

Research Article

# Evaluation of Tensile Strength of Sisal, Bamboo, and Pineapple Leaf Fiber Composite for Potential Use Infrastructure

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**Abstract:** The construction and infrastructure sectors are shifting toward lighter, low-emission, and sustainable materials in response to the high carbon footprint and excessive weight of common materials such as concrete and steel. One promising alternative widely developed is natural fiber-based composites. However, studies comparing mechanical properties of variations of natural fibers within a single framework remain limited. This study aims to evaluate and compare composite mechanical properties reinforced by sisal fiber, bamboo fiber, and pineapple leaf fiber to determine the optimal fiber type for sustainable infrastructure applications. The research methodology involved fabrication of composite specimens using a unidirectional fiber configuration with a resin matrix, molded following ASTM D638 Type I dimensional and geometrical requirements. Tensile testing was conducted to evaluate mechanical responses, including ultimate tensile behavior, deformation characteristics, and elastic properties, which were presented in tabular and graphical forms. The results show that incorporation of all natural fiber types significantly enhanced composite mechanical properties, exhibiting an average tensile strength of approximately 26 MPa. Pineapple leaf fiber demonstrated balanced mechanical behavior combining strength and ductility, while sisal fiber showed superior tensile resistance and rigidity. Bamboo fiber provided moderate mechanical improvement. Overall, natural fiber-reinforced composites demonstrate strong potential as environmentally friendly alternative materials for infrastructure applications, with mechanical characteristics adjustable based on reinforcing fiber type.

**Keywords:** Bamboo Fiber; Natural Fiber Composites; Pineapple Leaf Fiber; Sisal Fiber; Sustainable Infrastructure.

## 1. Introduction

The global construction and infrastructure sectors are currently undergoing a significant transition toward the use of lighter, energy-efficient, and environmentally friendly materials, driven by increasing concerns over climate change and sustainable development (Homod et al., 2025; Wang, 2025). Conventional materials such as concrete and steel continue to dominate infrastructure development based on their mechanical strength and durability; however, the production processes of these materials are known to contribute substantially to carbon emissions and energy consumption (Miller et al., 2018). The cement industry alone is reported to account for more than 7% of global CO<sub>2</sub> emissions, highlighting the urgent need for alternative materials that can reduce environmental impacts without compromising structural mechanical performance. In this context, natural fibers-reinforced composites have emerged as one of the most extensively studied material solutions over the past decades as substitutes for less sustainable conventional materials (Faruk et al., 2012).

Natural fibers offer several advantages, including low density, biodegradability, wide availability, and resulting in reduced carbon emissions relative to fossil-based synthetic fibers

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(Gauss et al., 2021). The use of natural fiber reinforcement in polymer matrices has been found to enhance tensile strength and stiffness while simultaneously reducing the environmental impact across the material life cycle. Sisal fiber, bamboo fiber, and pineapple leaf fiber are three types of natural fibers with distinct mechanical characteristics and strong potential as composite reinforcements for lightweight and sustainable infrastructure applications. Sisal fiber is known for its high stiffness and tensile strength, bamboo fiber exhibits a favorable strength-to-weight ratio, and pineapple leaf fiber provides a balanced combination of strength and ductility (Faruk et al., 2012). Although each of these fibers has been widely studied individually, comprehensive comparative investigations evaluating their mechanical performance within a single composite system under identical testing conditions remain limited. Therefore, a comparative study is necessary to determine the most optimal fiber type for sustainable infrastructure applications.

## 2. Literature Review

Natural Fiber Reinforced Polymer Composites (NFRPCs) have successfully developed rapidly as environmentally friendly alternatives to synthetic fiber-based composites for structural applications. This development is driven by the increasing demand for materials with lower carbon emissions, lightweight characteristics, and renewable resource availability (Joshi et al., 2004). Previous studies have reported that the properties of NFRPCs are strongly affected by several parameters, including volume of fiber or mass fraction, fiber orientation, and the matrix and interfacial bonding quality, all of which directly determine the efficiency of load transfer within the composite system (Jawaid & Abdul Khalil, 2011). A strong interfacial interaction of the fiber-matrix system is a key factor in enhancing the mechanical performance of natural fiber composites. Effective interfacial bonding allows the applied stress on the matrix to be efficiently transferred to the reinforcing fibers, thereby improving the overall tensile strength and stiffness of the material (Thakur et al., 2014). In addition, fiber orientation aligned with the loading direction has been observed to significantly improve the mechanical performance of composites compared to random fiber orientations, particularly for lightweight structural applications.

### 2.1. Sisal Fiber Composite

Sisal fiber is natural fibers that widely used as reinforcement substance in polymer composites. Its have high microfibril structure of cellulose structure, which is estimate to contribute on improvement of tensile strength and stiffness. According to literature, sisal fiber-reinforced composites significantly outperform neat polymer matrices in relation to tensile strength and elastic modulus (Andrade et al., 2008). This improvement is ascribed to sisal fibers' capacity to transfer applied loads efficiently because of their more uniform and persistent mechanical properties when compared with a few other natural fibers. In addition to its mechanical strength, sisal fiber also demonstrates good dimensional stability when used as reinforcement in lightweight structural composites. As a result, sisal fiber-reinforced composites have shown promising performance for engineering applications such as structural panels and semi-structural components (Ibrahim et al., 2016). However, hygroscopic nature of sisal fibers can influence the quality of the fiber-matrix interfacial bonding; therefore, proper control of fiber fraction and appropriate fiber treatments are required to maintain long-term mechanical performance.

### 2.2 Bamboo Fiber Composite

Bamboo fiber is recognized as promising natural fibers from a sustainability perspective due to its rapid growth rate, abundant availability, and ability to absorb carbon during its growth cycle. Bamboo fiber-reinforced composites exhibit a competitive strength-to-weight ratio, making them attractive for lightweight structural applications. These characteristics position bamboo as an economical and environmentally friendly alternative reinforcement material (Okubo et al., 2004). Despite its significant potential, the mechanical properties of bamboo fiber tend to vary due to differences in fiber age, growth location, and anatomical structure. Such variability affects the tensile strength and elastic modulus exhibited by bamboo fiber-reinforced composites, which generally fall within a moderate range compared to other natural fibers (Yu et al., 2011). Therefore, fiber quality control and optimization of fiber

orientation are critical factors in improving the consistency and reliability of the mechanical properties of composite that reinforcement by bamboo fiber.

### 2.3 Pineapple Leaf Fiber Composite

Pineapple Leaf Fiber (PALF) possesses a high cellulose content, which contributes to good tensile strength as well as a relatively high deformation capability before failure. PALF-reinforced composites are capable of providing a balanced combination of tensile strength and strain relative to other natural fiber-based composites (Asim et al., 2015). These characteristics make PALF particularly suitable for applications requiring semi-flexible behavior without compromising structural strength. In addition to its mechanical performance, the utilization of PALF offers significant environmental benefits by valorizing agricultural waste from pineapple leaves that previously had little or no economic value. The use of PALF as composite reinforcement supports the principles of the circular economy by reducing biomass waste while simultaneously producing value-added materials (Ramesh et al., 2013). Consequently, PALF-reinforced composites not only improve material mechanical performance while also contributing to sustainable resource management.

## 3. Proposed Method

This study employed an experimental method to assess the mechanical behavior of composite materials. Sisal fiber, bamboo fiber, and pineapple leaf fiber were used as reinforcement materials and integrated with a polymer resin matrix. To ensure uniform load distribution, the fibers were arranged in a unidirectional alignment within the mold. Composite specimens were fabricated with fiber mass variations from 0.10 g, 0.3 g, 0.50 g. All specimens were molded in accordance with the ASTM D638 type I tensile testing standard at Universitas Negeri Malang to ensure the validity and comparability of the test results (Maulana et al., 2025). In addition, control specimens without fiber reinforcement were prepared for comparison to evaluate the effect of fiber incorporation on the mechanical behavior of the composites.

### 3.1. Algorithm

The research procedure was conducted systematically to ensure the consistency and reliability of the results. The experimental stages began with material preparation and continued through specimen fabrication, tensile testing, and analysis of the obtained data.

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#### **Algorithm 1.** Research Procedure for Natural Fiber Reinforced Composite.

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INPUT: Type of natural fiber (sisal, bamboo, pineapple leaf), fiber mass (0.10–0.50 g), polymer resin matrix, specimen mold, ASTM D638 type I tensile testing standard

OUTPUT: Tensile strength (MPa), strain (%), and Young's modulus (MPa) of natural fiber-reinforced composites

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- 1: Prepare the natural fibers by cleaning them to remove impurities and drying them until a minimum moisture content is achieved.
  - 2: Weigh the fibers according to the specified mass variations (0.10 g to 0.50 g).
  - 3: Arrange the fibers in a unidirectional alignment inside the specimen mold.
  - 4: Pour the resin matrix into the mold until the fibers are uniformly impregnated
  - 5: Perform the curing process under predetermined conditions until the composite is fully hardened.
  - 6: Shape and finish the specimens according to the standard dimensions specified in ASTM D638 type I for tensile testing.
  - 7: Conduct tensile testing employing a universal testing machine and record the maximum load and elongation of the specimens
  - 8: Calculate the tensile strength, strain, and Young's modulus based on the experimental data obtained
  - 9: Analyze and compare the mechanical performance among different fiber types and fiber mass variations
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#### 3.1.1. Fiber Mass Variation

To achieve for examine the effects of fiber content on improving composite mechanical properties specifically, variations in tensile strength, strain, and Young's modulus in fiber mass were carried out. Theoretically, increasing the fiber fraction improves the ability to withstand tensile loading of the composite due to the contribution of the fibers as the primary reinforcing elements. However, excessive fiber content must be carefully controlled, as it may deteriorate the quality of the interfacial bonding between the fiber and matrix. The selection of fiber mass variations in this study was based on the following considerations:

- a. Increasing the contribution of fibers to the composite's tensile strength;
- b. Maintaining the interfacial bonding condition of the fibers within the resin matrix;
- c. Preventing fiber agglomeration that could reduce mechanical performance;
- d. Achieving a balance between strength, ductility, and stiffness of the composite

The fiber mass variations were systematically determined to identify the optimum composite configuration. The stages of fiber mass variation were designed as follows:

- 1) Low fiber mass (0.10 g) to assess the initial influence of fiber incorporation on the polymer matrix;
- 2) Medium fiber mass (0.30 g) to identify significant improvements in mechanical properties;
- 3) High fiber mass (0.50 g) to observe the maximum performance enhancement limit before degradation of interfacial bonding occurs.

This approach enables a systematic analysis of the relationship between fiber content and changes in composite mechanical properties, allowing the determination of the most optimal fiber mass configuration for sustainable infrastructure applications

### 3.2. Formatting of Mathematical Components

The fundamental calculation describing material mechanical properties was used to determine the composite's tensile strength. Equation (1), which represents the ratio between the highest tensile load and the test specimen's cross-sectional area, was employed to determine the tensile strength ( $\sigma$ ) in this investigation.

$$\sigma = F / A \quad (1)$$

The maximum load-bearing capacity of the material under tensile loading is determined using equation (1), where F is the highest tensile force observed during the experimental test (N) and A is the specimen's cross-sectional area (mm<sup>2</sup>). The primary parameter used to assess what happens when fiber mass and type affect the composites' mechanical performance is tensile strength. Young's modulus (E), which indicates the material's stiffness, is a crucial mechanical analysis metric in addition to tensile strength. The linear relationship between stress and strain within the elastic area of the stress–strain curve, as stated in Eq. (2), served as the basis for calculating Young's modulus.

$$E = \sigma / \epsilon \quad (2)$$

Equation (2) is used to determine the stiffness of the composite material, where  $\sigma$  denotes stress and  $\epsilon$  represents strain. A higher Young's modulus indicates a stiffer and more structurally stable material; therefore, this parameter provides a basis for assessing the suitability of the composite for structural or semi-structural applications.

## 4. Results and Discussion

The incorporation of natural fibers resulted in a significant improvement in the mechanical properties of the composites compared to the control specimens without fiber reinforcement, which exhibited an average tensile strength of 26.27 MPa. Among the investigated fibers, pineapple leaf fiber demonstrated the most balanced performance between strength and ductility (Kumar et al., 2021). At a fiber mass of 0.30 g, composites reinforced with pineapple leaf fibers exhibited a tensile strength of approximately 40.91 MPa with the highest strain value reaching up to 11%, indicating the ability of this fiber to sustain tensile loads while maintaining elastic deformation prior to failure. Sisal fiber provided the highest tensile strength and stiffness among all fiber types. At a fiber mass of 0.30 g, sisal fiber–reinforced composites reached a tensile strength of 52.96 MPa and exhibited the highest Young's modulus of approximately 7.38 MPa, confirming the effectiveness of sisal as a rigid and structurally stable reinforcement material. Bamboo fiber also showed a noticeable enhancement in

mechanical performance, although its properties remained below those of sisal and pineapple leaf fiber in terms of stiffness and ductility. At a fiber mass of 0.50 g, bamboo fiber–reinforced composites reached a tensile strength of up to 57.55 MPa; however, the corresponding strain and Young’s modulus values were relatively moderate.

**4.1. Figures and Tables**

Natural fiber reinforced composite specimens after the fabrication and curing process. The specimens are in the form of composite plates with unidirectional fiber orientation, which were subsequently cut according to ASTM D638 Type I standard for tensile testing(Venkatesh et al., 2023).



**Figure 1.** ASTM D638 Type I tensile test specimen.

**Table 1.** Tensile Strength of Natural Fiber Reinforced Composites.

Types of Fiber	Fiber Mass (g)	Average Tensile Strength (Mpa)
Bamboo	0,1	32.324
Bamboo	0,3	39.921
Bamboo	0,5	57.515
Pinepple	0,1	39.642
Pinepple	0,3	40.912
Pinepple	0,5	60.194
Sisal	0,1	38.908
Sisal	0,3	52.965
Sisal	0,5	54.454



**Figure 2.** average fiber ratio.

Tensile strength, strain, and Young's modulus comparisons of natural fiber-reinforced composites with varying fiber mass changes are shown in Figure 3. A clear comparison of the impact of fiber type and fiber mass on composite performance is made possible by the table,

which summarizes the mechanical characteristics of the control specimens and composites reinforced with sisal, bamboo, and pineapple leaf fibers.

ANOVA					
Sum of Squares	df	Mean Square	F	Sig.	
Between Groups	2917.356	3	972.452	12.717	.000
Within Groups	2446.990	32	76.469		
Total	5364.346	35			

  

i) jennasari	ii) jennasari	Mean Difference (I - J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
control	bambu	-14.98227 <sup>a</sup>	4.12226	.002	-28.5554	-5.3890
	nanas	-28.57318 <sup>a</sup>	4.12226	.000	-32.1684	-8.9800
	sisal	-23.01979 <sup>a</sup>	4.12226	.000	-34.8130	-11.4266
bambu	control	14.98227 <sup>a</sup>	4.12226	.002	5.3890	28.5554
	nanas	-3.61095	4.12226	1.000	-15.2041	7.9822
	sisal	-8.05795	4.12226	.809	-17.6588	5.5368
nanas	control	28.57318 <sup>a</sup>	4.12226	.000	8.9800	32.1684
	bambu	3.61095	4.12226	1.000	-7.9822	15.2041
	sisal	-2.44661	4.12226	1.000	-14.0398	9.1466
sisal	control	23.01979 <sup>a</sup>	4.12226	.000	11.4266	34.8130
	bambu	8.05795	4.12226	.809	-5.5368	17.6588
	nanas	2.44661	4.12226	1.000	-8.1466	14.0398

<sup>a</sup>. The mean difference is significant at the 0.05 level.

Figure 3. Diagram Anova.

Figure 4 presents the findings from the one-way ANOVA analysis conducted to evaluate the statistical significance of the differences in tensile strength among the tested composites. This analysis was performed to determine whether the variations in fiber type and fiber mass produced a statistically significant effect on mechanical features of the composites.

### 5. Comparison

A comparative analysis of the mechanical properties of composites shows that sisal fibers provide the most significant improvement regarding the tensile strength and Young’s modulus of the composites. This indicates the ability of sisal fibers to effectively transfer loads from the matrix to the fibers, resulting in composites with high stiffness and dimensional stability. Therefore, sisal fiber-reinforced composites are better suited for lightweight structural applications that require resistance to tensile loads and minimal deformation (Gebremichael et al., 2025; Sathishkumar et al., 2025).

In contrast, pineapple leaf fiber-reinforced composites exhibit a better balance between strength and flexibility, characterized by higher strain values before material failure. This characteristic makes them suitable for semi-flexible applications that require deformation capabilities without significant loss of strength. Meanwhile, bamboo fibers produce medium-level mechanical performance and offer advantages based on availability and sustainability, making them a viable economical reinforcement alternative for infrastructure applications with medium performance requirements.

### 6. Conclusions

This study confirms that the addition of natural fibers significantly enhances the mechanical properties of composites compared to materials without fiber reinforcement. Increasing the fiber mass from 0.10 g to 0.50 g consistently enhances the tensile strength, strain, and Young’s modulus, indicating that fiber content is essential for strengthening the composite structure. Composite without fiber exhibits a tensile strength of only about 26 MPa, while fiber-reinforced composites reach values of over 50 MPa, demonstrating the effectiveness of natural fibers as reinforcement materials. Among all tested fibers, pineapple fiber provides the most balanced performance between strength and flexibility. At a fiber mass of 0.30 g, the pineapple fiber composite achieves a tensile strength of approximately 40.91 MPa with

the highest strain (about 11%), indicating excellent load-bearing capacity while maintaining elasticity before failure.

In contrast, sisal fiber delivers the highest strength and stiffness, reaching a tensile strength of up to 52.96 MPa and a Young's modulus of around 7.38 MPa, making it highly suitable for structural applications requiring rigid and stable materials. From an application perspective, the results demonstrate that fiber selection can be tailored to specific functional requirements. Pineapple fiber is ideal for semi-flexible uses including protective panels and automotive parts, while sisal fiber is more appropriate for load-bearing structures that require high stiffness. Bamboo fiber also shows notable performance improvements, although lower than sisal and pineapple, making it a viable reinforcement alternative for general applications that demand a balance between strength and elasticity. Overall, natural fiber composites present a strong, flexible, and sustainable material solution..

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## References

- Andrade, F. de, Chawla, N., Dias, R., & Filho, D. T. (2008). Tensile behavior of high-performance natural (sisal) fibers. *Composites Science and Technology*, 68(15–16), 3438–3443. <https://doi.org/10.1016/j.compscitech.2008.10.001>
- Asim, M., Abdan, K., Jawaid, M., Nasir, M., Dashtizadeh, Z., Ishak, M. R., & Hoque, M. E. (2015). A review on pineapple leaves fibre and its composites. *Journal of Nanomaterials*, 2015, Article 950567. <https://doi.org/10.1155/2015/950567>
- Faruk, O., Bledzki, A. K., Fink, H., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11), 1552–1596. <https://doi.org/10.1016/j.progpolymsci.2012.04.003>
- Gauss, C., Pickering, K. L., & Muthe, L. P. (2021). The use of cellulose in bio-derived formulations for 3D/4D printing: A review. *Composites Part C: Open Access*, 4, Article 100113. <https://doi.org/10.1016/j.jcomc.2021.100113>
- Gebremichael, G., Mekonone, S. T., Baye, T. M., & Ejigu, A. A. (2025). Mechanical and microstructural characterization of sisal fiber-reinforced polyester laminate composites for improved durability in automotive applications. *Journal of Materials Science: Composites*, 6. <https://doi.org/10.1186/s42252-024-00064-4>
- Homod, R., Mohammed, H., Albadr, M. A. A., Albahri, A., Al-Fatlawi, A. W., Alhasnawi, B., Ismael, M., Hussein, A., Mahdi, J., Hamida, M. B., & Ali, H. M. (2025). Green building evolution: Enhancing energy efficiency and structural performance through innovative rice water and grey clay composite material. *Journal of Thermal Analysis and Calorimetry*, 150, 1669–1689. <https://doi.org/10.1007/s10973-024-13937-4>
- Ibrahim, I. D., Jamiru, T., Sadiku, E. R., Kehinde, W., Agwuncha, S. C., Ekundayo, G., Kupolati, K., & David, I. (2016). Mechanical properties of sisal fibre-reinforced polymer composites: A review. *Journal of Adhesion Science and Technology*, 30(6), 644–660. <https://doi.org/10.1080/09276440.2016.1087247>
- Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, 86(1), 1–18. <https://doi.org/10.1016/j.carbpol.2011.04.043>
- Joshi, S. V., Drzal, L. T., Mohanty, A. K., & Arora, S. (2004). Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A: Applied Science and Manufacturing*, 35(3), 371–376. <https://doi.org/10.1016/j.compositesa.2003.09.016>
- Kumar, S., Prasad, L., Patel, V., Kumar, V., Kumar, A., Yadav, A., & Winczek, J. (2021). Physical and mechanical properties of natural leaf fiber-reinforced epoxy polyester composites. *Polymers*, 13(9), Article 1369. <https://doi.org/10.3390/polym13091369>
- Maulana, J., Ilman, M., Sasongko, N., & Tsamroh, D. I. (2025). Surface modification of local natural fibers via alkali treatment for improved mechanical and molecular properties of bamboo fiber, pineapple leaf fiber, and sisal fiber. *Jurnal Teknik Mesin dan Industri*, 9(2), 524–538. <https://doi.org/10.17977/um016v9i22025p524>

- Miller, S. A., Horvath, A., & Monteiro, P. J. M. (2018). Impacts of booming concrete production on water resources worldwide. *Nature Sustainability*, 1(1), 69–76. <https://doi.org/10.1038/s41893-017-0009-5>
- Okubo, K., Fujii, T., & Yamamoto, Y. (2004). Development of bamboo-based polymer composites and their mechanical properties. *Composites Part A: Applied Science and Manufacturing*, 35(3), 377–383. <https://doi.org/10.1016/j.compositesa.2003.09.017>
- Ramesh, M., Palanikumar, K., & Reddy, K. H. (2013). Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites. *Composites Part B: Engineering*, 48, 1–9. <https://doi.org/10.1016/j.compositesb.2012.12.004>
- Sathishkumar, G., Devi, A., Prem, M., Reddy, K., Kanthe, V., Palaniswamy, D., Chakravarthy, P., Dubey, M., Majumder, H., & Srivastava, A. K. (2025). Experimental study on mechanical performance and microstructural characterization of optimized sisal fiber reinforced polyester composites. *Scientific Reports*, 15, Article 20177. <https://doi.org/10.1038/s41598-025-20177-5>
- Thakur, V. K., Thakur, M. K., & Gupta, R. K. (2014). Raw natural fiber-based polymer composites: A review. *International Journal of Polymer Analysis and Characterization*, 19(3), 256–271. <https://doi.org/10.1080/1023666X.2014.880016>
- Venkatesh, R., Ballal, S., Krishnan, A., Prabakaran, S., Mohankumar, S., & Ramaraj, E. (2023). Effect of fiber layer formation on mechanical and wear properties of natural fiber filled epoxy hybrid composites. *Heliyon*, 9, Article e15934. <https://doi.org/10.1016/j.heliyon.2023.e15934>
- Wang, X. (2025). Application of environmentally friendly building materials in urban construction. *Applied and Computational Engineering*. <https://doi.org/10.54254/2755-2721/2025.20030>
- Yu, Y., Tian, G., Wang, H., Fei, B., & Wang, G. (2011). Mechanical characterization of single bamboo fibers with nanoindentation and microtensile technique. *Holzforschung*, 65(1), 113–119. <https://doi.org/10.1515/hf.2011.009>