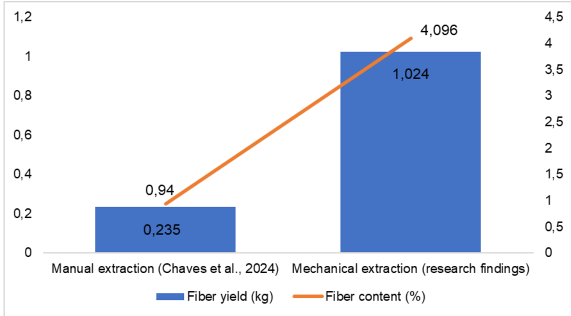
RESULTS AND DISCUSSION

Pineapple Leaf Fiber Results

The fibers produced using the mechanical extraction method are shown in Figure 3. Based on the data in Figure 3, the yield of pineapple leaf fiber obtained by mechanical extraction using a separator was 4.096%. These results indicate a significantly higher fiber productivity compared to manual extraction, as reported by Chaves *et al*. (2024), at 0.94%. The use of a separator in mechanical extraction was able to separate the fiber from the leaf pulp and unbroken fibers.

Fiber productivity is highly dependent on the growth phase of the plant. Leaves at optimal maturity, taken at harvest, had completely hardened fibers. Furthermore, the freshness of the leaves, which retained water, facilitated the mechanical separation process without damaging the fiber, thus maintaining the maximum yield (Singh *et al.,* 2020).

Pineapple fiber is a secondary lignocellulosic fiber obtained from pineapple leaf waste. Secondary lignocellulosic fibers contain 55–70% cellulose and non-cellulose components, namely hemicellulose (15–20%), lignin (8–12%), pectin (2–4%), and low proportions of extractable waxes and proteins (1–3%) (Pandit *et al.,* 2020).



Source: Processed primary data, 2026.

Figure 3. Results of pineapple leaf fiber using the mechanical extraction method

X-Ray Fluorescence (XRF) Analysis of Pineapple Leaf Fiber

The results of the X-ray Fluorescence (XRF) analysis in Figure 4 show the composition of inorganic elements contained in the leaf fibers of the Tamban variety of pineapple from Mekarsari District, Barito Kuala Regency.

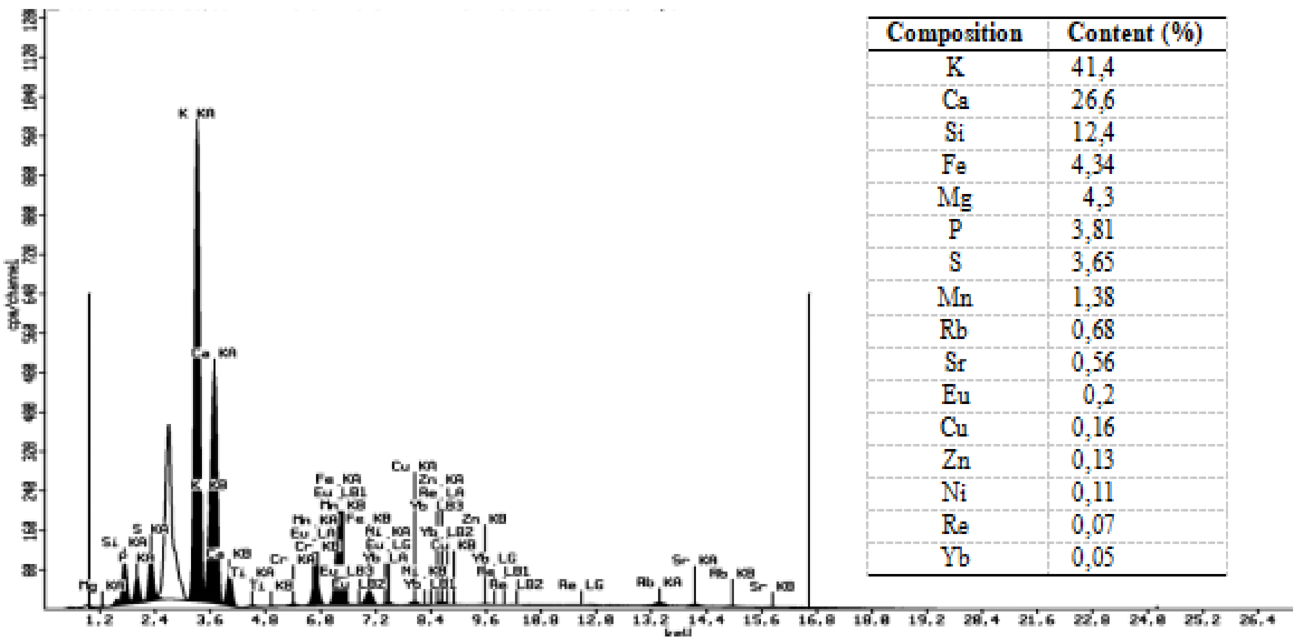
Based on the data in Figure 4, potassium (K) dominated the mineral composition at 41.4%, followed by calcium (Ca) at 26.6% and silicon (Si) at 12.4%. Calcination at 800°C caused the complete decomposition of the lignocellulosic components into ash. This compositional change was significant because it removed organic carbon, hydrogen, and oxygen from the material. However, the metal oxides detected by XRF reflected traces of native minerals bound within the cellular structure of the Tamban pineapple leaf fibers. This demonstrates the role of elements in forming bonds in natural fibers.

The presence of mineral elements such as K, Ca, and Si indicates that the fiber originates from mineral-rich wetland soil. Mineral retention in the fiber after mechanical extraction indicated that these basic cations were integrated into the cell wall structure during the growth phase and remained trapped within the fiber micropores. The presence of natural minerals such as calcium and silica on the fiber surface provided unique morphological characteristics, which strategically enhanced the potential for mechanical bonding with the composite matrix and could improve the material's thermal stability compared with fiber varieties from mineral-poor soils. The high K and Ca content contributed to the formation of fiber surface characteristics, which provided structural stability to the cellulose microfibrils. The presence of Si on the fiber surface mechanically increased the surface hardness and strong friction resistance when applied as a composite reinforcement. According to Johny *et al.* (2023), the presence of K plays a role in the formation of long, dense, and resistant fibers during the extraction process. Ca provides structural strength, and Si in natural fibers provides impact resistance and acts as an effective thermal protector.

The rich mineral content of wetland soil provides a natural advantage to its pineapple fiber. The magnesium (Mg) and sulfur (S) contents of the fiber were 4.3% and 3.65%, respectively, which acted as a natural reinforcing matrix, maintaining the structural integrity and flexibility of the Tamban pineapple fiber after mechanical extraction. The detection of europium (Eu), rhenium (Re), and ytterbium (Yb) specifically characterized the geochemical characteristics of the mineral-rich wetland soil. Their presence was a unique indicator that distinguished Tamban fiber from pineapple fiber from low-mineral soils. According to Gaba *et al.* (2021), the mineral content of pineapple fiber is highly dependent on soil nutrient composition. The specific mineral richness of wetlands provides functional added value to natural fibers as sustainable composite reinforcement materials.

X-Ray diffraction (XRD) Analysis of Pineapple Leaf Fiber

Based on the XRD analysis in Figure 5, the pineapple fiber of the Tamban variety showed a diffraction pattern that was in line with the JCPDS standard No. 03-0289. The main diffraction peak was detected at 2θ = 22.2675°, which correlated with the crystallographic plane (200) for Cellulose I-beta, showing a typical semi-crystalline profile of natural cellulose fiber of the Tamban variety. The secondary crystalline peak detected at 2θ = 34.4378°, which correlated with the crystal plane (004), indicated the regularity of the cellulose chain in the longitudinal direction of the fiber. Furthermore, the intensity on the main crystal plane and in the amorphous region was identified using the Segal method, as presented in Table 1. Table 1 shows a Crystallinity Index (CI) value of 23.68%, indicating that the Tamban variety of pineapple leaf fiber had a fairly dominant amorphous phase content (lignin and hemicellulose) when fresh and grown in mineral-rich wetlands. Compared to the CI value of 63.98% for the Smooth Cayenne variety reported (da Silva *et al.,* 2025) with a CI value of 63.98%, Gaba *et al.* (2021) reported an untreated PALF CI value of 62.2%, and Liao *et al*. (2025) reported that fresh PALF had an SSD-1 was 62.78%, an SSD-10 was 72.58%, and an SSD-11 was 83.1%.

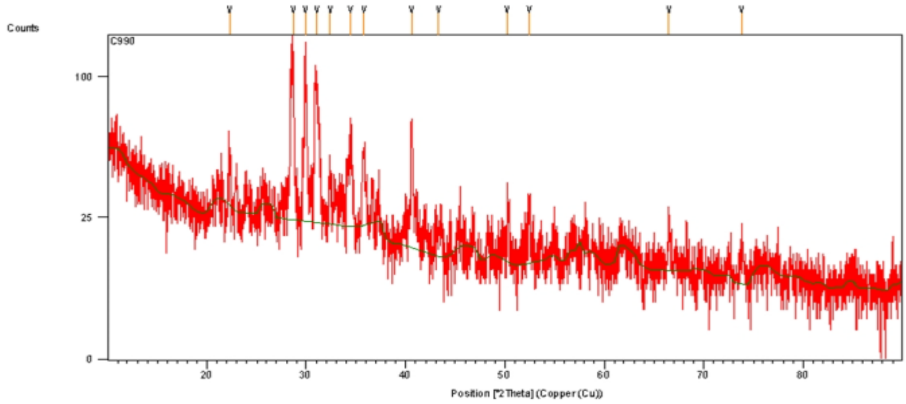


Composition	Content (%)
K	41,4
Ca	26,6
Si	12,4
Fe	4,34
Mg	4,3
P	3,81
S	3,65
Mn	1,38
Rb	0,68
Sr	0,56
Eu	0,2
Cu	0,16
Zn	0,13
Ni	0,11
Re	0,07
Yb	0,05

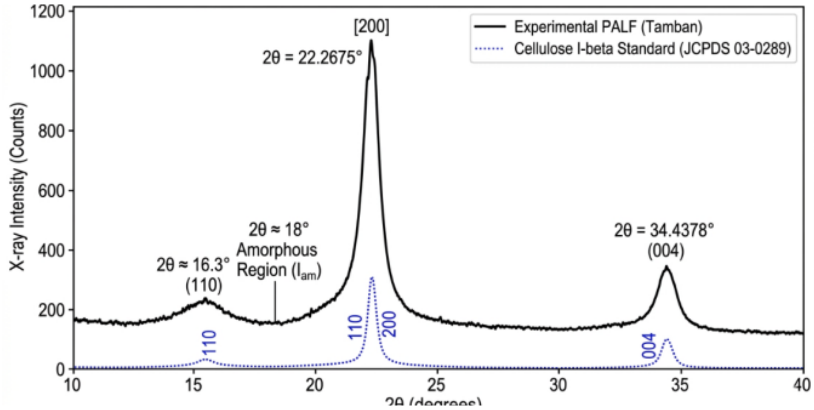
Source: Processed primary data, 2026

Figure 4. Elemental composition of pineapple leaf fiber

 DOI: https://doi.org/10.24961/j.tek.ind.pert.2026.36.2.206



(a)



(b)

Source: Processed primary data, 2026

Figure 5. X-ray diffraction pattern for Cellulose I-beta standard: (a) X-ray diffraction pattern of pineapple leaf fibers from the Tamban variety; (b) The primary and secondary peaks refer to the Cellulose I-beta standard (JCPDS No. 03-0289)

Table 1. Identification of X-ray diffraction peaks and crystallinity of pineapple fibers of the Tamban variety (Segal method)

Component	Position 2θ	Value	Descriptions
Main peak (I200)	22.2675°	38 counts	Crystalline cellulose peak
Amorphous point (IAM)	18.00°	29 counts	Amorphous area
Crystallinity index (CI)	-	23.68%	Crystallinity index of segal

Source: Processed primary data, 2026.

Although the high level of crystallinity in each fiber provided good stiffness, the literature showed that this condition was often accompanied by more brittle material properties, which correlated with a dominant cellulose content between 80% and 83%. In contrast, the Tamban pineapple leaf fiber exhibited a much lower CI value of 23.68%. Amorphous fractions such as lignin and hemicellulose still massively cover the cellulose microfibrils in their fresh state, providing flexibility and high energy adsorption capacity.

Furthermore, calculations using the Scherrer equation yielded a crystallite size of 17.15 nm, which is significantly larger than those reported by Liao *et al.* (2025), who reported fresh PALF SSD-1 (2.86 nm), SSD-10 (2.39 nm), and SSD-11 (2.72 nm). These results are also aligned with those of Gaba *et al.* (2021), who reported a crystallite size of 18.53 nm. The mechanical properties of natural fibers are determined by their cellulose content, which consists of a regular crystalline phase and an irregular amorphous phase. This nanoscale crystallite size indicates a fine distribution of crystalline domains within the cellulose fiber structure. The presence of an amorphous phase in the Tamban variety (76.32%) acted as an effective energy absorber, thus providing an optimal balance between stiffness and toughness for sustainable composite material application.

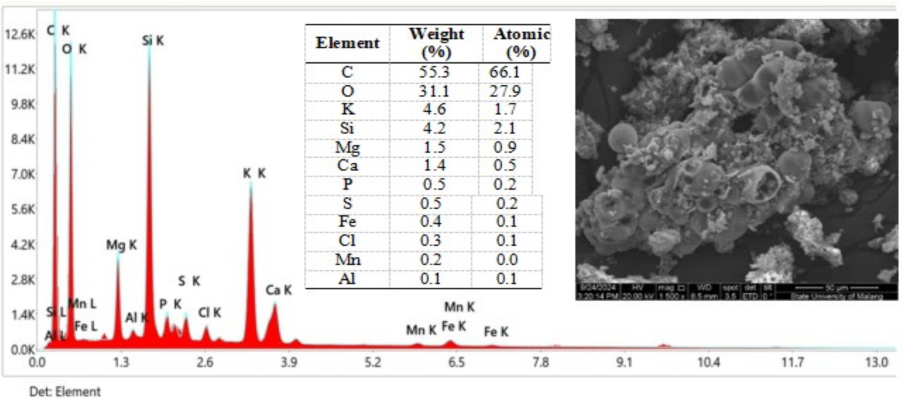
A comparison of the research data with CIF code 4114382 indicated that the primary constituent of pineapple leaf fiber from the Tamban variety was type I cellulose, a natural biopolymer with high structural regularity. The use of mechanical extraction methods is highly suitable because they do not damage the crystalline structure of the cellulose within the fiber. These results are in line with the research by French (2014), who stated that the standard for Cellulose Ib was most commonly found in natural fibers, referring to crystallographic data with CIF code 4114382. According to de Sá Barros *et al*. (2021), the crystal size of natural fiber cellulose is 11 nm.

Scanning Electron Microscopy-Energy Dispersive X-ray (SEM-EDX) Analysis of Pineapple Leaf Fibers

The characterization of the surface morphology of pineapple leaf fibers of the Tamban variety using Scanning Electron Microscopy (SEM) at 1500x magnification is shown in Figure 4. The results showed a distinctive cellulose structure resembling a honeycomb structure. The fiber surface exhibited pores and a rough, hollow texture with small, randomly distributed cavities. The rough and porous surface morphology can improve the interfacial adhesion between the fibers and the polymer matrix in composite materials. The rough, porous, and honeycomb-like surface of the fibers acted as a natural lock. In composite applications, when the resin liquid enters these pores and hardens, the fibers and matrix would bond very strongly. This ensured that the fibers would not easily come loose or shift when the material was loaded. This was supported by a crystallinity value of 23.68%, indicating that the fibers had a stable internal framework, making Tamban pineapple fiber a reinforcement that could blend perfectly with other materials and provide good structural strength. This characteristic bears a significant resemblance to the morphology of the aninga fibers reported by Lima Lopes Junior *et al.* (2024), who suggested that a honeycomb-like morphology could increase the overall bond strength.

The use of pineapple leaf fiber from the Tamban variety was an effective solution for increasing the added value of the agro-industry to reduce agricultural waste in pineapple-producing areas in Barito Kuala Regency. This potential was strongly supported by the XRD data, which showed a crystallinity index (CI) value of 23.68% with a stable Cellulose I-beta structure. This crystallinity data proved that pineapple leaf waste had a strong structural strength, making it suitable as the main reinforcing material in composites. This is in line with the principle of a circular economy, where biomass waste is no longer discarded or burned but returned to the industrial chain as a competitive functional product.

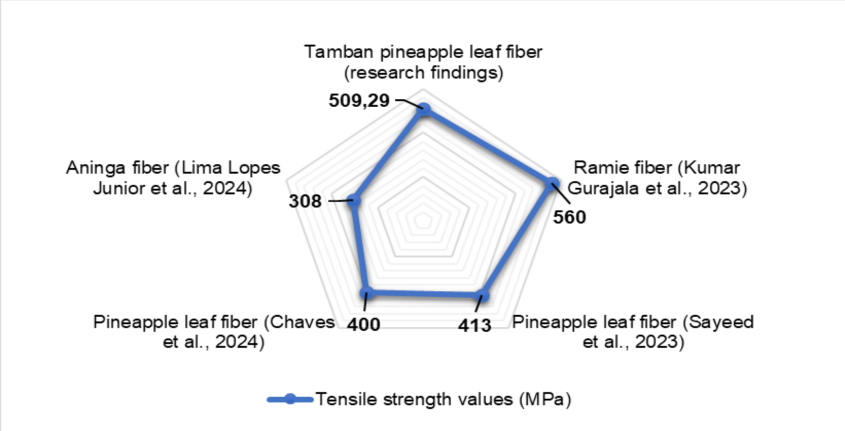
The EDX spectrum results in Figure 6 also show that the main components of the pineapple leaf fiber surface were dominated by carbon (C) at 55.3% and oxygen (O) at 31.1%. According to Kumar *et al.* (2022), the presence of C and O indicates that the natural fibers contain complex organic compounds such as cellulose, hemicellulose, and lignin, which are the main components of the cell walls and provide strength. In addition to organic elements (C and O), XRF analysis showed the presence of stable inorganic minerals, particularly silica. The presence of silica was crucial because it functioned as a natural protective layer that increased thermal resistance and created surface roughness at the microscale.



Element	Weight (%)	Atomic (%)
C	55.3	66.1
O	31.1	27.9
K	4.6	1.7
Si	4.2	2.1
Mg	1.5	0.9
Ca	1.4	0.5
P	0.5	0.2
S	0.5	0.2
Fe	0.4	0.1
Cl	0.3	0.1
Mn	0.2	0.0
Al	0.1	0.1

Source: Processed primary data, 2026.

Figure 6. Morphology and EDX spectrum of pineapple leaf fiber



Source: Primary data and secondary data processed, 2026.

Figure 7. Tensile strength values of pineapple leaf fiber, ramie fiber and aninga fiber

This supports the formation of stronger mechanical bonds when fibers are used as reinforcements in composite matrices. The XRD results proved that strong crystalline domains were finely distributed within the carbon-rich amorphous matrix (lignin). The combination of abundant organic elements and nanoscale crystal structure made pineapple leaf fiber from the Tamban variety a composite reinforcement material that was not only mechanically high quality but also environmentally sustainable.

Tensile Strength Value of Pineapple Leaf Fiber

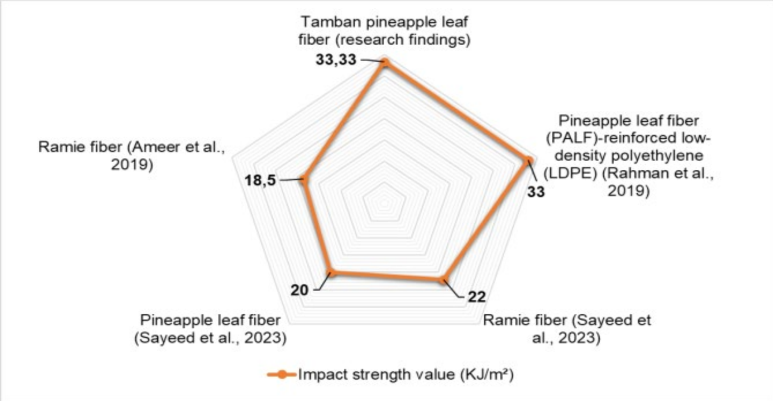
Fiber tensile strength testing using a Universal Testing Machine (UTM) instrument conformed to the ASTM D638 standard. Figure 7 presents a comprehensive comparison of the tensile strength of Tamban pineapple fiber with that of various other natural fibers from relevant studies. The test results indicated that the Tamban pineapple leaf fiber had a tensile strength of 509.29 MPa. This value indicates the maximum stress that the pineapple fiber cross-section can withstand before breaking, ranging from 400 MPa to 1600 Mpa.

The tensile strength of Tamban pineapple leaf fiber (509.29 MPa) significantly exceeded the strength of aninga fiber (308 MPa) reported by Lima Lopes Junior *et al*. (2024) and was above the strength limit of manually extracted pineapple fiber (400 MPa) (Chaves *et al*., 2024). Furthermore, the strength of Tamban pineapple fiber is comparable to that of ramie fiber, one of the strongest natural fibers, at 560 MPa (Kumar Gurajala *et al.,* 2023). Furthermore, a comparison of natural fibers with industry standards showed that Tamban pineapple leaf fiber met the tensile strength standards for natural fibers used in the global composite industry, including flax (345–1035 MPa) (Shadhin and Shuvo, 2019), hemp (310–750 MPa) (Prasad *et al*., 2022), and sisal (400–700 MPa) (Samouh *et al*., 2021). The use of mechanical extraction methods successfully maintained the natural lignin and hemicellulose layers in the fibers of the treated fibers. Although this resulted in a low crystallinity index (CI) (23.68%), the presence of hydrophobic and structural lignin helped distribute the tensile load evenly along the fiber bundle. This result was supported by the cellulose crystallite size of 17.15 nm detected through XRD analysis. This nanoscale crystallite size functioned as an effective internal reinforcement within the fiber. Furthermore, with an average cross-sectional area of 0.1237 mm², this fiber bundle was capable of withstanding a maximum force of 63.00 N before breaking. This capability proves that the Tamban variety has a competitive performance and is suitable for use as a composite reinforcement material to replace synthetic fibers.

Impact Strength Value of Pineapple Leaf Fiber

The impact strength of the material was tested using the Izod impact test method, which refers to the ASTM D256 standard test method. Figure 8 presents a comprehensive comparison of the impact strength of Tamban pineapple fiber with that of various natural fibers from relevant studies. The test results showed that the Tamban variety of pineapple leaf fiber had a significant shock resistance value of 33.33 kJ/m². This value indicates the material's ability to absorb shock loads of 2.75–4.00 J before experiencing structural failure. This proves that Tamban pineapple fiber has excellent flexibility. When subjected to shock loads, this fiber did not immediately break but was able to absorb and distribute the energy throughout the material structure.

 DOI: https://doi.org/10.24961/j.tek.ind.pert.2026.36.2.206



Source: Primary data and secondary data processed, 2026.

Figure 8. Impact strength value of pineapple leaf fiber and ramie fiber

In general, materials with high tensile strengths tend to be brittle. However, Tamban fiber was able to absorb a large impact energy (33.33 kJ/m²) owing to the support of its microstructure. The cellulose crystallite size of 17.15 nm detected through XRD provided a strong framework, while the amorphous phase (lignin) retained through mechanical extraction acted as an impact-energy absorber. The impact strength of pineapple leaf fiber from the Tamban variety was 33.33 kJ/m², which was equivalent to the results of Rahman *et al*. (2019), who reported an impact strength of 33 kJ/m ² for pineapple leaf fiber (PALF)-reinforced low-density polyethylene (LDPE). This value was higher than that reported by Sayeed *et al.* (2023), who reported an impact strength of only 20 kJ/m² for common pineapple leaf fiber. Tamban pineapple leaf fiber has even been shown to be stronger in terms of impact resistance than ramie fiber, which is known as a very strong natural fiber. In comparison, ramie had a resistance of 18.5 kJ/m² (Ameer *et al.,* 2019) to 22 kJ/m² (Sayeed *et al.,* 2023).

These results were supported by observations using Scanning Electron Microscopy (SEM), which showed that Tamban fiber had a rough and porous surface. This rough texture is highly advantageous because it creates strong mechanical locking when the fiber is used as a reinforcement in a composite matrix. The pores on the fiber surface allowed better matrix penetration, thereby increasing the contact area for the even distribution of impact energy. The ability of the fiber to withstand a tensile load of 509.29 MPa provided a solid structural foundation when subjected to shock loads. This high tensile strength ensured that the fiber bundle was less prone to premature failure or shattering when struck by an impact hammer with an absorbed energy of ≤ 4.00 J. This toughness was supported by the fine nanocrystallite size, combined with the rough outer surface (SEM observations), creating a dual defense system: the nanocrystallite inhibited crack propagation within the fiber, while the surface roughness absorbed impact energy, preventing it from easily breaking.

This synergy between strength and toughness demonstrates that the Tamban variety can overcome the common weakness of natural fibers, which are often brittle. Supported by SEM observations showing a rough and porous fiber surface, as well as a 17.15 nm crystallite nanostructure, this fiber offered strong mechanical bonds and the ability to absorb energy when exposed to impact; therefore, it was not easily broken. Thus, the use of pineapple leaf fiber of the Tamban variety through a mechanical extraction method was able to provide a high-performance material solution equivalent to synthetic fibers, but also supported the sustainability of an efficient green industry.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Mechanical extraction of pineapple leaf fiber from the Tamban variety produced a yield of 4.09% with highly competitive structural and mechanical characteristics. XRD analysis confirmed the formation of a Cellulose I-beta framework with a crystallinity index of 23.68%, which was validated by XRF and SEM-EDX data through the presence of organic elements (C and O) and minerals (K, Ca, Si) as stable cell wall constituents. The synergy between the regular crystalline structure and rough and porous surface morphology resulted in a robust mechanical performance, with a tensile strength value of 509.29 MPa and a shock resistance of 33.33 kJ/m². These results indicate that pineapple leaf fiber from the

Tamban variety has great potential as a sustainable reinforcing material for composite applications.

Recommendations

Based on the results of this research which had been conducted, suggestions for further development are as follows:

1. Further testing is needed on the performance of Tamban pineapple fiber when combined with various types of polymer matrices to determine the most appropriate industrial application.
2. Optimization studies are needed on mechanical extraction methods or a combination of mild chemical treatments (alkalization) to increase production efficiency without damaging the crystalline structure of the cellulose.
3. The integration of an inclusive agro-industrial model involves the active participation of farmer groups in the pineapple fiber supply chain through capacity building in efficient extraction technology.

ACKNOWLEDGMENTS

The Research Team would like to thank the Directorate of Research, Technology, and Community Service (DRTPM) for the funding provided for the Doctoral Dissertation Research (Number: 0667/E5/AL.04/2024).

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