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Research Article

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Experimental Investigation of Flexural Behavior of Hybrid Sisal and False Banana Fiber Reinforced Epoxy Composite

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Abstract

This study investigated the flexural performance of epoxy composites reinforced with sisal fiber (S), false banana fiber (B), and their hybrid combinations (100S, 100B, 80S20B, 50S50B, and 20S80B). Composite laminates were evaluated using a three-point bending test in accordance with ASTM D7264/D7264M. Five specimens were tested for each composition using a 10 KN universal testing machine at a crosshead speed of 0.5 mm min^{-1} and a support span of 128 mm. The flexural strength, flexural modulus, stress-strain response, and load-deflection behavior were analyzed to assess the effect of fiber hybridization. The results showed that hybridization significantly improved the flexural performance of the composites. Among the investigated laminates, the 50S50B hybrid composite exhibited the highest flexural strength and flexural modulus, indicating superior bending stiffness, load-bearing capacity, and deformation resistance compared with the single-fiber composites. The stress-strain and load-deflection responses further demonstrated enhanced toughness and energy absorption for the balanced hybrid laminate. The findings confirm that the balanced combination of sisal and false banana fibers is an effective reinforcement strategy for producing lightweight, sustainable composites suitable for structural and semi-structural engineering applications.

Keywords: False Banana fiber; Flexural Strength; Hybrid natural fiber composites; Natural fiber Epoxy composite; Sisal fiber.

1. Introduction

In recent years, the global manufacturing and automotive sectors have witnessed an unprecedented shift toward sustainable, eco-friendly, and lightweight materials driven by environmental regulations, resource depletion, and strict carbon-footprint reduction targets [1, 2]. Synthetic fiber-reinforced polymers primarily glass, carbon, and aramid composites have long dominated structural applications due to their exceptional specific mechanical strength and high modulus [3, 4]. However, their widespread industrial consumption is severely hindered by high processing energy demands, non-biodegradability, non-renewability, equipment abrasion, difficult end-of-life recycling, and health hazards associated with airborne synthetic dust during machining [5, 6]. Consequently, lignocellulosic natural fibers have emerged as viable, environmentally sustainable substitutes for synthetic reinforcements across diverse semi-structural and non-structural engineering fields, including automotive door panels, building materials, and acoustic insulation [7, 8].

Natural fiber-reinforced polymer composites (NFPCs) offer key technical advantages over synthetic alternatives, such as low density, low cost, non-toxicity, high specific strength-to-weight ratio, ease of processing, and full biodegradability at the end of service life [9, 10]. Lignocellulosic fibers derived from plant stems, leaves, seeds, and bast such as sisal, flax, jute, hemp, kenaf, coir, and enset consist primarily of cellulose microfibrils embedded in an amorphous matrix of hemicellulose, lignin, pectin, and waxes [11, 12]. Cellulose acts as the main load-bearing structural component, while hemicellulose and lignin provide thermal resistance, binder functions, and structural rigidity within the plant cell wall [13, 14].

Among the widely exploited leaf-derived fibers, sisal (*Agave sisalana*) stands out as a prominent high-performance natural reinforcement [15, 16]. Sisal fibers possess excellent tensile strength (350-700 MPa), high flexural modulus, low density ($\sim 1.45 \text{ g/cm}^3$), and superior abrasion resistance, making them well suited for structural polymer composites [17, 18]. Studies by Marichelvam et al. [19] and Mayakannan et al. [20] demonstrated that incorporating sisal fibers into thermosetting polymer matrices yields significant improvements in flexural stiffness, tensile properties, and impact resistance. However, single-fiber sisal composites often exhibit brittle failure modes, moderate water absorption, and localized stress concentration under high flexural deformation [21, 22].

Concurrently, false banana (*Ensete ventricosum*), an indigenous monocarpic perennial crop widely cultivated in East and Southern Africa (notably Ethiopia), yields long, highly flexible, low-density lignocellulosic fibers from its pseudostem [23, 24]. False banana fibers (often termed enset fibers) exhibit high ductility, smooth surface morphology, low specific gravity, and remarkable energy absorption capability under mechanical impacts [25, 26]. Recent investigations by Boset [27] and Furtos et al. [28] revealed that false banana fibers impart superior fracture toughness and strain energy capacity to thermoset and geopolymer matrices. Nonetheless, unhybridized false banana fiber composites frequently exhibit lower elastic and flexural moduli compared to stiffer natural fibers like sisal or flax, restricting their independent use in primary load-bearing structural elements [29, 30].

Thermosetting epoxy resins are widely used as matrix materials for advanced natural fiber composites due to their excellent dimensional stability, chemical resistance, absence of volatile sub-products during room-temperature curing, low shrinkage, and high mechanical adhesion to fibrous reinforcements [31, 32]. Epoxy provides a continuous rigid medium that protects natural fibers from ambient environmental degradation and efficiently transfers applied external loads to the reinforcing phase [33, 34]. Nevertheless, neat epoxy resin inherently suffers from low fracture toughness and brittle mechanical failure when subjected to high bending, impact, or shear loading [35, 36].

To mitigate the performance constraints associated with single-fiber natural composites such as moisture sensitivity, anisotropic mechanical behavior, and modest flexural strength the concept of fiber hybridization has gained widespread interest [37, 38]. Hybridization involves incorporating two or more distinct types of natural or synthetic fibers within a single polymer matrix to leverage the synergistic advantages of each constituent [39, 40]. In natural–natural fiber hybrid composites, combining a stiff, high-strength fiber (such as sisal) with a highly extensible, energy-absorbing fiber (such as false banana) creates a balanced mechanical architecture capable of offering high bending stiffness alongside superior strain energy absorption [41, 42].

Flexural loading represents one of the most critical mechanical evaluation criteria for composite structures, as components deployed in automotive interiors, structural panels, and load-bearing beam profiles simultaneously undergo tension, compression,

and interlaminar shear forces [43, 44]. The standard three-point bending test (ASTM D7264/D7264M) provides a rigorous, standardized framework for evaluating flexural strength, flexural modulus, maximum mid-span deflection, and failure modes of polymer matrix composites under static loading [45, 46]. The geometric span-to-thickness ratio (typically 32:1) specified in ASTM D7264 minimizes interlaminar shear deformation, ensuring that primary tensile and compressive outer-fiber stresses govern failure [47, 48].

While existing literature extensively covers hybrid composites combining sisal with jute, banana (*Musa*), coir, or synthetic glass fibers [17, 19], research on the hybrid combination of sisal (*Agave sisalana*) and false banana (*Ensete ventricosum*) leaf/pseudostem fibers remains limited [23]. Specifically, a critical knowledge gap remains regarding how systematically varying the weight ratio of stiff sisal fibers to ductile false banana fibers influences the flexural modulus, ultimate flexural strength, stress-strain linearity, and bending load capacity of epoxy composites prepared via room-temperature compression molding.

To address this gap, the present study investigates the flexural behavior of hybrid sisal and false banana fiber-reinforced epoxy composites manufactured via hand lay-up and compression molding. Five distinct weight formulation ratios unhybridized sisal (100S), unhybridized false banana (100B), and hybrid formulations (80S20B, 50S50B, and 20S80B) were evaluated using standard three-point bending tests in accordance with ASTM D7264/D7264M. The primary objective is to determine the optimal fiber hybridization ratio that yields maximum bending stiffness, ultimate flexural load capacity, and enhanced deformation resistance for lightweight structural and semi-structural applications.

2. Materials and Methods

The flexural properties of the fabricated sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber-reinforced epoxy composites (80S20B, 50S50B, and 20S80B) were evaluated using a three-point bending test in accordance with ASTM D7264/D7264M, the primary standard for determining the flexural properties of polymer matrix composite materials [45]. This standard provides a reliable procedure for evaluating the flexural strength, flexural modulus, and deformation behavior of fiber-reinforced polymer composites under static loading conditions [46].

The three-point bending test measures the force required to bend a specimen supported at two points while a concentrated load is applied at the midpoint. This method is widely employed to assess the load-bearing capacity, bending stiffness, and resistance to deformation of composite materials [43]. The flexural modulus obtained from the test serves as an important indicator of the material's stiffness and its ability to resist elastic deformation under bending loads [45, 47].

Composite laminates were fabricated and machined into standard test specimens according to the dimensional requirements specified in ASTM D7264/D7264M [45]. Five specimens were prepared for each composite configuration (100S, 100B, 80S20B, 50S50B, and 20S80B), resulting in a total of twenty-five specimens for flexural testing. Prior to testing, all specimens were inspected to ensure dimensional accuracy and the absence of visible defects.

The flexural tests were conducted using a Universal Testing Machine (UTM) equipped with a three-point bending fixture. The testing machine had a maximum load capacity of 10 kN and operated at a constant crosshead speed of 0.5 mm min^{-1} . The support span length was maintained at 128 mm, and the load was applied vertically at the midpoint of each specimen through the loading nose. All fixture dimensions and testing arrangements complied with the requirements of ASTM D7264/D7264M [45].

During testing, the applied load and corresponding mid-span deflection were continuously recorded until specimen failure occurred. The load–deflection data were subsequently used to determine the flexural strength, flexural modulus, and stress–strain behavior of the composites. These parameters were employed to evaluate the influence of fiber hybridization on bending stiffness, deformation characteristics, and failure mechanisms [38, 44].

To ensure the reliability and repeatability of the experimental results, five specimens were tested for each composite formulation. The average values and standard deviations were calculated for statistical comparison among the different fiber reinforcement ratios. The complete experimental program was carried out over two consecutive days under identical laboratory conditions to minimize experimental variability.

The adopted ASTM D7264 three-point bending methodology provided a comprehensive evaluation of the flexural performance of the fabricated natural fiber-reinforced epoxy

composites and enabled the assessment of the influence of sisal and false banana fiber hybridization on their mechanical behavior and structural performance.

2.1. Materials

The sisal and false banana fibers used in this study were obtained from cultivated and managed agricultural systems. *Ensete ventricosum* (false banana) and *Agave sisalana* (sisal) were sourced from locally cultivated agroforestry farmlands in Chichu Kebele, Dilla Zuria Woreda, Gedeo Zone, Ethiopia. The fibers were obtained from cultivated plants rather than wild populations, and permission to collect the plant fibers was obtained from the respective landowners prior to sampling. The collected plant fibers were used solely for the present research. Sampling and handling of the plant fibers were conducted in accordance with applicable local institutional and national requirements. The extracted sisal and false banana fibers used as natural reinforcements are shown in Fig. 1.

Based on previous studies [3, 22, 43], a (70/30) % epoxy resin/fiber ratio was selected for the present investigation because this composition was reported to provide improved flexural strength compared with other fiber-to-matrix proportions. The corresponding weight and volume fractions of the epoxy matrix and natural fibers were calculated according to the selected (70/30) % epoxy/fiber ratio. The extracted sisal and false banana fibers served as the primary natural fiber reinforcements. Prior to composite processing, both fibers were thoroughly washed with distilled water to remove surface contaminants, dried at 80 °C in a laboratory oven for 24 h to reduce moisture content, and cut to the targeted length. The prepared fibers were subsequently combined with the epoxy matrix according to the calculated weight and volume fractions for composite fabrication.

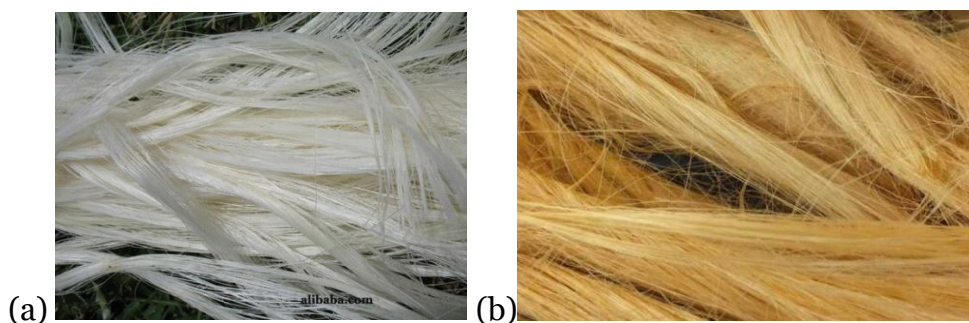


Fig. 1 (a) Sisal fiber and (b) false banana fiber

2.2. Composite Fabrication and Sample Design

Composite laminates were fabricated using the hand lay-up method followed by compression molding to ensure uniform thickness and minimize void formation. Five distinct composite formulations were prepared by varying the relative weight proportions of Sisal (S) and False Banana (B) fibers while keeping the total fiber content constant:

- 100S: 100% Sisal fiber reinforced epoxy composite
- 100B: 100% False Banana fiber reinforced epoxy composite
- 80S20B: Hybrid composite with 80 wt% Sisal and 20 wt% False Banana fibers
- 50S50B: Hybrid composite with 50 wt% Sisal and 50 wt% False Banana fibers
- 20S80B: Hybrid composite with 20 wt% Sisal and 80 wt% False Banana fibers

The liquid epoxy-hardener system was applied layer-by-layer to coat the fibers thoroughly. The mold was closed under uniform pressure and cured at room temperature (25°C) for 24 hours, followed by post-curing at 70°C for 4 hours to ensure complete crosslinking.

2.3. Specimen Preparation and Dimensional Standards

After curing, the composite laminates were machined into rectangular test specimens in strict compliance with ASTM D7264/D7264M (Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials). The nominal geometric dimensions of the prepared specimens were as follows:

- Overall Length (S): 200 mm
- Support Span Length (L): 128 mm (maintaining a standard span-to-thickness ratio of 32:1)
- Thickness (d): 4.0 mm
- Width (b): 13.0 mm

Five replicate specimens were produced and tested for each configuration (totaling 25 specimens) to ensure statistical reliability and experimental repeatability. Prior to testing, all specimens were visually inspected for surface defects, micro-cracks, or edge delamination, and measured using a digital vernier caliper.



Fig.1 Prepared test specimens for flexural testing showing different fiber composition ratios (100S, 100B, 80S20B, 50S50B, 20S80B).

2.4. Flexural Characterization (Three-Point Bending Test)

Flexural testing was performed using a Universal Testing Machine (UTM) housed in the Mechanical Testing Laboratory at the Wood Technology Research Center, equipped with a 10 KN maximum load capacity and a standard three-point bending fixture. The schematic representation of the three-point bending test geometry is illustrated in Figure 1, and the experimental test rig setup is shown in Figure 2.

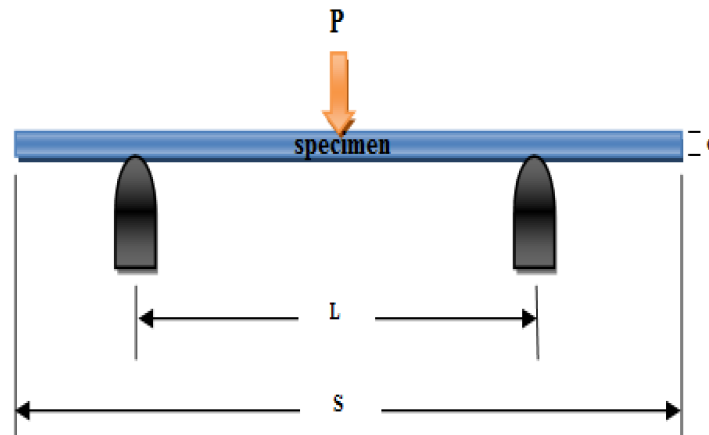


Fig.2 Schematic diagram of the three-point bending test setup (P = applied load, S = overall length [200 mm], L = support span length [128 mm], d = specimen thickness [4 mm]).



Fig.3 Universal Testing Machine (UTM) setup in the mechanical testing laboratory showing the three-point bending fixture and loaded composite specimen.

The mechanical testing parameters were specified as follows:

Test Mode: Static three-point bending

Crosshead Speed: 0.5 mm/min

Environmental Conditions: Standard room temperature ($23 \pm 2^\circ\text{C}$) and relative humidity ($50 \pm 5\%$)

During testing, the loading nose applied a vertical force at the midpoint until ultimate failure occurred. Following testing, fractured specimens were collected to observe deformation and fracture features.

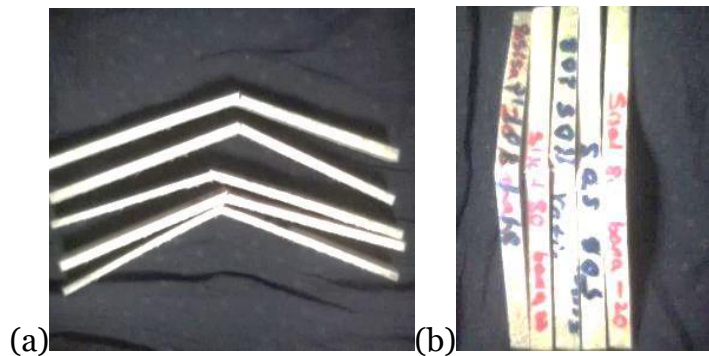


Fig.4(a-b) Composite specimens post flexural testing showing structural failure modes and macroscopic fracture behavior.

2.5. Analytical Calculations

During testing, mid-span deflection (δ) and applied load (P) were continuously recorded until complete specimen failure. The flexural parameters were calculated according to ASTM D7264 formulas:

1. *Flexural Strength (σ_f):*

$$\sigma_f = \frac{3P_{\max} L}{2bd^2}$$

1

Where $P_{\max}$ is the maximum load at failure (N), L is the support span length (mm), b is the width (mm), and d is the specimen thickness (mm).

2. *Flexural Modulus (E_f):*

Where m is the slope of the initial linear portion of the load–deflection curve

$$\Delta P / \Delta \delta (\text{N/mm}). E_f = \frac{L^3 m}{4bd^3} \quad 2$$

3. *Flexural Strain (ε_f):*

$$\varepsilon_f = \frac{6\delta d}{L^2} \quad 3$$

Where δ is the maximum mid-span deflection (mm)

Data processing included calculating mean values and standard deviations for each composite system to evaluate the impact of hybridization on flexural performance. All test series were performed over two consecutive days under consistent laboratory conditions to minimize experimental variability.

3. Results and Discussions

This section presents and discusses the experimental results obtained from the three-point bending tests conducted on epoxy composites reinforced with sisal fiber (100S), false banana fiber (100B), and their hybrid combinations (20S80B, 50S50B, and 80S20B). The flexural performance of the composites was evaluated in terms of flexural strength, flexural modulus, stress-strain behavior, and load–deflection response. Statistical analyses, including mean values, standard deviations, and data distribution, were used to assess the repeatability and reliability of the experimental measurements.

The influence of fiber hybridization on the mechanical behavior of the composites was examined by comparing the performance of single-fiber reinforced composites with that of hybrid composites. The experimental results provide insight into the synergistic interaction between sisal and false banana fibers and their contribution to load transfer efficiency, bending stiffness, deformation characteristics, and failure behavior under flexural loading. Furthermore, the observed trends are interpreted in relation to fiber composition, reinforcement distribution, and the fiber–matrix interface to identify the optimum hybrid configuration for enhanced flexural performance. Overall, this discussion establishes the relationship between composite architecture and mechanical response and highlights the potential of hybrid natural fiber-reinforced epoxy composites for lightweight and sustainable structural applications.

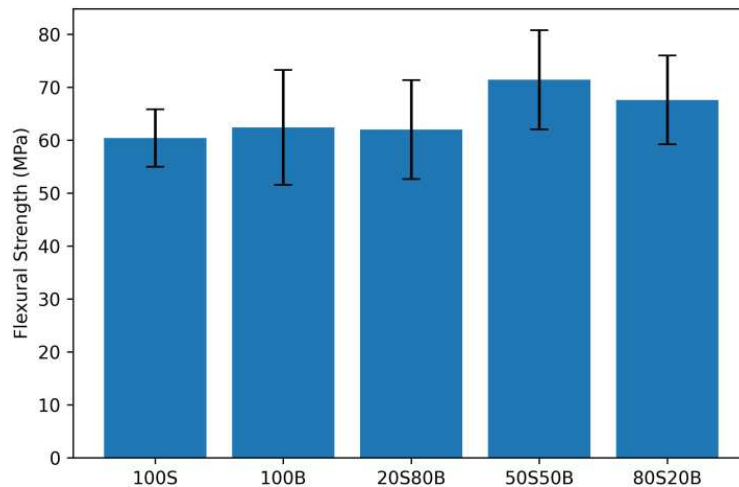


Fig.5 Flexural Strength of Hybrid Sisal and False Banana Fiber Reinforced Epoxy Composites

Figure 5. Mean flexural strength of sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber reinforced epoxy composites obtained from three-point bending tests. Error bars represent the standard deviation of five replicate specimens. The balanced hybrid composite (50S50B) exhibited the highest average flexural strength, demonstrating the beneficial effect of fiber hybridization on load transfer efficiency and resistance to bending failure. The results indicate that hybrid reinforcement significantly enhances the flexural performance compared with single-fiber reinforced composites.

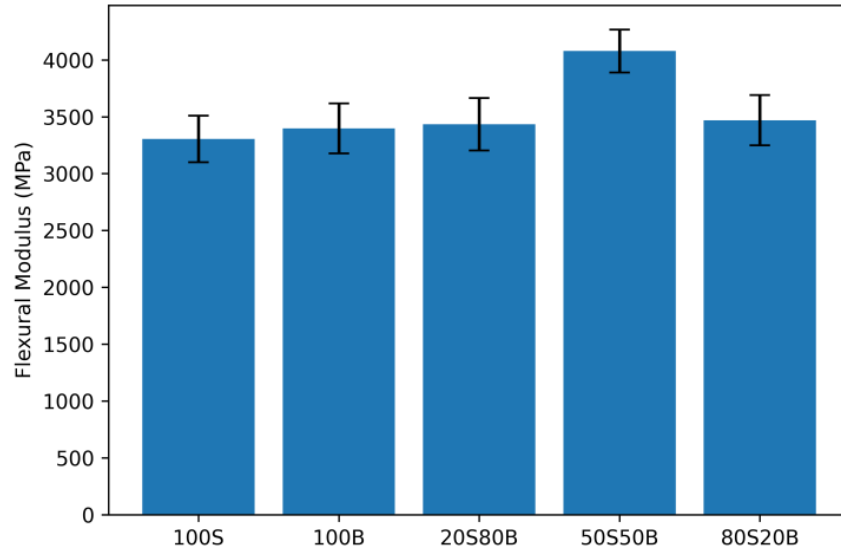


Fig.6 Flexural Modulus of Hybrid Sisal and False Banana Fiber Reinforced Epoxy Composites

Figure 6. Mean flexural modulus of sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber reinforced epoxy composites. Error bars indicate the standard deviation of five replicate measurements. The 50S50B hybrid composite exhibited the highest flexural modulus, indicating greater stiffness and improved resistance to elastic deformation. The increase in flexural modulus demonstrates the positive influence of balanced fiber hybridization on the rigidity of the epoxy composite.

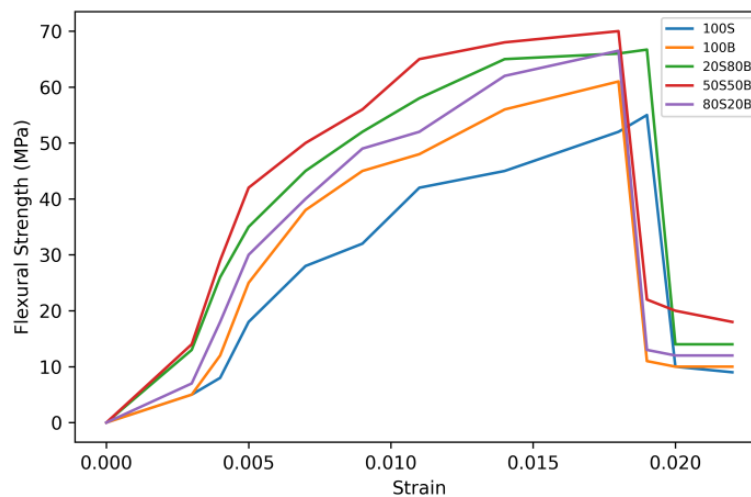


Fig.7 Flexural Stress–Strain Curves of Hybrid Composites

Figure 7. Flexural stress–strain curves of sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber reinforced epoxy composites obtained during three-point bending tests. The curves illustrate the elastic deformation, nonlinear response,

and failure characteristics of each composite. The 50S50B hybrid composite exhibited the highest peak flexural stress and sustained larger strain before failure, indicating enhanced toughness, improved stress transfer between the reinforcing fibers and epoxy matrix, and superior energy absorption capacity.

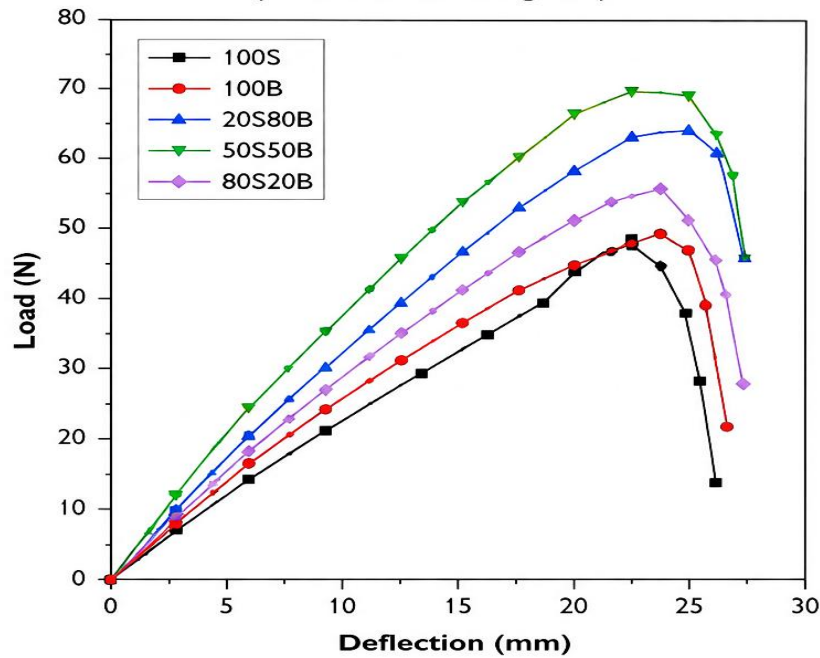


Fig.8 Load–Deflection Curves of Hybrid Composites

Figure 8. Load–deflection curves of sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber reinforced epoxy composites obtained from three-point bending tests. The curves describe the bending response of each composite throughout the loading process. The 50S50B hybrid composite sustained the highest applied load before failure and exhibited greater resistance to deformation, reflecting improved flexural stiffness and enhanced load-bearing capacity due to the synergistic interaction between sisal and false banana fibers. Conversely, the single-fiber composites exhibited lower maximum loads and earlier failure under flexural loading.

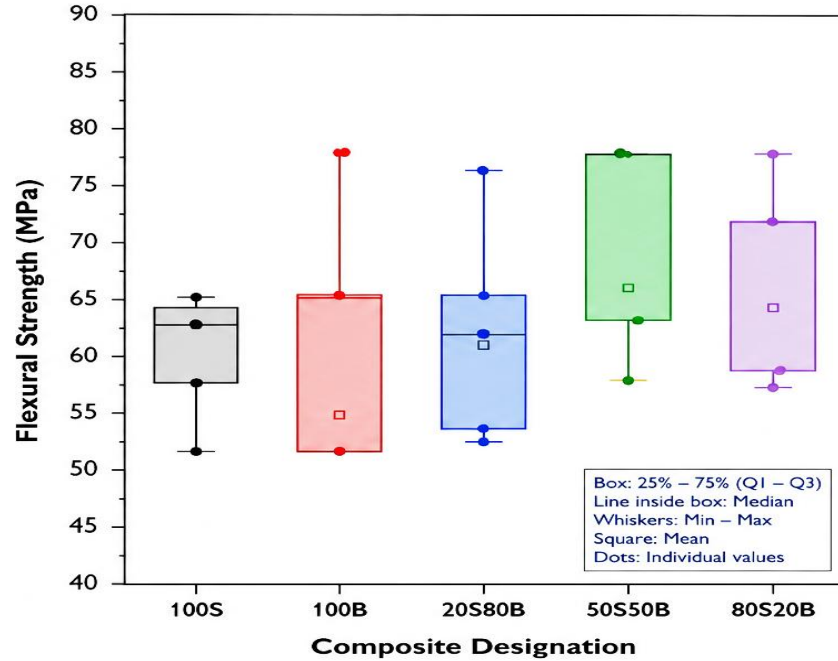


Fig.9 Box Plot of Flexural Strength

Figure 9. Box plots showing the distribution of flexural strength for sisal fiber (100S), false banana fiber (100B), and hybrid sisal/false banana fiber reinforced epoxy composites based on five replicate specimens. The box plots present the median, interquartile range, minimum and maximum values, and the variability of the experimental measurements. The 50S50B hybrid composite exhibited the highest median flexural strength with relatively low dispersion, indicating superior mechanical performance and good experimental repeatability. The observed variation among the composite configurations reflects the influence of fiber composition on flexural behavior and demonstrates the consistency of the composite fabrication process.

4. Conclusion

This study experimentally investigated the flexural behavior of epoxy composites reinforced with sisal fiber, false banana fiber, and their hybrid combinations through three-point bending tests. The results demonstrated that fiber hybridization had a significant influence on both the flexural strength and stiffness of the composites. Among the investigated formulations, the 50S50B hybrid composite exhibited the best overall mechanical performance, achieving the highest average flexural strength and

flexural modulus while maintaining relatively low experimental variability, indicating excellent structural integrity and consistent fabrication quality.

The flexural stress-strain and load-deflection responses revealed that the balanced hybrid composite sustained higher stresses and loads before failure and exhibited greater resistance to deformation than the single-fiber reinforced composites. These findings indicate that the balanced incorporation of sisal and false banana fibers promotes more efficient stress transfer between the reinforcement and epoxy matrix, resulting in improved load-bearing capacity, enhanced stiffness, and increased energy absorption under flexural loading.

Statistical evaluation of the experimental data further confirmed the reliability of the results. The relatively small standard deviations observed for most composite configurations demonstrate good repeatability of the manufacturing process and consistent mechanical performance. The box plot analysis also showed that the 50S50B composite possessed the highest median flexural strength with comparatively lower dispersion than the other composite systems, confirming the effectiveness of balanced fiber hybridization.

Overall, the experimental findings demonstrate that hybridization of sisal and false banana fibers is an effective strategy for enhancing the flexural properties of natural fiber-reinforced epoxy composites. The balanced 50S50B composite offers the most favorable combination of strength, stiffness, and deformation resistance, making it a promising sustainable material for lightweight engineering applications, including automotive interior components, furniture panels, building materials, and other structural products where high specific mechanical performance and environmental sustainability are required.

Future research should investigate the effects of fiber surface treatments, different fiber volume fractions, laminate stacking sequences, environmental aging, moisture absorption, impact resistance, fatigue performance, and microstructural failure mechanisms using scanning electron microscopy (SEM). Such investigations would provide a more comprehensive understanding of the reinforcement mechanisms and support the optimization and broader engineering application of hybrid natural fiber-reinforced polymer composites.

Declaration:**Author Contributions**

Lemi Demissie Boset: Conceptualization, investigation, data analysis, writing original draft preparation, and writing review and editing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Clinical Trial Number: Not applicable.

Ethics Approval: Not Applicable.

Consent to Participate: Not Applicable.

Consent for Publication: Not Applicable.

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