

TENSILE STRENGTH AND STRAIN OF VACUUM INFUSION BANANA FIBER REINFORCED COMPOSITE USING EPOXY RESIN

HASABO ABDELBAGI MOHAMED AHMED¹, RAMADAN MOHMMED¹, NEVIN GURSOY², PELIN ALTAY², YOUSIF, A.A³

¹Textile Department, College of Engineering and Technology of Industries, Sudan University of Science and Technology, Khartoum, Sudan.

²Faculty of Textile Technology and Design, Istanbul Technical University.

³Polymer Department, College of Engineering and Technology of Industries, Sudan University of Science and Technology, Khartoum, Sudan.

Hasabo Abdelbagi Mohamed Ahmed: profhasabo@gmail.com

Corresponding Author: HASABO ABDELBAGI MOHAMED AHMED, Tel +905013541382

ABSTRACT

Banana fiber is regarded as one of the natural fibers suitable for spinning and weaving, owing to its adequate length, durability, environmental impact, abundance and fine texture. Its significance has been increasing, especially in line with the global environmental issues, where green composites are capturing the attention of researchers worldwide. Banana fibers are applicable in various areas of life, including clothing, home decor, and paneling. The use of panels is particularly favored in sectors like automotive, aerospace, construction, and other industrial applications. Additionally, banana fiber composites have drawn interest for their thermal and acoustic insulation properties, attributed to their unique hollow fiber structure containing cavities and a high porosity ratio. In this study production of panels using banana fiber as a reinforcement employing epoxy resin as a matrix is performed using vacuum infusion process (VIP). The produced panels have been tested for tensile strength and strain according to ISO 527-4. The study showed a promising result compared to similar natural fibers. The results fall within a common range observed for natural fiber composites, but it's generally on the lower to mid-range compared to some of the higher-performing banana fiber epoxy composites reported. By addressing these factors, the mechanical performance of banana fiber epoxy composites can be significantly enhanced, making them more competitive for various applications.

1. INTRODUCTION

The banana plant features a stem that typically measures between 3 and 9 meters in height, with a diameter ranging from 200 to 370 millimeters. This stem is composed of multiple concentric layers containing longitudinal fibers, which make up roughly 24% of the pseudo-stem. After harvesting, the pseudo-stem is usually discarded or repurposed as mulch. Banana fibers can be extracted manually from the pseudo-stems using simple, low-cost techniques, though the yield is relatively low—about 1% to 2% of the dry weight. To improve efficiency, a mechanical decorticator has been developed, capable of producing approximately 1.75 kilograms of dry fiber per man-hour [1-5]. It is widely recognized that the banana is among the earliest plants cultivated by humans. The term “banana” is derived from the Arabic word meaning “finger.” Belonging to the *Musaceae* family, there are around 300 known species of banana, though only about 20 varieties are commonly grown for food. Tropical and subtropical regions produce approximately 70 million metric tons of bananas each year [6-8].

1.1 BANANA ELEMENTS

In recent years, there has been growing interest in research and development focused on natural fiber composites, primarily because of their excellent formability, wide availability, renewability, cost-effectiveness, and low carbon footprint. [9-11].

In recent years, natural fiber composites have gained significant use in diverse engineering applications to enhance strength while reducing both the weight and cost of products. Fibers such as coir, sisal, jute, and banana are commonly utilized as reinforcing materials in these composites. [12, 13].

Raj N, S. *et al* stressed the use of natural fibers for composites due to their renewability and abundance [14]. Banana fibers hold an advantage over many other natural fibers because they are derived from agricultural waste, specifically, the leftover material that farmers typically discard or even pay to remove after harvesting banana fruits. Utilizing these fibers not only provides a valuable resource but also supports the concept of maintaining a cleaner and more sustainable environment [15,16]. However, several studies have investigated the characteristics of banana fibers and their potential use as reinforcement materials in composite panels for diverse applications. [17-20]. There have been comparative studies on blend of banana with other natural and synthetic fibers [21-26]. Natural fibers offer clear benefits compared to synthetic reinforcement materials, including lower cost and density, non-toxicity, comparable strength, and reduced waste disposal issues. [27]. Motaleb, K.Z.M., and colleagues conducted studies on non-woven banana fibers obtained from different sections of the banana stem, demonstrating variations in their physical properties and chemical composition [28].

1.2 CHEMICAL STRUCTURE

In general, the chemical composition of natural or plant fibers includes cellulose, hemicellulose, lignin, pectin, and other minor components. The characterization of plant fibers is typically carried out by analyzing their cellular structure. [29]. Each fiber cell contains crystalline cellulose areas, known as microfibrils, which are linked together by hemicellulose and lignin components. In this structure, lignin functions as the matrix that binds and supports the fibrils. A natural fiber cell consists of a single thin primary wall and three thicker secondary walls. [30]. The primary wall is the first layer formed during cell growth, surrounding the secondary wall. I. Elfaleh *et al. and others* described the secondary wall as consisting of three layers, with the thick middle layer enhancing the mechanical properties of the fiber [31-34]. Guruji Ramakrishna and Dr. G. R. Selokar stated that cellulose, the crystalline region, is the major component that provides strength, stiffness, and structural stability to the fiber's thick middle layer, thereby enhancing the fiber's mechanical properties [35]. However, various scholars reported that lignin consists of nine-carbon units originating from substituted cinnamyl alcohols, specifically coumaroyl, coniferyl, and syringyl alcohols. Lignin interacts with hemicelluloses and contributes significantly to the natural resistance of lignocellulosic materials against decay. [30, 36].

Table 1 Banana fiber content [30, 37, 38]

S. No	Constituents	Percentage
1.	Cellulose	31.27 ± 3.61
2.	Hemicellulose	14.98 ± 2.03
3.	Lignin	15.07 ± 0.66
4.	Extractives	4.46 ± 0.11
5.	Moisture	9.74 ± 1.42
6.	Ashes	8.65 ± 0.10

M. E. Alves Fidelis *et al* [39] mentioned that the mechanical properties of natural fibers are closely correlated with their morphology. While natural fibers are lightweight, renewable, biodegradable, and mechanically robust, they can show weaknesses in strength. The tensile characteristics of these fibers have been the focus of several studies [39-43]

1.3 ACOUSTICS AND THERMAL PROPERTIES OF BANANA FIBERS

Effective acoustic insulation is essential in architectural design to minimize damage and protect occupants from the sound produced by explosive events [44]. The widespread environmental impact of conventional non-biodegradable thermal insulation in buildings has catalyzed research efforts worldwide to investigate natural fibers as sustainable and eco-friendly alternatives.

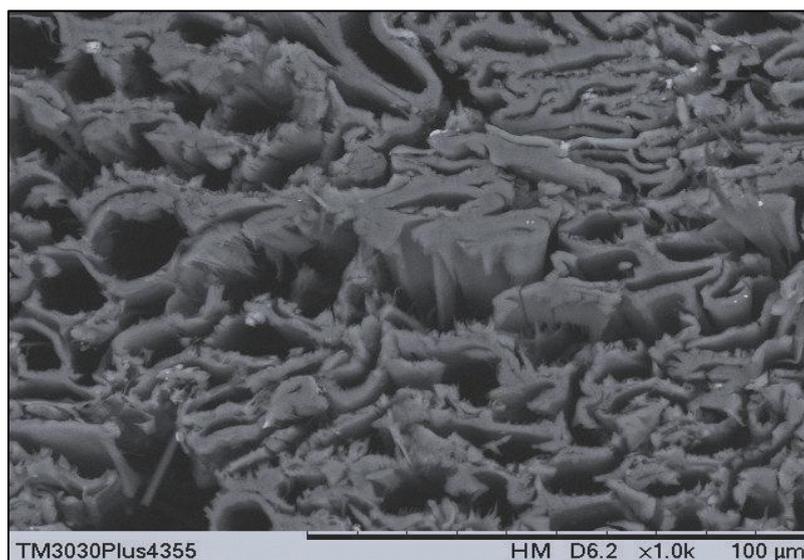


Fig. 1 SEM image of banana Fiber cross-section

K. Manohar and A. A. Adeyanju examined the thermal insulation characteristics of banana fibers, evaluating their performance relative to traditional insulation materials to determine their suitability for use in building applications.[45]. Thermal insulation depends on a material’s thermal conductivity (λ , W/m·K). Common insulators like glass wool and rock wool have λ around 0.040 W/m·K, which means they require relatively thick layers to provide effective insulation. In contrast, advanced materials such as silica aerogels have a much lower λ of about 0.015 W/m·K, offering superior insulating performance. However, their high production cost limits their widespread use in construction. Overall, the choice of insulating material involves a trade-off between thermal efficiency and cost. [46-50]. Considering the SEM image of the banana fiber cross-section, as in Fig. 1, it is characterized by cavities and a high porosity percentage, as expected. In this sense, the banana fiber is expected to hold a high amount of air volume and, consequently, good acoustic and thermal insulation properties.

Studies have clearly shown the acoustic performance of banana fiber composites relative to commonly used natural and synthetic insulation materials. See Table 2.

Table 2 Comparison of Acoustic Performance of Banana Fiber and Conventional Insulation Materials

Material	Density (kg/m ³)	Sound Absorption Coefficient, α (500–4000 Hz)	Thickness (mm)	Key Advantages	Limitations
Banana fiber composite	80–200	0.50 – 0.90	20–50	Renewable, biodegradable, agricultural waste-based, good mid–high frequency absorption	Property variability, moisture sensitivity
Glass wool	10–40	0.60 – 0.95	25–50	Excellent acoustic absorption, widely used	Non-biodegradable, health concerns during handling
Rock wool (mineral wool)	40–150	0.65 – 0.95	25–50	Fire resistant, durable, high absorption	High embodied energy, non-renewable
Jute fiber composite	100–250	0.45 – 0.85	20–50	Natural, good acoustic performance, low cost	Lower durability, moisture absorption
Coir fiber composite	100–300	0.40 – 0.80	20–50	High resilience, good low-frequency absorption	Higher density, moderate absorption efficiency

1.4 RESEARCH OBJECTIVES

The primary objective of this research is to systematically investigate the suitability of banana fiber as a sustainable reinforcement material for acoustic composites intended for building and engineering applications. Specifically, this study aims to:

1. Develop banana fiber–based composite materials using epoxy resin matrices and assess their tensile properties.
2. Evaluate the visual image of banana fiber cross-section using Scanning Electron Microscope to ensure the presence of voids that enhances sound absorption coefficients. Analyze structure–property relationships linking fiber composition, porosity, and microstructure to acoustic and thermal performance.
3. Insure the banana fiber composites against traditional synthetic insulation materials, identifying their potential for practical applications.

1.5 RESEARCH HYPOTHESES

Based on the inherent chemical composition and porous microstructure of banana fibers, the following hypotheses are proposed:

- H1: Banana fiber–reinforced composites exhibit comparable tenacity performance to conventional fibrous materials.
- H2: The air-filled cavities within banana fiber structures significantly reduce heat transfer, resulting in thermal conductivity values suitable for building insulation applications.
- H3: Variations in fiber morphology and chemical composition (cellulose, hemicellulose, and lignin content) directly influence the acoustic and thermal efficiency of banana fiber composites.
- H4: Banana fiber composites can achieve acceptable mechanical stability for panels while maintaining low density and high functional performance.

- H5: The utilization of banana fiber derived from agricultural waste leads to lower environmental impact and improved sustainability metrics compared to synthetic insulation materials, without compromising functional performance.

2. MATERIALS AND METHODS

2.1 MATERIALS

Banana fibers were extracted from plants sourced in the Singa area of Sudan’s Blue Nile Region (coordinates: 13° 9' 0" N, 33° 56' 0" E), a region recognized for its extensive banana cultivation, as illustrated in Figure 2.”

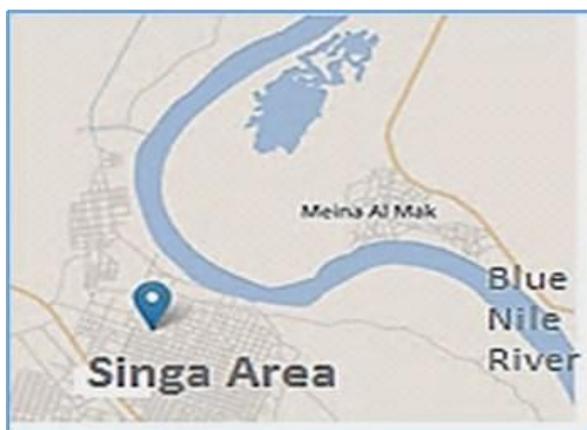


Figure 2: Banana production area

They were mechanically extracted using a semi-automatic machine. The cellular tissues and pectin surrounding bast-fiber bundles facilitated the separation of the fiber from the stem. Fibers were subsequently sun-dried for 24 h, then dried in an oven for 4 h at 70–80 °C to remove water present in the fiber.

2.1 REINFORCEMENT

STRAND PREPARATION

Initially, the entangled banana fibers were manually combed using a hand comb to align and straighten them, ensuring they became parallel to one another. After alignment, the fibers were cut to match the dimensions of the composite laminate, measuring 150 × 230 mm. They were then arranged uniformly to achieve an approximate thickness of 3 mm in the fabricated specimen panel. The detailed properties of the banana fibers are presented in Table 3.

Table 3. Physical and mechanical properties of banana fibers used in composites

Water absorption after 24 h (%)	Density (g/mm ²)	Diameter (mm)	Elongation (%)	Fiber length (mm)	Tensile strength (MPa)
12–25	1.3	0.1–0.2	1.5–3	20–50	400–900

2.2 COMPOSITE FABRICATION

The Vacuum Infusion Process (VIP) is a type of closed mold technique that stands out for its use of atmospheric pressure alone to draw resin into the reinforcement cavity. In this method, the mold setup can consist of a single-sided mold covered with a flexible nylon vacuum bag that acts as a soft “envelope.” The process offers excellent control, as it operates based on D’Arcy’s Law, meaning that the resin flow is influenced by only three main variables.

Three parameters control the vacuum infusion: the permeability of the laminate, the viscosity of the resin, and the pressure differential between the cavity and ambient air. When those parameters do not change, the resin advances through the reinforcement in a repeatable manner for every injection of a particular part. That repeatability keeps resin and fiber usage constant, allowing for an accurate, reliable bill of materials.

2.2.1 FITTINGS

Flow Regulator, Resin Line Holder, Spring Clamp, Vacuum Tubing T-Fittings, Zip Strips, Filter Jacket, Spiral Tubing,

2.2.2 PEEL PLY

Peel Ply is a nylon fabric that has been treated with a release coating to prevent epoxy adhesion. It is commonly laid over a freshly laminated composite surface and removed after curing, resulting in a clean and uniform texture that facilitates the bonding of subsequent epoxy layers.

2.2.3 LANTOR SORIC

Lantor Soric is a flow media for resin infusion. The carrier sheet incorporates hexagonal flow channels that facilitate uniform resin distribution and promote a stable, controlled flow during infusion.

2.2.4 VACUUM INFUSION PROCESS SET-UP

The vacuum infusion process setting is carefully handled as shown in Figure 3.

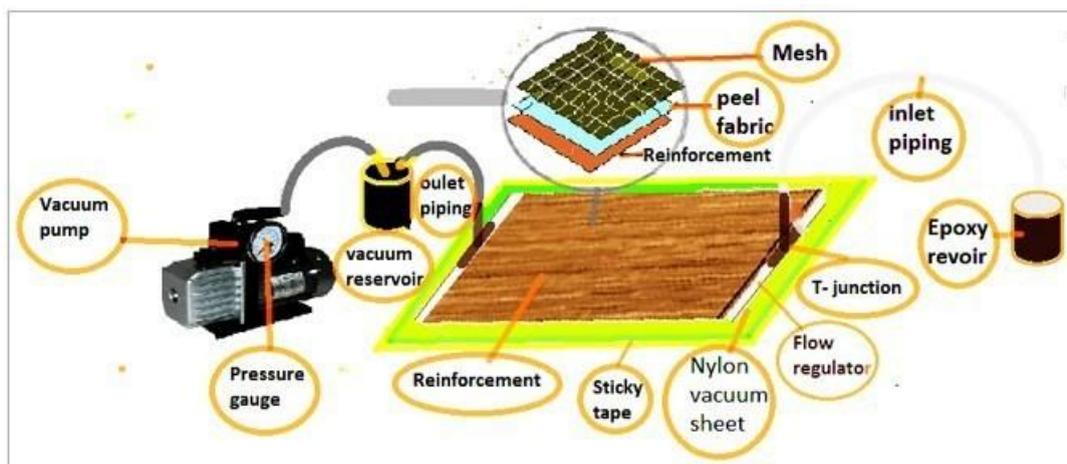


Figure 3: Vacuum infusion set up

The steps taken to set up the VIP system are as indicated in Figure 4. Care is taken to ensure no air leakage from the piping and the nylon vacuum sheet, which may harm the produced panel, causing bubbles and consequently weak places, see Figure 4.

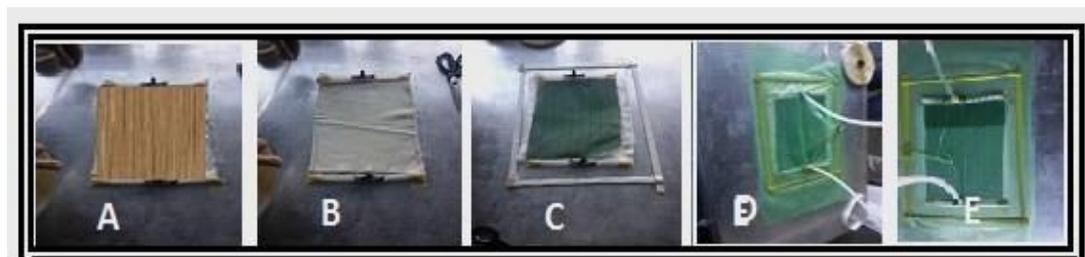


Figure 4 A: Prepared fiber reinforcement, B: fiber tuft covering by peel fabric C: covering by mesh D: covering by Nylon vacuum bag and connecting by Silicon piping, E: Epoxy resin moving through the reinforcement

2.2.4 MATRIX

2.2.4.1 EPOXY RESIN

Epoxy resin used is derived from Oxiranes (ethylene oxide) is characterized by strength and thermosetting properties when mixed with aliphatic amines as a hardener, being the most reactive used, which offers high binding properties between the fiber layers and the matrix. Epoxy resin is a clear white substance with a viscosity of 12500 CP and a density of 1.16 g/cm³. Epoxy resin has good mechanical adhesive strength and curing contractions.

2.2.4.2 POLYAMINE HARDENERS

Polyamine-based hardener is selected to cure epoxy resins at room temperature. It is characterized by low viscosity, good surface appearance, good mechanical performance, and good balance between hardness and flexibility. The resin-to-hardener weight ratio was 10:1.

2.3 METHODS

2.3.1 FLOW OF RESIN THROUGH THE REINFORCEMENT

The movement of resin through a porous reinforcement material is governed by a principle known as Darcy’s Law. Although this law was originally formulated to describe the flow of water through aquifers, it is equally applicable to the flow of resin within porous laminates. Mathematically, Darcy’s Law can be expressed as follows

$$Q = (K A \Delta p) / \mu L \dots\dots\dots (1) [51]$$

Where:

Q = volume rate of flow

K = permeability of the material (a measure of the ease that resin can flow through the material)

A = area of the cross-section through which the resin is flowing

Δp = pressure difference across a section of laminate whose length is L

μ = (dynamic) viscosity of the resin

L = distance the resin has to travel

The determined quantity of banana fibers was taken. Epoxy resin hardener was mixed in a ratio by weight. For the specimen composite plate, the total Fiber content is kept 40% and the Matrix material is kept at 60% by volume fraction.

Epoxy resin curing agent (10: 1 weight ratio) was mixed using a mechanical agitator (agitator speed 300 rpm for 5–7 minutes). The resin has a low volatility and a lack of odor, factors which are responsible for its agreeable handling characteristics.

The calculations were performed based on a fiber volume fraction of 0.4, corresponding to 40% fiber and 60% resin.

If V_f , ρ_f , and W_f are the volume, density, and weight of fiber, respectively.

If V_m , ρ_m , and W_m are the volume, density, and weight of the matrix, respectively, then,

$$\text{Volume fraction} = \frac{V_f}{V_f + V_m} \dots\dots\dots(2)$$

In this work, by considering the overall dimensions of the composite plate (150 mm × 230 mm × 4 mm), the total volume of the plate is:

$$150 \text{ mm} \times 230 \text{ mm} = 34,500 \text{ mm}^2$$

$$34,500 \text{ mm}^2 \times 4 \text{ mm} = 138,000 \text{ mm}^3$$

So the plate volume is 138,000 mm³, which is equivalent to 138 cm³ (since 1 cm³ = 1,000 mm³) or 1.38 × 10⁻⁴ m³.

Volume V = Length×Width×Thickness

For a 40 percent volume fraction, the fiber volume will be = 0.0000552 m³

Matrix density = 1.16 g/cm³

In composite materials, the fibers provide stiffness and strength. Therefore, the greater the number of fibers, the better these mechanical properties will be. The number of fibers is usually expressed in terms of fiber volume fraction (V_f), which is defined as

$$\text{Volume fraction} \dots\dots\dots(3) \\ = \frac{V_f}{V_c}$$

Where V_f is the volume of fibers and V_c is the volume of the composite material.

Properties such as the stiffness of a unidirectional composite along the axial direction are given by the rule of mixtures:

$$E_c = E_f V_f + V_m E_m \dots\dots\dots(4)$$

Where subscript *f* refers to fiber and *m* refers to matrix.

The fiber volume fraction and matrix volume fraction are related by:

$$V_f + V_m = 1 \dots\dots\dots(5)$$

Where V_m is the matrix volume fraction.

For good quality composites, the amount of voids should be a minimum (less than 1%)

After setting all parameters, the vacuum pump was activated to evacuate air until the bag fully conformed to the reinforcement. The pump was temporarily turned off to verify system integrity via the pressure gauge. It was then reactivated to draw resin through the reinforcement until fully impregnated. The pump was finally switched off, and the panel was allowed to cure for 24 hours.

2.4 PREPARATION OF SPECIMEN FOR TESTING

The composite laminate produced through the Vacuum Infusion Process (VIP) was used to prepare the test specimens. The specimens were precisely cut from the laminate using a CNC machine in accordance with the ISO 527-4 standard for tensile testing. Each specimen measured 250 mm × 15 mm. Tensile tests were carried out using an Instron Universal Testing Machine (UTM). A total of four specimens were prepared for each fiber orientation, as presented in Table 3 and Figure 5. [52].

Table 4. Test conditions and details

Sample Name	Banana Fiber Composite Plate	Test Entry Number	1	Method File Name	Tensile Test
Test Date	19.04.2022	Conditioning Date/Time		Conditioning Conditions (Tem./Humidity)	23+2 °C/ 65%+-10 RH
Test Conditions (Temp./Humidity)	20 °C 63.6 RH	Load Capacity	5000N	Speed	2 mm/min
Distance Between Holding Tools	150 mm	Operator		Approval	*****
Sample Name	Banana Fiber Composite Plate	Test Entry Number		Method File Name	“*****” Tensile Test .xmas
Test Date	19.04.2022	Conditioning Date/Time		Conditioning Conditions (Tem./Humidity)	23+2 °C/ 50+-10 % RH
Test Conditions (Temp./Humidity)	20 °C 63.6 RH	Load Capacity	5000N	Speed	2 mm/min
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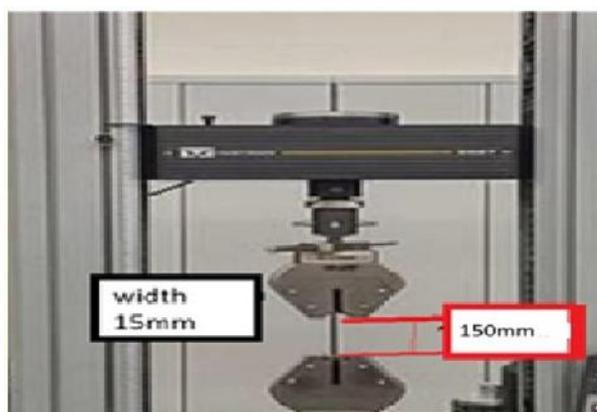


Figure 5: Instron universal testing machine

3. RESULTS AND DISCUSSION

A tensile strength of 25-40 (Average 32.8 MPa) for banana fiber epoxy resin composites is acquired. This falls within a common range observed for natural fiber composites, but it's generally on the lower to mid-range compared to some of the higher-performing banana fiber epoxy composites reported in literature Table 3,4 and Figure 6.

3.1 COMPARISON WITH SIMILAR STUDIES:

- Higher-Performing Banana Fiber Composites: Several studies reported significantly higher tensile strengths for banana fiber epoxy composites. For example:

- One study achieved a tensile strength of $62.3 \hat{A} \pm 0.67$ MPa with a 40% fiber volume fraction of banana fiber reinforced epoxy composites (BFRECM) [53, 54].
- Another found a range of 44-50 MPa for banana fiber epoxy composites [54].
- Another reported a tensile strength range of 11.35 to 17.42 MPa, but also mentioned a composite of 50:50 banana fiber and epoxy resin yielding 112.58 MPa. This highlights the significant impact of fiber content and other additives [55].
- One study showed that 15 wt% banana fiber resulted in a maximum tensile strength [56].
- One study of banana fiber composite with 30% fiber/70% epoxy achieved 42 MPa [57].
- Treated woven banana fiber composites have shown superior tensile properties owing to the woven structure.
- Other Natural Fiber Epoxy Composites: When comparing to other natural fiber epoxy composites, the 25-40 MPa range is quite typical [1].
 - Abaca fiber epoxy composites can reach up to 111.45 MPa.[58]
 - Hemp fiber epoxy composites can range from 99.97 MPa to 189.479 MPa [59].
 - General natural fiber epoxy composites can have tensile strengths ranging from 35-100 MPa [31, 60, 61].

While (Average 32.8 MPa) might seem lower than the peak values reported, it's important to consider:

- In this study, we used a 40% fiber volume fraction as mentioned earlier. The Fiber Volume/Weight Fraction and the amount of banana fiber incorporated into the epoxy matrix significantly impact the composite's strength. Higher fiber loading often, but not always, leads to improved tensile strength up to an optimal point, after which it may decrease due to poor fiber-matrix adhesion or voids. A composite with 35 wt% banana macro particles was reported to have a tensile strength of 24.36 MPa, suggesting that even within this range, variations in fiber content can play a role. In this study, there have been several variables that have impacted the results of the tensile strength of the manufactured composite panel, including [62].
- Fiber Treatment: Chemical treatments (e.g., alkali treatment with NaOH, KMnO₄) are widely used to improve the adhesion between the hydrophilic natural fibers and the hydrophobic epoxy matrix. Untreated fibers often result in lower mechanical properties due to poor interfacial bonding. Studies show significant gains in tensile strength with treated fibers. For example, KMnO₄-treated banana fibers showed a 470.77% gain in tensile strength compared to unreinforced epoxy [63]. The banana fibers in this study were untreated and this could explain the relatively lower values.
- Fiber Length and Orientation:
 - Fiber Length: There's an optimal fiber length for maximizing mechanical properties. Too short, and stress transfer is inefficient; too long, and processing becomes difficult, and fiber entanglement can lead to defects. One study found optimal tensile strength at 15 mm fiber length. In this study, banana fiber was used with its full length without cutting.
 - Fiber Orientation: Aligned, continuous fibers generally provide superior strength compared to randomly oriented short fibers. Woven mats can also offer better properties. If your composite uses short, randomly oriented fibers, this could limit the tensile strength. In this study, fibers were combed enough to be straight and parallel.
- Manufacturing Process:
 - Void Content: Voids or air bubbles introduced during the manufacturing process (e.g., hand lay-up, vacuum infusion) can significantly reduce the mechanical properties of composites by acting as stress concentration points. During the VIP the bubbles were reduced by ensuring no leaks in pressure.
 - Curing Conditions: Proper curing of the epoxy resin is crucial for achieving its full mechanical potential. Suboptimal curing temperature or time can lead to a weaker matrix. The curing time was 24 hours according to the manufacturer's recommendation.
- Type and Quality of Banana Fiber: Banana fibers can vary in their properties (e.g., cellulose content, fineness, strength) depending on the species of banana plant, the part of the plant used (outer vs. inner sheaths), and extraction methods. The inherent strength of the raw banana fiber directly influences the composite's strength. The banana fibers were selected to ensure maturity, avoiding immature fibers.
- Epoxy Resin Type: While generally robust, different types of epoxy resins have varying properties. The specific epoxy formulation (e.g., type of hardener, presence of toughening agents) can influence the composite's overall performance. The epoxy resin was chosen with the best specifications and the proper hardener and percent mix.
- Testing Conditions: Adherence to standards (e.g., ISO 527-4 standard for tensile strength) is important for comparable results. Variations in test speed, gripping, and specimen geometry can influence the measured values.

3.2 CONCLUSION FOR 25-40 MPA (AVERAGE 32.8 MPA) RESULTS SEE TABLES 3,4 AND 5 AND FIGURE 6:

A tensile strength average of 32.8 MPa for a banana fiber epoxy composite is a respectable starting point, demonstrating the potential of banana fibers as reinforcement. However, it indicates that there may be avenues for improvement by washing and by using coupling agents. These results are comparable to some natural fiber composites, particularly those with less optimized processing or fiber treatment. To achieve higher strengths closer to the upper range reported in literature (e.g., 60-100+ MPa), future work could focus on:

- Optimizing fiber content and length.
- Implementing effective chemical or physical fiber treatments to enhance fiber-matrix adhesion.
- Improving manufacturing techniques to minimize void content.
- Exploring different banana fiber sources or types.

A tensile strength average of 32.8 MPa for banana fiber epoxy resin composites falls within a common range observed for natural fiber composites, but it's generally on the lower to mid-range compared to some of the higher-performing banana fiber epoxy composites reported in literature. By addressing these factors, the mechanical performance of banana fiber epoxy composites can be significantly enhanced, making them more competitive for various applications.

The elongation at break is a crucial mechanical property for composite materials, indicating their ductility and ability to deform before fracture. For banana fiber-reinforced epoxy resin composites, reported elongation values can vary, but generally fall within a range that reflects the brittle nature of epoxy matrices and the inherent properties of natural fibers.

3.3 ELONGATION RESULTS OF BANANA FIBER EPOXY COMPOSITES TABLE 4,5 AND FIGURE 6

An elongation at break of 1.5% to 2.5% for a banana fiber epoxy resin composite is a relatively low value, which is characteristic of many natural fiber-reinforced polymer composites. Here's what this range signifies:

- **Limited Ductility:** This low elongation indicates that the material is relatively brittle and will not undergo significant plastic deformation before breaking. While some applications require high ductility, many structural and semi-structural applications prioritize stiffness and strength, where lower elongation is acceptable or even desirable.
- **Fiber-Matrix Interaction:** The elongation at break is heavily influenced by the interface between the banana fibers and the epoxy matrix. Poor adhesion or voids can lead to premature failure and lower elongation. Chemical treatments of banana fibers (e.g., alkali treatment with NaOH) are often employed to improve wettability and bonding with the polymer matrix, which can in turn improve mechanical properties, including elongation, by allowing for more efficient stress transfer.
- **Fiber Characteristics:** Banana fibers themselves have a relatively low elongation at break 1.5-3.0% compared to some synthetic fibers. Their lignocellulosic nature means they are stiffer and less ductile than, for example, many synthetic polymers.
- **Fiber Content and Length:** The fiber content and length also play a role. Increasing fiber content generally increases stiffness and strength but can sometimes lead to reduced elongation if the fibers are not well dispersed or if there is poor interfacial adhesion.

3.4 COMPARISON WITH SIMILAR OTHER NATURAL FIBER COMPOSITES

When comparing the elongation of 1.5% to 2.5% for banana fiber epoxy composites with other natural fiber-reinforced epoxy composites, several points emerge, see Table:

- **General Trend for Natural Fiber Composites:** Natural fiber composites, in general, tend to have lower elongation at break compared to many synthetic fiber composites (e.g., glass fiber composites, which can exhibit higher elongations). This is due to the inherent brittle nature of natural fibers.
- **Variety Among Natural Fibers:** The elongation varies significantly among different types of natural fibers. For instance:
 - **Sisal fiber epoxy composites:** Often show elongation values in a similar range to banana, typically around 2-4%.
 - **Jute fiber epoxy composites:** Can also exhibit elongations in the low single digits, often between 3-6%.
 - **Hemp fiber epoxy composites:** May have elongations in a similar range, often 1-3.5%.
 - **Coconut (Coir) fiber epoxy composites:** Coir fibers are known for their higher elongation compared to other natural fibers, with reported values for coir composites often ranging from 15-30% for the fiber itself, which can translate to higher composite elongation depending on the fiber loading and matrix.
 - **Kenaf fiber epoxy composites:** Typically show elongations between 1.5-2.7%.
- **Impact of Treatments:** As mentioned, chemical treatments like alkalization can improve the interfacial bonding and, consequently, the mechanical properties, including elongation. Treated fibers generally lead to composites with better performance compared to untreated ones. For example, some studies report that alkaline-treated banana materials show fewer occurrences of pull-outs and fractures, leading to better mechanical performance.
- **Comparison to Pure Epoxy:** The elongation at break of the composite is generally lower than that of the pure epoxy matrix. This is because the fibers, being stiffer, restrict the deformation of the matrix and bear a significant portion of the load, leading to earlier failure if the fiber itself is brittle or the interface is weak.

In conclusion, an elongation of 1.5% to 2.5% for a banana fiber composite with epoxy resin is a typical value within the spectrum of natural fiber composites. While it indicates limited ductility, it is often acceptable for applications where stiffness and strength are primary requirements. The specific value is influenced by fiber properties, fiber-matrix adhesion, and processing conditions, and it compares reasonably with other common natural fibers like sisal, jute, and hemp, although

it is notably lower than highly ductile fibers like coir.

Table 5: Tensile and elongation

Name	Break Elongation	Break_% Elongation	YP(Points) _Force	YP(Points) _Elongation	Elastic	Thickness
Parameters	Precision: 10	Precision: 10	3 Signs	3 Signs	Force 2-8 N	
Unit	mm	%	N	mm	N/mm ²	mm
Average	1,60363	2,00288	1055,66	1,60363	3280,82	3,8625
Standard Deviation	0,38815	0,48416	232,979	0,38815	8050,91	0,24958
Variation	0,24205	0,24173	0,22069	0,24205	2,45394	0,09740

Table 6 Statistical Analysis[64]

Name Parameters	Width	Primary Length	Curve_ Standard	Chord	Curve Beam	Max_Ext.1
			Force 2 - 8 N	Ext.1(Strain) 0,1 - 0,3 %	Ext.1(Strain) 0,1 - 0,3 %	All Area Calculation
Unit	Mm	mm	N/mm	N/mm ²	N/mm	mm
Average	12,9950	80,0618	2511,82	3729,80	2478,36	0,67825
Standard Deviation	0,11446	0,06073	5568,71	412,387	469,470	0,30179
Variation	0,00881	0,00076	2,21700	0,11057	0,18943	0,44495

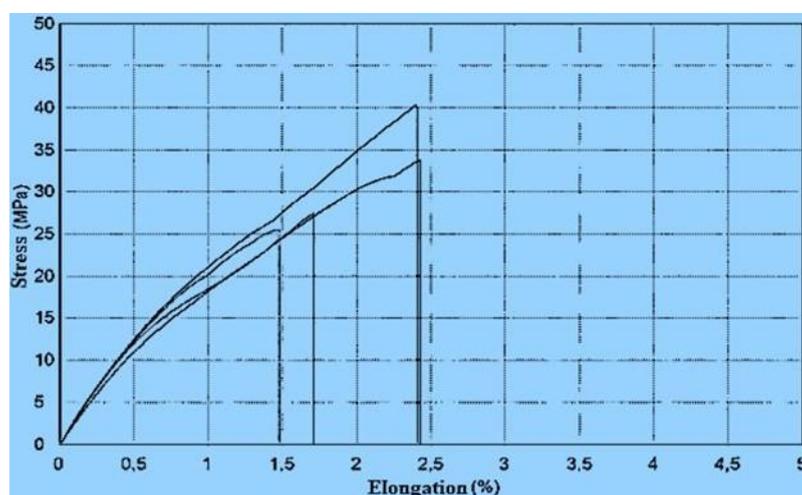


Figure 6: Stress elongation curve of Banana fiber composite

Table 7: Mechanical Properties of Polyester resin

Property	Polyester resin
Density (g/cm ³)	1.2–1.5
Young modulus (MPa)	2000–4500
Tensile strength (MPa)	40–90
Compressive strength (MPa)	90–250
Tensile elongation at break (%)	2
Water absorption 24h at 20°C	0.1–0.3
Flexural modulus (GPa)	11.0
Poisson's ratio	0.37–0.38

4. CONCLUSION

The composite panels were successfully manufactured utilizing banana fiber as a sustainable reinforcement material, demonstrating a viable and environmentally conscious approach to composite production. This project meticulously followed a multi-stage process, beginning with the crucial preparation of the raw banana fibers. The initial steps of fiber extraction and thorough cleaning were paramount in removing impurities and ensuring the integrity of the individual fibers, which directly impacts their bonding capabilities within the polymer matrix. This was followed by a critical manual combing process, which aligned the banana fibers, enhancing their continuous nature and optimizing their load-bearing potential in the final composite.

Once the banana fiber mats were adequately prepared, the project transitioned to the intricate phase of panel preparation for vacuum infusion. This involved carefully laying up the banana fiber plies within a mold, strategically placing the resin distribution channels, and ensuring a robust vacuum seal. The choice of the vacuum infusion technique was deliberate, as it allowed for superior resin impregnation, minimized void content, and facilitated a high fiber-volume fraction, all contributing to enhanced mechanical properties. The controlled infusion of the resin system through the evacuated mold ensured a uniform and complete saturation of the banana fiber reinforcement.

Following the infusion, the composite panels underwent a critical curing period of 24 hours. This duration, under controlled environmental conditions, allowed for the complete polymerization and cross-linking of the resin, resulting in a solidified and robust composite structure. The careful monitoring of the curing process was vital to achieve optimal mechanical performance and dimensional stability.

The final stage involved the preparation of samples for tensile testing, which entailed precisely cutting specimens from the cured composite panels. This meticulous cutting process ensured that the samples conformed to established standards for mechanical characterization, allowing for accurate and reliable data collection according to ISO 527-4. The subsequent tensile testing would provide crucial insights into the strength, stiffness, and overall mechanical integrity of the banana fiber composite panels, validating the effectiveness of the chosen manufacturing methodology and the potential of banana fibers as a sustainable composite reinforcement. Comparing the acquired tensile strength of up to 40 MPa of the panel give a promising results of banana composites. Ultimately, this project not only outlines a comprehensive manufacturing pathway for banana fiber composites but also lays the groundwork for further exploration into their diverse applications and optimization.

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