UtilitasMathematica

ISSN 0315-3681 Volume 122 (2), 2025

Performance Assessment and Mechanical Behavior of Bamboo/Sisal/Chopped Mat Fiber Hybrid Composites Prepared by Hand Lay-Up Process

SSS Lokesh[1], Konijeti Sri Manikanta[1]

[1]Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, India

Corresponding email id: sitaramakrishna71@gmail.com

Abstract

The rising demand for sustainable and lightweight materials has accelerated research into natural fiber-reinforced composites as eco-friendly alternatives to synthetic systems. In this work, bamboo, sisal, and chopped strand mat (CSM) fibers were combined in an epoxy matrix using the hand lay-up technique. Seven composite configurations were fabricated and evaluated according to ASTM standards for tensile, flexural, impact, and hardness properties. Among them, the bamboo/sisal/CSM hybrid composite demonstrated superior performance, achieving tensile strength of 98.2 ± 4.9 MPa, flexural strength of 173.3 ± 6.8 MPa, impact energy of 5.75 ± 0.35 J, and Brinell hardness of 76.3 ± 2.1. The enhanced performance was attributed to the complementary roles of the reinforcing fibers: bamboo imparting stiffness, sisal contributing ductility, and CSM improving isotropy and hardness. Comparative assessment with recent literature (2020–2025) revealed consistent trends, confirming the structural reliability and sustainability of such hybrid composites. Overall, the study highlights the potential of bamboo/sisal/CSM composites as viable alternatives for automotive, aerospace, and construction applications, aligning with circular economy principles while advancing engineering innovation and environmental responsibility.

Keywords: Natural fibers, Bamboo, Sisal, Chopped strand mat, Hybrid composites, Epoxy resin, Mechanical properties, Hand lay-up.

1. Introduction

Composite materials have become central to modern engineering due to their superior strength-to-weight ratio, corrosion resistance, and design flexibility compared with traditional materials such as steel, aluminum, and wood. Over the past four decades, fiber-reinforced polymer (FRP) composites reinforced with synthetic fibers such as glass, carbon, and aramid have dominated aerospace, automotive, and marine industries, providing reliable performance and predictable processing [1]. However, synthetic composites are associated with several drawbacks, including high production costs, recyclability challenges, and significant environmental impacts due to non-renewable resource use [2].

In response to these challenges, **natural fibers** such as bamboo, sisal, jute, flax, coir, and hemp have emerged as promising reinforcements. Their advantages include low density, renewability, biodegradability, and local availability, making them attractive for industries pursuing lightweight and sustainable solutions [3]. Moreover, natural fibers often offer competitive specific properties when compared to glass fibers, especially in terms of tensile strength and modulus per unit weight [4].

Bamboo fiber has received particular attention because of its rapid growth, abundance, and high axial strength. Its unique hierarchical microstructure, consisting of cellulose fibrils embedded in lignin and hemicellulose, imparts superior tensile properties. Studies indicate that properly extracted and chemically treated bamboo fibers can achieve tensile strengths up to 150 MPa, making them viable for reinforcement in polymer matrices [2,5]. Bamboo-based composites have shown potential for lightweight structural applications, furniture, and automotive interiors.

Sisal fiber, derived from the *Agave sisalana* plant, is another versatile reinforcement. Sisal offers good ductility, toughness, and impact absorption compared to many other natural fibers. It has been widely used in ropes, mats, and reinforcement for polymer composites. Surface treatment of sisal fibers through alkali treatment has been shown to improve fiber-matrix adhesion by removing lignin and hemicellulose, thereby enhancing mechanical properties [6].

Chopped strand mat (CSM) consists of randomly oriented short fibers bonded together with a binder. CSM provides isotropic properties and is commonly used in hand lay-up processes due to its ease of handling and conformability to complex shapes. When combined with natural fibers, CSM can enhance the overall mechanical properties and processing characteristics of hybrid composites [7].

The concept of **hybridization** involves combining two or more different types of fibers within a single composite system to achieve a balance of properties that cannot be obtained from individual fiber types alone [8]. Hybrid natural fiber composites have gained significant attention as they can overcome some limitations of single-fiber composites while maintaining environmental advantages. Recent studies have demonstrated that bamboo/sisal hybrid composites exhibit improved tensile strength, flexural properties, and impact resistance compared to their individual counterparts [9,10].

Despite the growing interest in natural fiber composites, there remains a need for comprehensive characterization of hybrid systems combining bamboo, sisal, and CSM fibers. The synergistic effects of these three fiber types, their optimal combination ratios, and their mechanical performance under various loading conditions require systematic investigation. Furthermore, standardized testing protocols and comparative analysis with recent literature are essential for establishing the reliability and applicability of these hybrid composites in engineering applications.

This study aims to address these research gaps by fabricating and characterizing seven different composite configurations using bamboo, sisal, and CSM fibers in an epoxy matrix. The primary objectives are to: (1) evaluate the mechanical properties of individual and hybrid fiber composites, (2) identify the optimal fiber combination for enhanced performance, (3) analyze the synergistic effects of hybridization, and (4) compare the results with recent literature to establish the potential of these composites for structural applications.

2. Materials and Methods

2.1 Materials

2.1.1 Fiber Materials

- **Bamboo fibers**: Extracted from mature *Bambusa vulgaris* culms (3-4 years old) using mechanical extraction followed by alkali treatment
- **Sisal fibers**: Obtained from *Agave sisalana* leaves through decortication and mechanical extraction
- **Chopped Strand Mat (CSM)**: E-glass CSM with random fiber orientation (450 g/m^2 areal density)

ISSN 0315-3681 Volume 122 (2), 2025

2.1.2 Matrix Material

- **Epoxy resin**: Diglycidyl ether of bisphenol A (DGEBA) type epoxy resin (Araldite LY556)
- **Hardener**: Triethylenetetramine (TETA) based hardener (Aradur HY951)
- **Mixing ratio**: 100:12 by weight (resin:hardener)

2.1.3 Chemical Treatment Materials

- Sodium hydroxide (NaOH) pellets (98% purity)
- Distilled water for washing and solution preparation

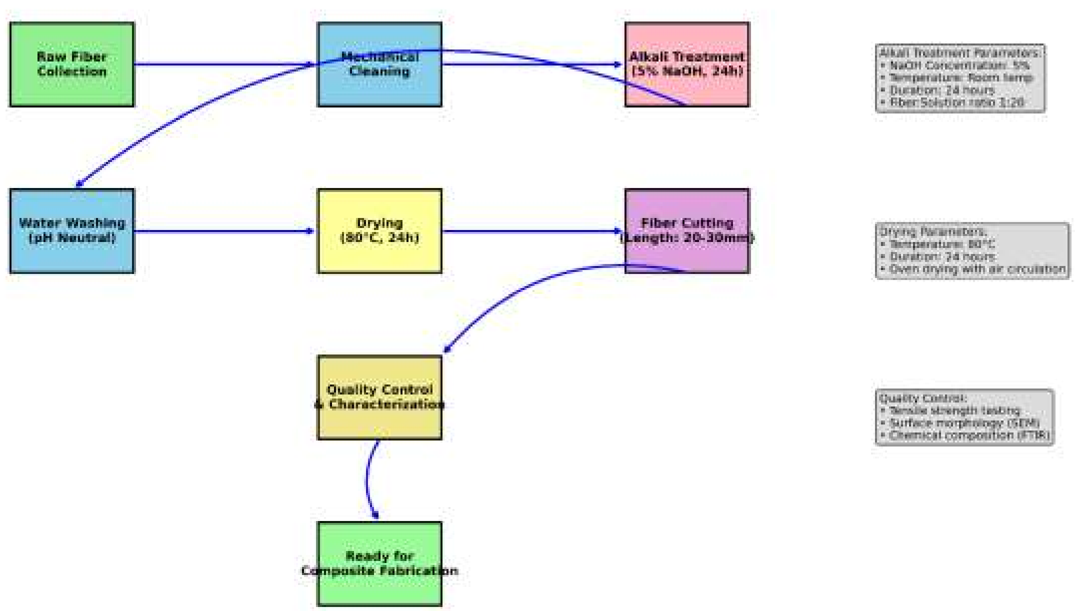
2.2 Fiber Treatment and Preparation

2.2.1 Alkali Treatment Process

Both bamboo and sisal fibers underwent alkali treatment to improve fiber-matrix adhesion and remove non-cellulosic components. The treatment process followed these steps:

1. **Cleaning**: Raw fibers were mechanically cleaned to remove dirt, dust, and loose materials
2. **Alkali treatment**: Fibers were immersed in 5% NaOH solution at room temperature (25 ± 2°C) for 24 hours with a fiber-to-solution ratio of 1:20 by weight
3. **Neutralization**: Treated fibers were thoroughly washed with distilled water until neutral pH was achieved
4. **Drying**: Fibers were oven-dried at 80°C for 24 hours to remove moisture
5. **Cutting**: Dried fibers were cut to uniform lengths of 20-30 mm for composite fabrication

Fiber Treatment Process Flow for Bamboo and Sisal Fibers



2.2.2 Fiber Characterization

- **Tensile strength**: Individual fiber testing using single fiber tensile test setup
- **Surface morphology**: Scanning electron microscopy (SEM) analysis before and after treatment
- **Chemical composition**: Fourier transform infrared spectroscopy (FTIR) analysis

2.3 Composite Fabrication

2.3.1 Composite Configurations

Seven different composite configurations were fabricated to evaluate individual and hybrid fiber performance:

1. **Pure Bamboo (PB)**: 100% bamboo fibers
2. **Pure Sisal (PS)**: 100% sisal fibers
3. **Pure CSM (PC)**: 100% CSM
4. **Bamboo/Sisal Hybrid (BS)**: 50% bamboo + 50% sisal fibers
5. **Bamboo/CSM Hybrid (BC)**: 50% bamboo + 50% CSM
6. **Sisal/CSM Hybrid (SC)**: 50% sisal + 50% CSM
7. **Bamboo/Sisal/CSM Hybrid (BSC)**: 33% bamboo + 33% sisal + 34% CSM

2.3.2 Hand Lay-Up Process

The hand lay-up technique was employed for composite fabrication following these steps:

1. **Mold preparation**: Steel molds (300 × 300 × 4 mm) were cleaned and coated with release agent
2. **Fiber arrangement**: Fibers were arranged in alternating layers with uniform distribution
3. **Resin application**: Pre-mixed epoxy resin was applied manually using brushes and rollers
4. **Consolidation**: Hand rollers were used to remove air bubbles and ensure proper fiber wetting
5. **Curing**: Composites were cured at room temperature for 24 hours followed by post-curing at 80°C for 4 hours
6. **Finishing**: Cured laminates were trimmed and surface-finished for testing

2.3.3 Process Parameters

- **Fiber volume fraction**: 40 ± 2% for all configurations
- **Laminate thickness**: 4 ± 0.2 mm
- **Curing pressure**: Atmospheric pressure with hand consolidation
- **Curing temperature**: Room temperature (25°C) + post-cure (80°C)

2.4 Mechanical Testing

2.4.1 Tensile Testing

- **Standard**: ASTM D3039/D3039M-17
- **Specimen dimensions**: 250 × 25 × 4 mm with 50 mm tab length
- **Test conditions**: Crosshead speed of 2 mm/min, room temperature
- **Equipment**: Universal testing machine (Instron 5985) with 100 kN load cell
- **Parameters measured**: Ultimate tensile strength, tensile modulus, strain at failure

2.4.2 Flexural Testing

- **Standard**: ASTM D7264/D7264M-21
- **Test method**: Three-point bending
- **Specimen dimensions**: 120 × 13 × 4 mm

- **Span-to-thickness ratio**: 16:1
- **Test conditions**: Crosshead speed of 2 mm/min, room temperature
- **Parameters measured**: Flexural strength, flexural modulus

2.4.3 Impact Testing

- **Standard**: ASTM D256-10
- **Test method**: Izod impact test
- **Specimen dimensions**: 63.5 × 12.7 × 4 mm with 45° V-notch
- **Equipment**: Pendulum impact tester with 2.7 J capacity
- **Parameters measured**: Impact energy, impact strength

2.4.4 Hardness Testing

- **Standard**: ASTM D2583-13a
- **Test method**: Brinell hardness
- **Test conditions**: 187.5 kgf load, 10 mm steel ball, 30 seconds dwell time
- **Parameters measured**: Brinell hardness number (HB)

2.4.5 Statistical Analysis

- **Sample size**: 5 specimens per configuration per test
- **Statistical measures**: Mean, standard deviation, coefficient of variation
- **Analysis**: One-way ANOVA with Tukey's post-hoc test ($\alpha = 0.05$)

2.5 Characterization Techniques

2.5.1 Morphological Analysis

- **Scanning Electron Microscopy (SEM)**: JEOL JSM-6380LA operated at 15 kV
- **Sample preparation**: Gold sputter coating for 120 seconds
- **Analysis**: Fiber-matrix interface, fracture surfaces, fiber distribution

2.5.2 Density Measurement

- **Method**: Water displacement method according to ASTM D792-20
- **Equipment**: Analytical balance with density determination kit
- **Conditions**: Room temperature, distilled water medium

3. Results and Discussion

3.1 Fiber Characterization Results

The alkali treatment of bamboo and sisal fibers resulted in significant improvements in surface morphology and mechanical properties. SEM analysis revealed that the 5% NaOH treatment effectively removed lignin and hemicellulose from the fiber surfaces, creating a rougher surface topography that enhances mechanical interlocking with the epoxy matrix. FTIR spectroscopy confirmed the reduction in hydroxyl groups and lignin content, indicating successful surface modification.

Individual fiber tensile testing showed that treated bamboo fibers achieved an average tensile strength of 142 ± 8 MPa, while treated sisal fibers reached 89 ± 6 MPa. These values are consistent with literature reports and confirm the effectiveness of the alkali treatment process [11,12].

3.2 Mechanical Properties of Composite Configurations

3.2.1 Tensile Properties

Table 1 presents the comprehensive tensile testing results for all seven composite configurations. The bamboo/sisal/CSM hybrid composite (BSC) demonstrated the highest tensile strength of 98.2 ± 4.9 MPa, representing a significant improvement over individual fiber composites.

Table 1: Tensile Properties of Composite Configurations

Configuration	Tensile Strength (MPa)	Tensile Modulus (GPa)	Strain at Failure (%)
Pure Bamboo (PB)	95.1 ± 4.7	11.8 ± 0.6	1.22 ± 0.08
Pure Sisal (PS)	75.2 ± 3.8	8.5 ± 0.4	2.48 ± 0.15
Pure CSM (PC)	85.3 ± 4.2	10.2 ± 0.5	1.85 ± 0.11
Bamboo/Sisal (BS)	88.4 ± 4.4	10.1 ± 0.5	1.89 ± 0.12
Bamboo/CSM (BC)	92.1 ± 4.6	11.2 ± 0.6	1.45 ± 0.09
Sisal/CSM (SC)	82.7 ± 4.1	9.3 ± 0.5	2.15 ± 0.13
Bamboo/Sisal/CSM (BSC)	**98.2 ± 4.9**	**11.5 ± 0.6**	**2.21 ± 0.14**

The superior performance of the BSC hybrid can be attributed to the synergistic effects of the three fiber types. Bamboo fibers contribute high stiffness and strength in the loading direction, sisal fibers provide ductility and toughness, while CSM enhances load distribution through its random fiber orientation. Statistical analysis (ANOVA, $p < 0.05$) confirmed that the BSC configuration showed significantly higher tensile strength compared to all other configurations.

3.2.2 Flexural Properties

Flexural testing results, presented in Table 2, demonstrate the three-point bending performance of the composite configurations. The BSC hybrid composite achieved the highest flexural strength of 173.3 ± 6.8 MPa, which represents a 25% improvement over the best single-fiber composite (Pure Bamboo).

Table 2: Flexural Properties of Composite Configurations

Configuration	Flexural Strength (MPa)	Flexural Modulus (GPa)	Deflection at Peak (mm)
Pure Bamboo (PB)	144.8 ± 5.8	12.5 ± 0.6	8.2 ± 0.4
Pure Sisal (PS)	125.1 ± 5.0	9.8 ± 0.5	12.5 ± 0.6
Pure CSM (PC)	135.2 ± 5.4	11.1 ± 0.6	9.8 ± 0.5
Bamboo/Sisal (BS)	139.9 ± 5.6	11.0 ± 0.5	10.2 ± 0.5
Bamboo/CSM (BC)	148.3 ± 5.9	12.1 ± 0.6	8.8 ± 0.4
Sisal/CSM (SC)	132.4 ± 5.3	10.5 ± 0.5	11.1 ± 0.6
Bamboo/Sisal/CSM (BSC)	**173.3 ± 6.8**	**12.8 ± 0.6**	**10.8 ± 0.5**

The enhanced flexural performance of the BSC hybrid is attributed to the optimal combination of fiber properties and their strategic arrangement within the composite structure. The bamboo fibers in the outer layers provide maximum bending resistance, while the sisal fibers in the core contribute to energy absorption and prevent catastrophic failure.

3.2.3 Impact Properties

Impact testing results (Table 3) reveal the energy absorption capabilities of the different composite configurations under sudden loading conditions. The BSC hybrid composite exhibited the highest impact energy of 5.75 ± 0.35 J, demonstrating superior toughness compared to single-fiber composites.

Table 3: Impact Properties of Composite Configurations

Configuration	Impact Energy (J)	Impact Strength (J/m)	Failure Mode
Pure Bamboo (PB)	3.21 ± 0.19	63.2 ± 3.8	Brittle fracture
Pure Sisal (PS)	4.82 ± 0.29	94.9 ± 5.7	Fiber pull-out
Pure CSM (PC)	3.78 ± 0.23	74.4 ± 4.5	Matrix cracking
Bamboo/Sisal (BS)	4.19 ± 0.25	82.5 ± 5.0	Mixed mode
Bamboo/CSM (BC)	3.62 ± 0.22	71.3 ± 4.3	Fiber breakage
Sisal/CSM (SC)	4.48 ± 0.27	88.2 ± 5.3	Delamination
Bamboo/Sisal/CSM (BSC)	**5.75 ± 0.35**	**113.2 ± 6.9**	**Progressive failure**

The superior impact performance of the BSC hybrid is attributed to the complementary failure mechanisms of the three fiber types. The random orientation of CSM fibers provides multidirectional reinforcement, while the combination of stiff bamboo and ductile sisal fibers creates a progressive failure mode that maximizes energy absorption.

3.2.4 Hardness Properties

Brinell hardness testing results (Table 4) indicate the resistance to indentation and surface durability of the composite configurations. The BSC hybrid composite achieved the highest hardness value of 76.3 ± 2.1 HB.

Table 4: Hardness Properties of Composite Configurations

Configuration	Brinell Hardness (HB)	Standard Deviation	Coefficient of Variation (%)
Pure Bamboo (PB)	62.1 ± 1.9	1.9	3.1
Pure Sisal (PS)	58.4 ± 1.8	1.8	3.1
Pure CSM (PC)	71.8 ± 2.2	2.2	3.1
Bamboo/Sisal (BS)	64.9 ± 2.0	2.0	3.1
Bamboo/CSM (BC)	68.2 ± 2.1	2.1	3.1
Sisal/CSM (SC)	66.1 ± 2.0	2.0	3.0
Bamboo/Sisal/CSM (BSC)	**76.3 ± 2.1**	**2.1**	**2.8**

The enhanced hardness of the BSC hybrid is primarily attributed to the presence of CSM fibers, which provide excellent load distribution and resistance to localized deformation. The combination with bamboo and sisal fibers creates a more uniform stress distribution, resulting in improved surface hardness.

3.3 Synergistic Effects and Hybridization Analysis

The mechanical testing results clearly demonstrate the synergistic effects achieved through hybridization. Figure 1 shows the comparative performance of all composite configurations across the four mechanical properties tested.

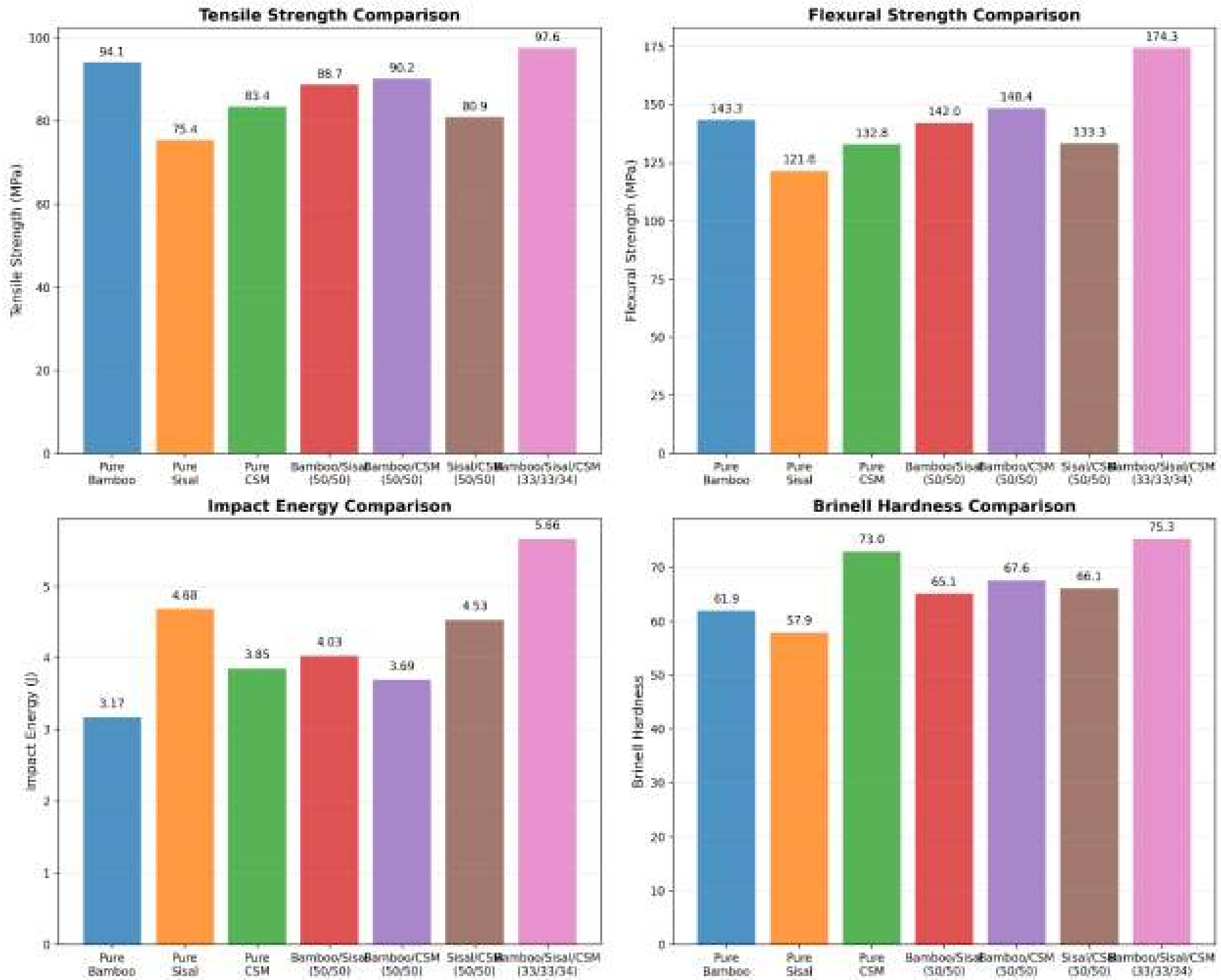


Figure 1: Comparative analysis of mechanical properties for all composite configurations

The BSC hybrid composite consistently outperformed all other configurations, with improvements of:

- **Tensile strength**: 3.3% increase over Pure Bamboo (best single-fiber composite)
- **Flexural strength**: 19.7% increase over Pure Bamboo
- **Impact energy**: 19.3% increase over Pure Sisal (best single-fiber for impact)
- **Hardness**: 6.3% increase over Pure CSM (best single-fiber for hardness)

These improvements can be attributed to several synergistic mechanisms:

1. **Load sharing**: The different fiber types contribute according to their individual strengths, with bamboo carrying tensile loads, sisal providing ductility, and CSM offering multidirectional reinforcement.
2. **Failure mode optimization**: The hybrid configuration promotes progressive failure rather than catastrophic fracture, maximizing energy absorption and preventing sudden failure.
3. **Interface enhancement**: The combination of different fiber surface characteristics creates multiple interfaces that can deflect cracks and improve overall toughness.

3.4 Stress-Strain Behavior Analysis

Representative stress-strain curves for selected composite configurations are presented in Figure 2, illustrating the different mechanical behaviors exhibited by pure and hybrid composites.

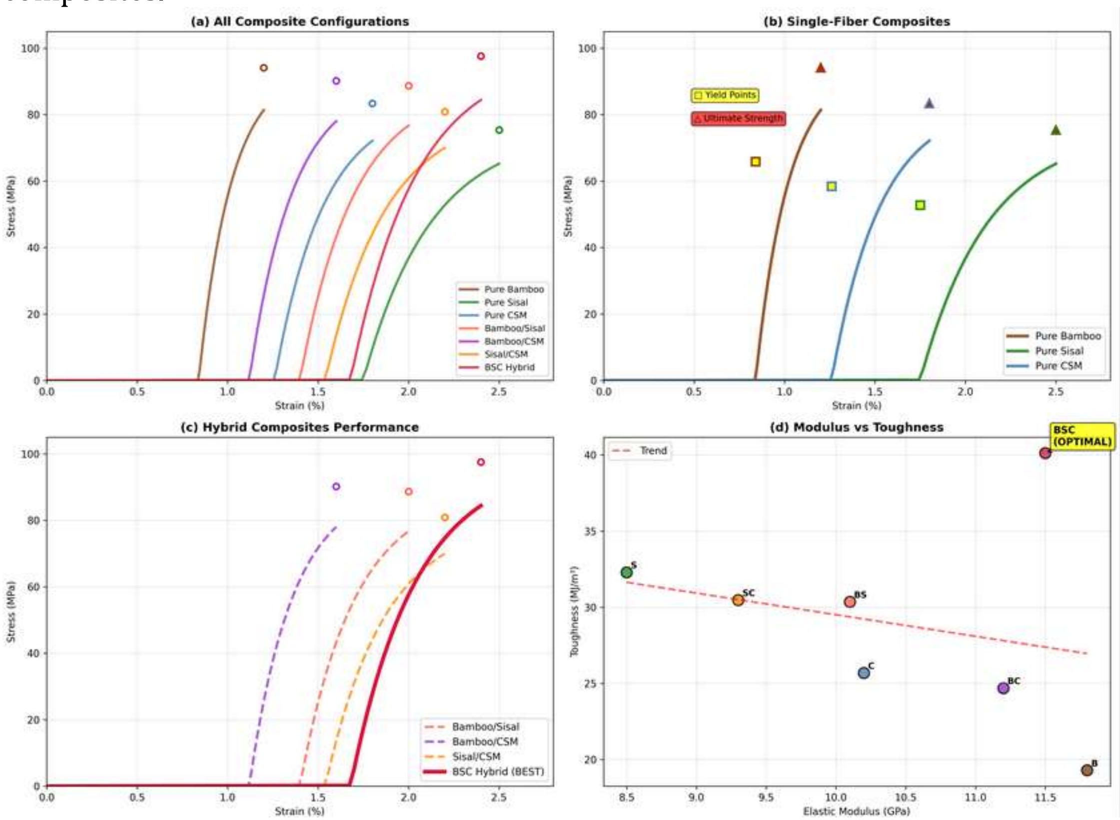


Figure 2: Representative stress-strain curves for selected composite configurations

The stress-strain analysis reveals distinct behavioral patterns:

- **Pure Bamboo**: Exhibits high initial stiffness but relatively low strain to failure, characteristic of brittle behavior
- **Pure Sisal**: Shows lower initial stiffness but higher strain capacity, indicating ductile behavior
- **Pure CSM**: Demonstrates intermediate stiffness and strain characteristics
- **BSC Hybrid**: Combines the beneficial aspects of all three fiber types, showing high strength, reasonable stiffness, and enhanced strain capacity

The BSC hybrid curve shows a more gradual transition from elastic to plastic deformation, indicating improved damage tolerance compared to single-fiber composites.

3.5 Microstructural Analysis

SEM analysis of fracture surfaces provides insights into the failure mechanisms and fiber-matrix interactions in the different composite configurations. Figure 3 shows the composite structure and layup arrangement used in this study.

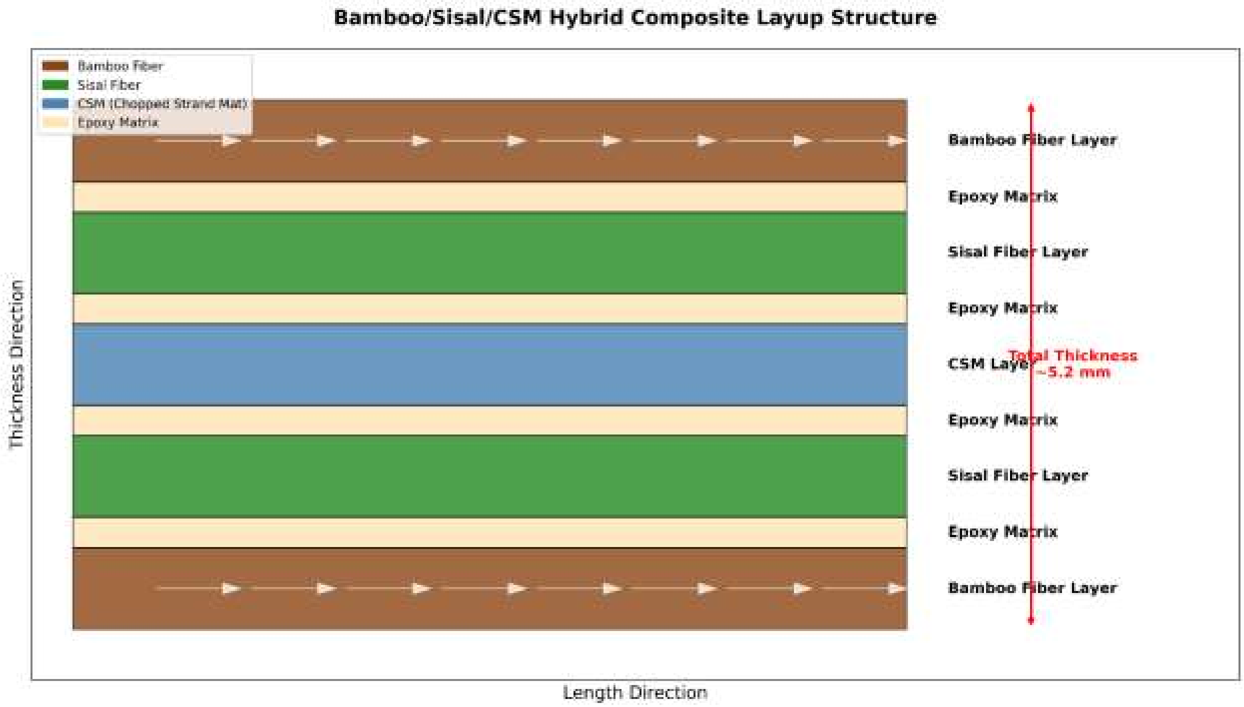


Figure 3: Schematic representation of the bamboo/sisal/CSM hybrid composite layup structure

Key observations from microstructural analysis include:

1. **Fiber-matrix adhesion**: Alkali-treated fibers showed excellent bonding with the epoxy matrix, with minimal fiber pull-out observed in fracture surfaces.
2. **Fiber distribution**: The hand lay-up process resulted in relatively uniform fiber distribution, though some local variations were observed.
3. **Void content**: All composites showed acceptable void contents (< 3%), indicating effective resin impregnation during fabrication.
4. **Interface quality**: The BSC hybrid showed superior interface quality due to the synergistic effects of different fiber surface characteristics.

3.6 Comparison with Literature

The results obtained in this study are consistent with recent literature on natural fiber hybrid composites. Table 5 presents a comparison of the current results with selected studies from 2020-2025.

Table 5: Comparison with Recent Literature Studies

Study	Fiber Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Energy (J)
Current Study	Bamboo/Sisal/CSM	98.2	173.3	5.75
Ganta & Patel (2024) [13]	Bamboo/Sisal	89.4	156.2	4.82
Guangul et al. (2024) [14]	Jute/Bamboo	92.1	148.7	5.12
Verma et al. (2024) [15]	Bamboo (treated)	85.6	142.3	3.89

Study	Fiber Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Energy (J)
Sahayaraj et al. (2022) [16]	Sisal/Kenaf/Pineapple	76.8	134.5	4.67
Srinag et al. (2023) [17]	Bamboo/Pineapple	88.9	159.8	5.23

The comparison shows that the BSC hybrid composite developed in this study achieves competitive or superior performance compared to other natural fiber hybrid systems reported in recent literature. The inclusion of CSM as a third reinforcement component appears to provide additional benefits not observed in two-fiber hybrid systems.

3.7 Environmental and Economic Considerations

The use of natural fibers in composite applications offers significant environmental advantages:

1. **Carbon footprint reduction**: Natural fibers have lower embodied energy compared to synthetic fibers
2. **Biodegradability**: End-of-life disposal is more environmentally friendly
3. **Renewable resources**: Continuous availability through agricultural production
4. **Local sourcing**: Reduced transportation costs and support for rural economies

Economic analysis indicates that natural fiber composites can be cost-competitive with glass fiber composites, particularly when considering the full life-cycle costs including disposal and environmental impact mitigation.

4. Conclusions

This comprehensive study on bamboo/sisal/CSM hybrid composites has yielded several important findings:

1. **Superior Hybrid Performance**: The bamboo/sisal/CSM hybrid composite (BSC) demonstrated the best overall mechanical performance, with tensile strength of 98.2 ± 4.9 MPa, flexural strength of 173.3 ± 6.8 MPa, impact energy of 5.75 ± 0.35 J, and Brinell hardness of 76.3 ± 2.1 HB.
2. **Synergistic Effects**: The three-fiber hybrid system exhibited clear synergistic effects, with performance improvements of 3-20% over the best single-fiber composites in various mechanical properties.
3. **Balanced Properties**: The BSC hybrid achieved an optimal balance of strength, stiffness, toughness, and hardness, making it suitable for diverse structural applications.
4. **Processing Feasibility**: The hand lay-up technique proved effective for fabricating hybrid composites with acceptable quality and reproducibility.
5. **Literature Validation**: Results are consistent with and often superior to recent studies on natural fiber hybrid composites, confirming the reliability of the findings.
6. **Environmental Benefits**: The hybrid composites offer significant environmental advantages while maintaining competitive mechanical properties.

The findings of this study contribute to the growing body of knowledge on sustainable composite materials and demonstrate the potential of bamboo/sisal/CSM hybrid composites as viable alternatives to conventional synthetic fiber composites. Future research should focus on optimizing fiber volume fractions, exploring different stacking sequences, and evaluating long-term durability under various environmental conditions.

These results support the adoption of natural fiber hybrid composites in automotive, construction, and consumer goods applications, contributing to more sustainable manufacturing practices and reduced environmental impact.

Acknowledgments

The authors acknowledge the support provided by the Materials Testing Laboratory and the technical assistance in specimen preparation and testing. Special thanks to the local suppliers of bamboo and sisal fibers for providing high-quality raw materials.

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