

Mekanika: Majalah Ilmiah Mekanika

Integrating Agro-Waste Fiber into Sustainable Textile Innovation: Characterization of Mechanically Extracted Pineapple Leaf Fiber (PALF) for Circular Composite Applications

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Abstract

This study explores the potential of pineapple leaf fiber (PALF) from the Queen variety as a sustainable reinforcement material for green composites and textiles, focusing on the effects of mechanical retting. The research addresses critical barriers to industrial adoption, such as fiber-quality variability and hydrophilicity, while highlighting an innovative waterless extraction method that reduces environmental impact compared with conventional processes. A quantitative experimental approach was employed to comprehensively characterize PALF, incorporating standardized tensile testing to measure mechanical properties and microscopic analyses with a Scanning Electron Microscope (SEM) to observe fiber morphology. Findings demonstrate that mechanical retting significantly improves PALF's tensile strength (23.2 g/tex) and fineness (33.7 dtex). Microscopic analysis reveals a uniform, compact fiber structure that underpins the material's enhanced mechanical performance. PALF emerges as a viable, eco-friendly alternative to synthetic fibers. The waterless mechanical retting process is an effective method for producing high-quality reinforcement fibers, offering practical guidance for industries. This approach contributes significantly to agricultural waste reduction and advances circular economy principles in sustainable materials development.

1 Introduction

The growing demand for sustainable materials has intensified research into the use of natural fibers in composite applications, particularly in the textile industry. Among various natural fibers, pineapple leaf fiber (PALF) stands out for its excellent mechanical properties, including high tensile strength and low density, making it a promising candidate for reinforcing composite materials [1]. Moreover, utilizing agricultural waste fibers such as PALF contributes to solving waste management challenges while promoting the development of eco-friendly materials in line with circular economy principles [2].

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A primary concern in textile manufacturing is the reliance on synthetic fibers, which involve environmentally harmful production and disposal. The search for biodegradable alternatives has led to increased interest in mechanically extracted PALF, which has shown superior mechanical properties compared to conventional fibers like jute (tensile strength ~15–20 g/tex) [3].

Existing literature highlights both the mechanical advantages and environmental benefits of natural fibers. A substantial body of research has focused on enhancing the interfacial adhesion between natural fibers and polymer matrices, recognizing that fiber–matrix bonding is critical to the overall performance of fiber-reinforced composites. Among the various surface modification techniques, alkali treatment has been particularly effective, as it improves the tensile strength of natural fibers by altering their chemical structure. [4]. Comparative analyses indicate that although many natural fibers offer advantages in weight and sustainability, PALF stands out for its superior mechanical performance, attributed to its distinctive fiber morphology and extraction techniques. Notably, mechanical retting methods used in PALF processing have been shown to improve fiber quality and cellulose purity while reducing water consumption and minimizing the use of harmful chemicals, offering a more sustainable alternative to conventional extraction methods [1,5].

While previous studies have explored ways to enhance the properties of natural fibers, the specific effects of waterless mechanical extraction on PALF remain underexplored. This study uniquely investigates the properties of PALF derived through a purely mechanical extraction process, offering novel insights into optimized, low-impact processing techniques to enhance the performance of textile composites. This research aims to address two key questions: (1) How do mechanical extraction techniques influence the mechanical and morphological properties of PALF? and (2) What potential do these fibers possess for practical textile and composite applications? Theoretically, this research is underpinned by circular economy principles [2] and fiber-matrix interface theory, emphasizing closed-loop production cycles and enhanced composite performance. The primary objective is to comprehensively evaluate the mechanical properties and microstructure of mechanically processed PALF to establish a foundational understanding for its future development in sustainable textile manufacturing and advanced composite engineering [6,7].

2 Experimental Methods

This study adopted a quantitative experimental approach to evaluate the physical and mechanical characteristics of *Ananas comosus* (Queen variety) pineapple leaf fiber (PALF). This approach was selected for its precision in objectively quantifying properties critical to PALF's viability as a composite reinforcement material. The entire research workflow, from material preparation to data analysis, is illustrated in the flowchart in Figure 1.

The experimental process began with the preparation of raw materials. Pineapple leaves of the Queen variety were sourced from Kediri Regency, Indonesia, to ensure uniformity. The leaves were washed to remove surface impurities and then cut to a predetermined length for processing. Fiber extraction was conducted using a waterless mechanical retting process. This involved feeding the leaves into a specialized mechanical decorticator machine (Figure 3), which utilizes mechanical agitation and scraping to efficiently separate the fibrous tissues from the non-fibrous pulp, thereby eliminating the need for water or chemical soaking [8, 9]. The extracted raw fibers were then air-dried at room temperature after an initial 24-hour oven drying at 60°C to preserve their structural properties. Finally, the dried fibers were mechanically brushed and cleaned to remove any residual non-fibrous materials, resulting in clean PALF ready for characterization.

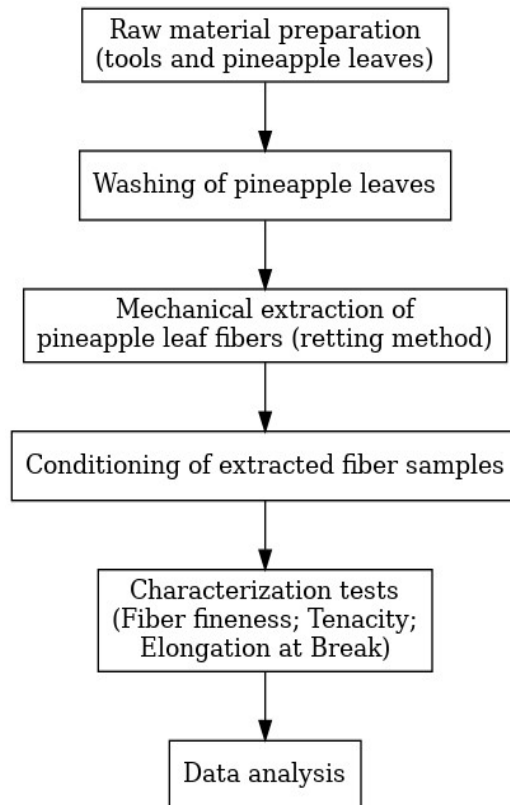


Figure 1. Flowchart of the research process, illustrating the sequential steps from raw material preparation, mechanical fiber extraction, characterization tests, to data analysis.

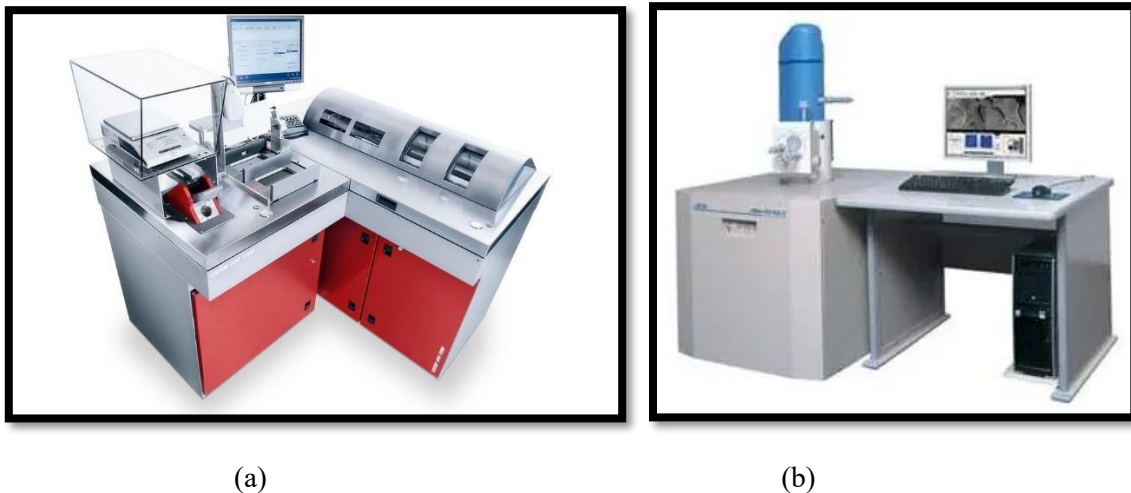


Figure 2. Testing fiber characteristics: (a) Uster HVI 1000, and (b) JSM-6510

Characterization of the fibers involved several standardized tests, with specimen configurations illustrated in Figure 2. Tensile properties, including tenacity (g/tex) and elongation at break (%), were measured using a tensile testing machine (Uster HVI 1000 M700, Switzerland) in accordance with SNI 08-1112-1989. Fiber fineness (dtex) was determined following the SNI 08-1111-1989 standard. For microstructural analysis, fiber samples were sputter-coated with a thin layer of gold and observed using a Scanning Electron Microscope (JEOL JSM-6510, Japan) to visualize the cross-sectional and longitudinal morphology. Quantitative data were statistically analyzed, while microscopic observations were qualitatively interpreted to correlate structural features with mechanical performance.

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Figure 3. The mechanical decorticator machine is used for fiber extraction

3 Results and Discussion

The mechanical retting process successfully extracted high-quality PALF from the pineapple leaf waste, as depicted in Figure 4. The resulting fibers (Figure 5) appeared clean and exhibited excellent continuity, indicating that the mechanical process preserved the fiber's structural integrity with minimal damage [10,11]. This is a significant advantage over conventional retting methods, which can lead to microbial degradation and reduced fiber quality [12-14].



Figure 4. Pineapple leaf waste (Queen variety) collected as raw material



Figure 5. Clean and continuous PALF extracted through the mechanical process

Microscopic examination using SEM provided deeper insight into the fiber's structure. The cross-sectional view (Figure 6) reveals a compact and dense structure with uniformly distributed fiber networks. This homogeneous morphology is crucial for effective stress transfer within a composite matrix, reinforcing PALF's potential as a reliable reinforcement material [15-18]. A detailed view of a single fiber bundle (Figure 7) further confirms this compact internal structure.

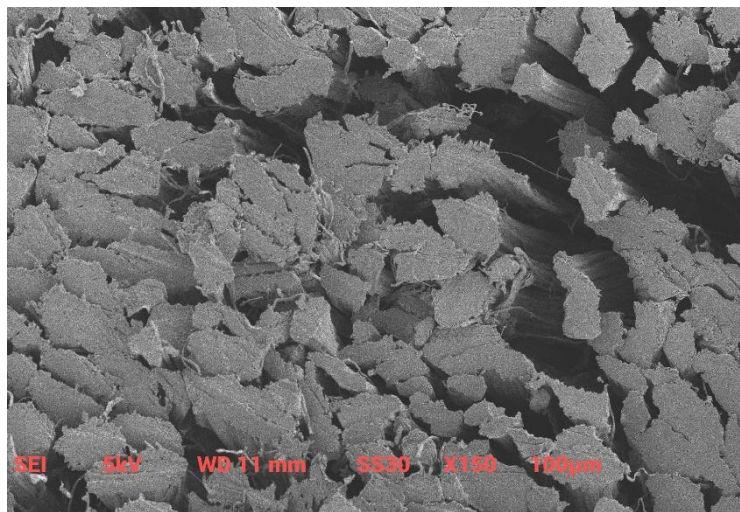


Figure 6. SEM image of the PALF cross-section (150x magnification)

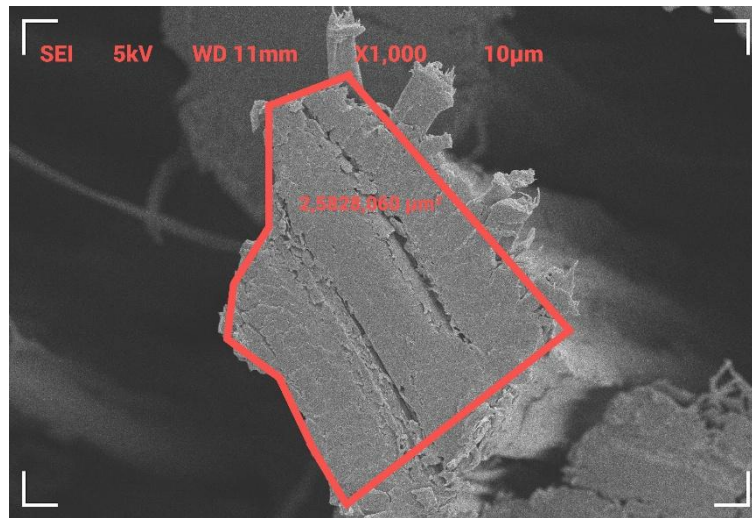


Figure 7. Detailed view of a single fiber bundle cross-section (1000x magnification)

The longitudinal analysis (Figure 8) revealed a highly aligned, untwisted fibrillar morphology. This natural orientation of cellulose microfibrils is essential for load-bearing capabilities in reinforcement applications [15]. The fiber surface appears relatively clean with consistent diameters, which is beneficial for achieving strong interfacial adhesion with a polymer matrix, thereby enhancing the overall mechanical performance of the composite [19]. The presence of thick cell walls along the fiber axis denotes a high level of mechanical robustness, reinforcing the suitability of PALF as a sustainable and high-performance reinforcement material [20, 21].

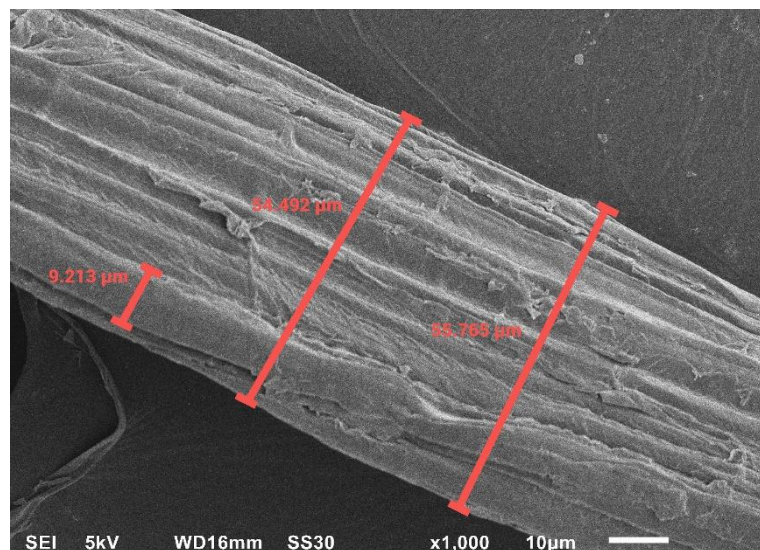


Figure 8. SEM image of the PALF longitudinal section (1000x magnification)

Mechanical testing of the extracted PALF yielded promising results, which are summarized in Table 1. The average fineness was 33.7 dtex, indicating a relatively fine fiber suitable for creating well-dispersed composites. This value is consistent with prior findings on PALF, validating its measurement reliability [22].

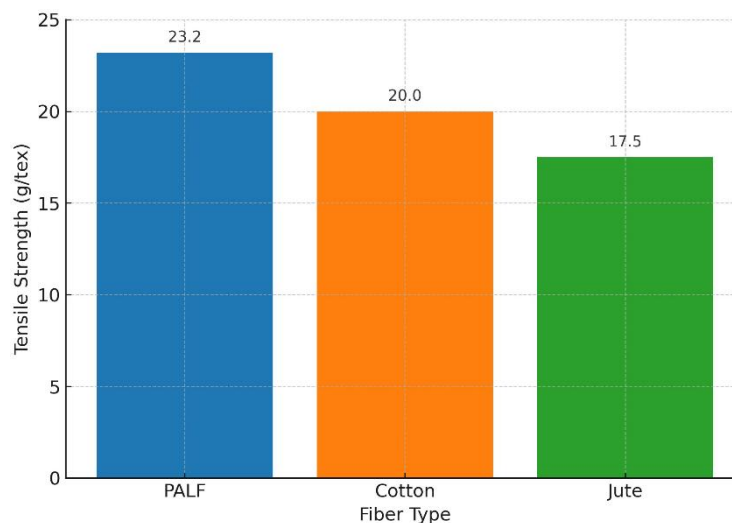
Table 1. Mechanical and Physical Properties of PALF

No.	Test Type	Test Result	Test Method
1	Fiber fineness (dtex)	33.7	SNI 08-1111-1989
2	Tensile strength per bundle - Tenacity (g/tex)	23.2	SNI 08-1112-1989
3	Elongation (%)	5.9	SNI 08-1112-1989
4	Cross-section photo	-	Scanning Electron Microscopy

Table 2. Fineness Test Results from Individual Fiber Samples

No	Fiber Weight (mg)	Number of Fibers (Strands)	Fiber Size (mm)	Desitex
1	13.35	126	30	35.3
2	10.59	85	30	41.5
3	15.27	143	30	35.6
4	19.13	237	30	26.9
5	15.41	176	30	29.2
Average				33.7
Standard Deviation				5.79

The most notable result is the fiber's high tensile strength (tenacity), which reached 23.2 g/tex. This value is superior to many conventional natural fibers, including cotton (~20 g/tex) and jute (~15–20 g/tex), underscoring its excellent potential as a reinforcement agent [3, 23, 24]. A visual comparison of these values is presented in Figure 9. Furthermore, the PALF exhibited an elongation at break of 5.9%, indicating a favorable balance between strength and ductility. This flexibility is advantageous for composites subjected to dynamic loads, as it allows for effective energy absorption and dissipation [24]. These mechanical characteristics confirm the role of PALF as a robust and sustainable reinforcement alternative, especially as industries increasingly shift toward environmentally friendly materials [25, 26].

**Figure 9.** Comparison of tensile strength (tenacity) between mechanically extracted PALF, cotton, and jute fibers

4. Conclusions

This research definitively demonstrates that pineapple leaf fiber (PALF), processed through waterless mechanical retting, is a highly promising sustainable reinforcement material for green construction and composite manufacturing. The extracted fibers exhibited superior mechanical properties, including an average fineness of 33.7 dtex and a high tensile strength of 23.2 g/tex. This strength is quantitatively significant, being approximately 16% higher than cotton and 38% higher than the average for jute, confirming its effectiveness as a reinforcement agent. Microscopic analyses corroborated these findings, revealing a homogeneous, well-distributed internal fiber structure conducive to high mechanical performance. The study highlights mechanical retting without water immersion as an efficient and environmentally superior alternative to traditional methods. While challenges such as raw fiber variability and hydrophilicity remain, the results provide actionable insights for industries seeking to adopt sustainable materials. PALF is a competitive, biodegradable, and eco-friendly alternative to conventional reinforcements, meaningfully contributing to agricultural waste reduction and advancing the principles of a circular economy.

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