Mechanical Behaviour Analysis and Evaluation of Kenaf–Sisal Hybrid Composite Materials

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Abstract - The increasing demand for lightweight, sustainable, and high-performance materials has accelerated the development of natural fiber–reinforced composites. This study investigates the mechanical behaviour and performance evaluation of kenaf–sisal hybrid composite materials fabricated using epoxy resin as the matrix. Kenaf fibers contribute high tensile strength, while sisal fibers enhance toughness and durability, resulting in a balanced hybrid composite system. The composites were fabricated through the hand lay-up technique followed by controlled compression and curing to achieve uniform thickness and improved fiber–matrix bonding. Mechanical characterization was carried out using tensile, flexural, and impact tests in accordance with ASTM standards to evaluate strength, stiffness, and energy absorption capability. In addition, scanning electron microscopy (SEM) was employed to examine fiber distribution, interfacial bonding, and fracture mechanisms. The results demonstrate that the kenaf–sisal hybrid composite exhibits improved mechanical performance compared to single-fiber composites, with enhanced load-bearing capacity and impact resistance. SEM observations confirmed effective resin impregnation and strong fiber–matrix adhesion, contributing to improved mechanical behaviour. The developed hybrid composite offers a lightweight, eco-friendly, and cost-effective alternative to conventional synthetic composites, making it suitable for applications such as automotive interior components and structural panels.

Key Words: Kenaf fiber; Sisal fiber; Hybrid composite; Natural fiber reinforced polymer; Mechanical behaviour; Tensile strength; Flexural strength; Impact resistance; Epoxy matrix; SEM analysis; Sustainable materials; Automotive applications

1. INTRODUCTION

In recent years, there has been a growing demand for lightweight, high-strength, and environmentally sustainable materials in engineering and industrial applications. Conventional synthetic fiber-reinforced composites such as glass, carbon, and aramid fibers offer excellent mechanical properties; however, they are associated with high cost, non-biodegradability, and environmental concerns during production and disposal. These limitations have motivated researchers to explore natural fiber-reinforced polymer composites as viable alternatives due to their renewable nature, low density, biodegradability, and reduced environmental impact.

Natural fibers such as kenaf and sisal have attracted significant attention in composite manufacturing because of their favorable mechanical properties and wide availability. Kenaf fibers are known for their high tensile strength and stiffness, making them suitable for load-bearing applications. Sisal fibers, on the other hand, exhibit good toughness, impact resistance, and durability, contributing to improved energy absorption characteristics in composite structures. Individually, these fibers possess certain limitations; however, combining them in a hybrid configuration can overcome the drawbacks of single-fiber composites and lead to enhanced overall performance.

Hybrid composites reinforced with two or more types of fibers offer the advantage of tailoring mechanical properties by optimizing fiber content, orientation, and stacking sequence. The synergistic interaction between kenaf and sisal fibers within an epoxy matrix can result in improved strength, stiffness, and impact resistance while maintaining low weight and cost. Epoxy resin is commonly used as the matrix material due to its excellent adhesion, chemical resistance, and superior mechanical properties, ensuring effective stress transfer between the fibers and the matrix.

The fabrication technique plays a crucial role in determining the quality and performance of composite materials. Among various methods, the hand lay-up technique remains a simple, cost-effective, and widely used process for producing natural fiber composites. Proper fiber treatment, resin impregnation, and curing conditions are essential to minimize voids, enhance fiber–matrix bonding, and improve mechanical behaviour.

The present study focuses on the mechanical behaviour analysis and evaluation of kenaf–sisal hybrid composite materials fabricated using epoxy resin. Tensile, flexural, and impact tests are conducted in accordance with ASTM standards to assess the strength and stiffness characteristics of the composites. Furthermore, scanning electron microscopy (SEM) is employed to examine fracture surfaces and interfacial bonding mechanisms. The outcomes of this research aim to demonstrate the potential of kenaf–sisal hybrid composites as lightweight, eco-friendly, and cost-effective alternatives to synthetic composites for applications such as automotive interior components and structural panels.

2. PROBLEM STATEMENT

The increasing use of synthetic fiber–reinforced composites in automotive, construction, and industrial applications has raised serious concerns related to environmental sustainability, recyclability, and disposal. Although materials such as glass and carbon fiber composites provide high strength and stiffness, they are expensive, energy-intensive to produce, nonbiodegradable, and contribute to environmental pollution. These limitations create a strong need for alternative materials that can meet mechanical performance requirements while reducing environmental impact and cost.

Natural fiber composites offer an eco-friendly solution; however, composites reinforced with a single type of natural fiber often suffer from limitations such as lower impact resistance, inconsistent mechanical properties, moisture sensitivity, and weak fiber–matrix bonding. These issues restrict their widespread adoption in structural and semi-structural applications. In particular, kenaf fibers exhibit good tensile strength but limited toughness, while sisal fibers provide better impact resistance but lower stiffness when used individually.

There is a lack of comprehensive experimental studies on hybrid natural fiber composites that combine kenaf and sisal fibers to exploit their complementary properties. The optimal fiber ratio, orientation, and interfacial bonding conditions required to achieve balanced mechanical performance are not well established. Additionally, limited microstructural analysis exists to correlate fracture mechanisms with mechanical behaviour in kenaf–sisal hybrid systems.

Therefore, the primary problem addressed in this study is the development and evaluation of a kenaf–sisal hybrid composite that overcomes the limitations of single-fiber natural composites while providing improved tensile, flexural, and impact properties. This research aims to experimentally investigate the mechanical behaviour and fracture characteristics of the hybrid composite and assess its feasibility as a sustainable and cost-effective alternative to synthetic composites for engineering applications.

3. NEED FOR THE STUDY

The growing emphasis on sustainable development and environmental conservation has created a strong demand for eco-friendly materials that can replace conventional synthetic composites in engineering applications. Synthetic fiber–reinforced composites, although mechanically superior, pose serious challenges such as high manufacturing costs, non-biodegradability, difficulty in recycling, and environmental pollution. These concerns highlight the urgent need to develop alternative materials that are lightweight, cost-effective, and environmentally sustainable without significantly compromising mechanical performance.

Natural fiber–reinforced composites offer significant advantages, including renewability, low density, biodegradability, and reduced carbon footprint. However, composites reinforced with a single natural fiber often exhibit limitations such as inadequate impact resistance, variability in mechanical properties, moisture absorption, and weak fiber–matrix interfacial bonding. These shortcomings restrict their use in structural and semi-structural applications where consistent and reliable performance is essential.

Hybridization of natural fibers is an effective approach to overcome the limitations of single-fiber composites by combining fibers with complementary mechanical characteristics. Kenaf fibers provide high tensile strength and stiffness, while sisal fibers contribute improved toughness and impact resistance. Despite the potential benefits, limited experimental research is available on kenaf–sisal hybrid composites, particularly in terms of mechanical behaviour, fracture mechanisms, and structure–property relationships.

Therefore, this study is necessary to systematically investigate the mechanical performance of kenaf–sisal hybrid composites fabricated using an epoxy matrix. The study aims to establish the influence of fiber hybridization on tensile, flexural, and impact properties and to correlate microstructural features observed through scanning electron microscopy (SEM) with mechanical behaviour. The outcomes of this research are expected to support the development of sustainable, high-performance natural fiber composites suitable for applications such as automotive interior components, construction panels, and lightweight structural materials.

4. LITERATURE REVIEW

In recent years, extensive research has been carried out on natural fiber–reinforced polymer composites as sustainable alternatives to synthetic composites. Researchers have reported that natural fibers such as jute, kenaf, sisal, flax, and hemp offer advantages including low density, renewability, biodegradability, and reduced environmental impact. However, their mechanical performance is often lower and more inconsistent compared to synthetic fibers, which limits their application in high-load-bearing components.

Several studies have focused on kenaf fiber–reinforced polymer composites due to their high tensile strength and stiffness. Researchers have shown that kenaf fibers can significantly improve tensile and flexural properties when properly bonded with polymer matrices such as epoxy or polyester. However, kenaf-based composites tend to exhibit limited impact resistance and brittle failure behavior, especially under dynamic loading conditions. Moisture absorption and weak interfacial bonding have also been identified as key challenges affecting long-term durability.

Sisal fiber–reinforced composites have been widely studied for their toughness, impact resistance, and good energy absorption capability. Literature indicates that sisal fibers improve crack resistance and delay failure under bending and impact loads. Nevertheless, sisal composites often show lower stiffness and tensile strength compared to other natural fibers, which restricts their use in structural applications where high strength is required.

To overcome the limitations of single-fiber composites, researchers have explored hybrid natural fiber composites by combining two or more types of fibers. Hybridization has been reported to enhance mechanical performance by exploiting the complementary properties of different fibers. Studies on hybrid systems such as jute–sisal, kenaf–jute, and flax–sisal composites have demonstrated improvements in tensile, flexural, and impact properties compared to mono-fiber composites. The stacking sequence, fiber orientation, and fiber volume fraction were found to play a significant role in determining the overall mechanical behavior of hybrid composites.

Epoxy resin is commonly used as a matrix material in natural fiber composites due to its excellent adhesion, chemical resistance, and superior mechanical properties. Researchers have highlighted that proper fiber surface preparation, resin impregnation, and curing conditions are essential to minimize voids and improve fiber–matrix bonding. Advanced characterization techniques such as scanning electron microscopy (SEM) have been extensively employed to study fracture mechanisms, fiber pull-out, debonding, and void formation, providing valuable insights into failure behavior.

Despite the growing body of research on hybrid natural fiber composites, limited studies have specifically investigated kenaf–sisal hybrid composites with detailed mechanical testing and microstructural analysis. There is a lack of comprehensive experimental data correlating mechanical performance with fiber orientation, hybrid ratio, and fracture morphology. Therefore, further investigation is required to establish the mechanical behaviour and application potential of kenaf–sisal hybrid composites as sustainable alternatives to synthetic composites.

5. METHODOLOGY

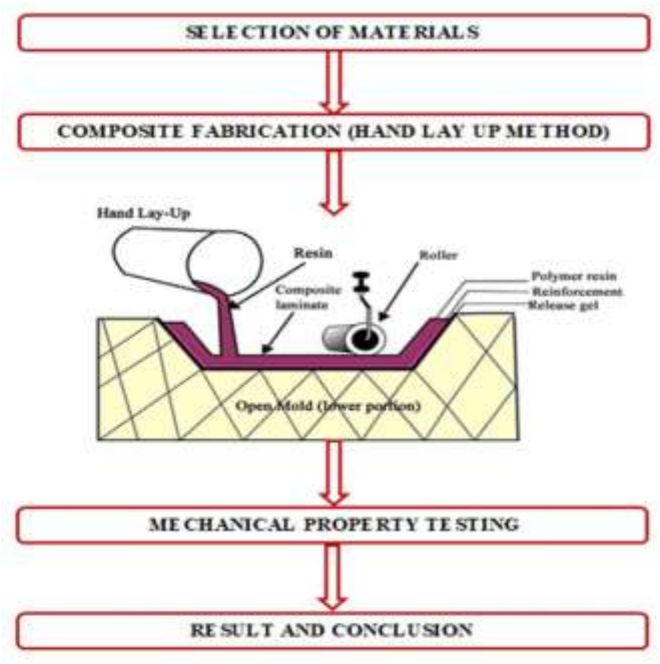

Fig-1: Block Diagram

The methodology adopted for the mechanical behaviour analysis of kenaf–sisal hybrid composite materials consists of systematic steps, including material selection, composite fabrication, specimen preparation, mechanical testing, and result evaluation.

Initially, suitable materials were selected for composite fabrication. Kenaf and sisal fibers were chosen as reinforcement materials due to their lightweight nature, good mechanical properties, availability, and environmental sustainability. Epoxy resin was selected as the matrix material because of its excellent bonding characteristics, high strength, and chemical resistance. The fibers were cleaned, dried, and cut to the required lengths to ensure uniformity and effective bonding with the matrix.

The hybrid composite laminates were fabricated using the hand lay-up method, which is a simple and cost-effective technique for producing natural fiber composites. A mold surface was first prepared by applying a release agent to prevent sticking. The epoxy resin and hardener were mixed in the recommended ratio to obtain a uniform resin mixture. Kenaf and sisal fibers were then arranged in the desired orientation and stacking sequence inside the mold. Each fiber layer was thoroughly impregnated with the resin mixture using brushes and rollers to ensure complete wetting and proper fiber–matrix adhesion. Rolling action was applied to remove entrapped air bubbles and excess resin, minimizing void formation. After lay-up, the laminate was subjected to uniform compression and allowed to cure at room temperature for a specified duration to achieve proper solidification.

Once curing was completed, the composite laminate was carefully removed from the mold and trimmed to obtain smooth edges. Standard test specimens were prepared according to ASTM standards for mechanical testing. Tensile test specimens were prepared as per ASTM D3039, flexural test specimens as per ASTM D790, and impact test specimens as per ASTM D256.

Mechanical property evaluation was carried out using a Universal Testing Machine (UTM) for tensile and flexural tests, while impact strength was determined using a pendulum-type impact testing machine. The tensile test provided information on tensile strength, modulus, and elongation, whereas the flexural test evaluated bending strength and stiffness. Impact testing measured the energy absorption capability and toughness of the composite.

After mechanical testing, the fractured specimens were examined using scanning electron microscopy (SEM) to study fiber–matrix bonding, fiber pull-out, voids, and failure mechanisms. Finally, the experimental results were analyzed and correlated with microstructural observations to evaluate the overall mechanical behaviour of the kenaf–sisal hybrid composite and to draw meaningful conclusions regarding its performance and application potential.

6. MATERIALS

The materials selected for the fabrication of the kenaf–sisal hybrid composite were chosen based on their mechanical properties, availability, cost-effectiveness, and environmental sustainability. The composite system consists of natural fibers as reinforcement and a thermosetting polymer as the matrix material.

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6.1 Kenaf Fiber

Fig-2: Kenaf Fiber

Kenaf fiber was used as one of the primary reinforcement materials due to its high tensile strength, low density, and good stiffness compared to many other natural fibers. Kenaf fibers are derived from renewable plant sources and exhibit favorable load-bearing characteristics, making them suitable for structural and semi-structural composite applications. In addition, kenaf fibers offer advantages such as biodegradability, low cost, and reduced environmental impact.

6.2 Sisal Fiber

Fig-3: Sisal Fiber

Sisal fiber was selected as the secondary reinforcement material to improve the toughness and impact resistance of the composite. Sisal fibers are known for their good durability, abrasion resistance, and energy absorption capability. The incorporation of sisal fibers complements the mechanical performance of kenaf fibers by enhancing crack resistance and delaying failure under dynamic and bending loads. Sisal fibers are also environmentally friendly, readily available, and economically viable.

6.3 Epoxy Resin

Fig-4: Epoxy Resin

Epoxy resin was used as the matrix material due to its excellent adhesion to natural fibers, high mechanical strength, and good chemical and thermal stability. The epoxy matrix ensures effective stress transfer between the fibers and provides structural integrity to the composite. A compatible hardener was used to initiate the curing process and achieve complete polymerization of the resin.

6.4 Release Agent and Accessories

A suitable mold release agent was applied to the mold surface to facilitate easy removal of the cured composite laminate. Additional accessories such as brushes, rollers, and molds were used during the hand lay-up process to ensure uniform resin distribution, proper fiber wetting, and void-free composite fabrication.

The selected combination of kenaf and sisal fibers with an epoxy matrix enables the development of a hybrid composite material that offers a balance of strength, toughness, sustainability, and cost-effectiveness for engineering applications.

7. WORKING PRINCIPLE

The working principle of the kenaf–sisal hybrid composite is based on effective load transfer between natural fiber reinforcements and the epoxy matrix through strong interfacial bonding. The composite functions by combining the individual advantages of kenaf and sisal fibers within a polymer matrix to achieve enhanced mechanical performance.

During fabrication using the hand lay-up method, layers of kenaf and sisal fibers are placed in a predefined sequence inside the mold. Epoxy resin mixed with a suitable hardener is applied to each layer to ensure complete wetting of the fibers. The resin penetrates the fiber network and surrounds the fibers, forming a continuous matrix phase after curing. Rolling action removes entrapped air and excess resin, resulting in a dense and uniform laminate.

Once cured, the epoxy matrix binds the fibers together and transfers externally applied loads to the reinforcement fibers. Under tensile loading, the applied force is distributed from the epoxy matrix to the kenaf fibers, which primarily resist axial stresses due to their high tensile strength. Sisal fibers contribute to delaying crack initiation and propagation, thereby improving toughness and energy absorption. The hybridization effect ensures balanced stress distribution and reduced stress concentration within the composite.

During flexural loading, the composite resists bending through combined action of fiber reinforcement and matrix stiffness. Kenaf fibers enhance bending strength and stiffness, while sisal fibers improve resistance to crack growth on the tensile side of the specimen. Under impact loading, sisal fibers absorb sudden energy through fiber stretching and pull-out mechanisms, whereas the epoxy matrix maintains structural integrity.

The mechanical behaviour of the composite is strongly influenced by fiber orientation, volume fraction, and fiber–matrix adhesion. Scanning electron microscopy (SEM) reveals the failure mechanisms such as fiber pull-out, matrix cracking, and interfacial debonding, which explain the observed mechanical performance. Overall, the kenaf–sisal hybrid composite operates on the principle of synergistic reinforcement, where the combined fibers provide superior strength, stiffness, and toughness compared to single-fiber composites.

8. COMPOSITE FABRICATION PROCESS

The kenaf–sisal hybrid composite laminates were fabricated using the hand lay-up method, which is a simple, cost-effective, and widely adopted technique for manufacturing natural fiber–reinforced polymer composites. This method allows effective control over fiber placement, orientation, and resin impregnation.

Initially, a suitable mold was selected and thoroughly cleaned to remove dust and surface contaminants. A mold release agent was uniformly applied to the mold surface to facilitate easy demolding of the composite laminate after curing. Kenaf and sisal fibers were cleaned, dried, and cut to the required dimensions. The fibers were then arranged according to the predetermined hybrid stacking sequence and orientation to achieve balanced mechanical properties.

Epoxy resin and hardener were mixed in the manufacturer-recommended ratio to obtain a homogeneous resin mixture. The resin mixture was slowly stirred to minimize air entrapment. During the lay-up process, the first layer of fiber reinforcement was placed inside the mold, followed by the application of epoxy resin using brushes. Each fiber layer was thoroughly impregnated to ensure complete wetting. Subsequent layers of kenaf and sisal fibers were placed alternately, and resin was applied after each layer.

A hand roller was used to compact the laminate and remove entrapped air bubbles and excess resin, thereby reducing void content and improving fiber–matrix adhesion. After completing the lay-up, the laminate was subjected to uniform compression using controlled weights or a hydraulic press to maintain consistent thickness and improve consolidation.

The fabricated laminate was allowed to cure at room temperature for approximately 48 hours to achieve initial solidification. Post-curing was then carried out at an elevated temperature to complete the polymerization process and enhance the mechanical and thermal stability of the composite. After curing, the composite panel was carefully demolded, trimmed, and finished to obtain a smooth surface. Standard test specimens were machined from the laminate according to ASTM standards for subsequent mechanical testing.

9. TEST AND ANALYSIS PROCEDURE

After fabrication and curing of the kenaf–sisal hybrid composite laminates, mechanical testing was carried out to evaluate their strength, stiffness, and energy absorption characteristics. All test specimens were prepared according to relevant ASTM standards to ensure accuracy and repeatability of results.

9.1 Tensile Testing

Tensile tests were conducted using a Universal Testing Machine (UTM) in accordance with ASTM D3039. The specimens were mounted securely between the grips of the testing machine, and a uniaxial tensile load was applied at a constant crosshead speed until failure occurred. Load and displacement data were recorded continuously during the test. Tensile strength, Young's modulus, and percentage elongation were calculated from the stress–strain curves. The tensile behaviour provided insight into load-bearing capacity and fiber–matrix stress transfer efficiency.

9.2 Flexural Testing

Flexural properties were evaluated using a three-point bending test as per ASTM D790. Each specimen was placed on two supports with a specified span length, and a load was applied at the center at a constant rate. The maximum load at failure and corresponding deflection were recorded. Flexural strength and flexural modulus were determined to assess bending resistance and stiffness of the composite. The test also highlighted the influence of fiber orientation on bending performance.

9.3 Impact Testing

Impact strength was measured using a pendulum-type impact testing machine following ASTM D256. Notched specimens were subjected to a sudden impact load, and the energy absorbed during fracture was recorded. This test evaluated the toughness and impact resistance of the composite, indicating its ability to withstand sudden and dynamic loads.

9.4 Microstructural Analysis

After mechanical testing, fractured specimens from tensile, flexural, and impact tests were collected for microstructural examination. Scanning Electron Microscopy (SEM) was used to observe fiber–matrix interfacial bonding, fiber pull-out, matrix cracking, voids, and fracture patterns. SEM analysis helped correlate the observed failure mechanisms with the measured mechanical properties.

9.5 Data Analysis

The experimental results were analyzed and compared for different fiber combinations and orientations. Average values were calculated from multiple specimens to ensure reliability. The mechanical performance was correlated with microstructural observations to understand the influence of hybridization on strength and failure behaviour. Based on the analysis, conclusions were drawn regarding the suitability of kenaf–sisal hybrid composites for structural and automotive applications.

10. RESULTS AND DISCUSSION

The mechanical performance of the fabricated kenaf–sisal hybrid composite laminates was evaluated through tensile, flexural, and impact testing in accordance with ASTM standards. The experimental results demonstrate the effectiveness of hybridization in improving the overall mechanical behaviour of natural fiber–reinforced composites. The influence of fiber reinforcement, interfacial bonding, and fiber orientation on the mechanical properties is discussed in this section.

10.1 Tensile Properties

The tensile test results indicate that the kenaf–sisal hybrid composite exhibits improved tensile strength and modulus compared to single natural fiber composites. The presence of kenaf fibers significantly contributes to load-bearing capacity due to their higher tensile strength, while sisal fibers help in delaying crack initiation and propagation. The stress–strain curves show a gradual failure behaviour, indicating effective stress transfer between the epoxy matrix and the fibers. Improved fiber–matrix adhesion achieved during the hand lay-up process resulted in enhanced tensile performance and reduced premature failure.

10.2 Flexural Properties

Flexural testing revealed that the hybrid composite possesses good bending strength and stiffness. Under three-point bending, the composite demonstrated resistance to crack formation on the tensile side of the specimen. Kenaf fibers primarily enhanced stiffness and bending strength, whereas sisal fibers improved resistance to delamination and crack growth. The synergistic interaction between the two fibers resulted in better flexural performance compared to mono-fiber composites, making the material suitable for structural and semi-structural applications.

10.3 Impact Properties

Impact test results show that the kenaf–sisal hybrid composite has improved energy absorption capacity. The inclusion of sisal fibers increased toughness and impact resistance by absorbing sudden loads through fiber stretching, debonding, and pull-out mechanisms. The hybrid composite exhibited less brittle failure compared to epoxy-based single-fiber composites, indicating its suitability for applications subjected to dynamic and impact loading conditions.

10.4 Scanning Electron Microscopy (SEM) Analysis

SEM analysis of fractured specimens provided insight into the failure mechanisms and microstructural characteristics of the composite. The micrographs revealed good fiber distribution and effective resin impregnation. Limited fiber pull-out and reduced void content confirmed strong interfacial bonding between the fibers and epoxy matrix. Matrix cracking, fiber breakage, and controlled fiber pull-out were observed, which explains the improved mechanical properties of the hybrid composite. The SEM results strongly support the mechanical test findings and highlight the role of fiber hybridization in enhancing performance.

11. ADVANTAGES

Lightweight: The composite reduces overall structural weight compared to metal or synthetic fiber composites, contributing to fuel efficiency and easier handling.

High Mechanical Strength: Exhibits good tensile, flexural, and impact properties due to the synergistic effect of kenaf and sisal fibers.

Eco-Friendly: Made from renewable natural fibers, biodegradable, and environmentally sustainable.

Cost-Effective: Cheaper than synthetic fiber composites like carbon or glass fibers.

Durable: Enhanced toughness and resistance to cracking under mechanical loads.

Versatile: Suitable for structural and semi-structural applications, especially in automotive and construction industries.

12. APPLICATIONS

Automotive Industry: Door panels, dashboard trims, seat components, trunk linings, and roof/floor panels.

Construction and Infrastructure: Lightweight panels, partitions, and decorative elements.

Consumer Products: Packaging materials, furniture components, and household items.

Sports and Recreational Equipment: Panels or shells for bicycles, helmets, or other protective gear.

Industrial Applications: Components requiring moderate load-bearing capacity with impact resistance and reduced weight.

13. CONCLUSION

The present study on kenaf–sisal hybrid composite materials demonstrates that combining natural fibers in a polymer matrix can significantly enhance mechanical performance compared to single-fiber composites. The fabricated hybrid composite exhibited improved tensile strength, flexural strength, and impact resistance, confirming the synergistic effect of kenaf and sisal fibers. Scanning Electron Microscopy (SEM) analysis revealed good fiber–matrix adhesion, uniform fiber distribution, and minimal void content, which contributed to the observed mechanical behaviour. The hybrid composite is lightweight, durable, cost-effective, and environmentally sustainable, making it a promising alternative to conventional synthetic composites. Its favorable mechanical properties and eco-friendly nature suggest potential applications in automotive components, construction materials, and other semi-structural engineering sectors. Overall, the study highlights the feasibility of developing sustainable hybrid composites that balance mechanical performance with environmental considerations.

14. FUTURE SCOPE

Optimization of Fiber Ratios: Future studies can explore different kenaf-to-sisal fiber ratios to identify the optimal combination for specific mechanical properties.

Surface Treatment of Fibers: Chemical or physical treatments such as alkali treatment, silane coupling, or plasma treatment can enhance fiber–matrix adhesion and improve durability.

Hybridization with Other Fibers: Incorporating additional natural or synthetic fibers may further improve strength, stiffness, and impact resistance for specialized applications.

Thermal and Moisture Resistance Studies: Investigation of the composite's behavior under high temperature, humidity, or water absorption will expand its applicability in diverse environments.

Advanced Fabrication Techniques: Techniques like vacuum-assisted resin transfer molding (VARTM) or compression molding can be explored for producing higher-quality laminates with reduced voids.

Industrial Applications: Future work can include real-world testing of components such as automotive panels, construction materials, and sports equipment to validate laboratory findings.

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