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Experimental Investigation Of The Mechanical Behaviour Of Banana–Basalt Reinforced Epoxy Hybrid Laminates

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Abstract

Natural fibres are light, sustainable and high in performance, leading to a rapid growth in the development of natural fibre-based hybrid composites for use in structural engineering applications. In this research, five different fibre stacking sequence hybrid banana–basalt reinforced epoxy laminates were manufactured and the mechanical behaviour of them were investigated experimentally. The laminates were produced using the hand lay-up process and the vacuum bagging process to provide uniform impregnation of resin, enhanced wetting of the fibres and reduced void content. Mechanical property tests were performed using tensile, flexural and impact tests according to the corresponding ASTM standards. The results of the experiments showed that the fibre stacking sequence is an important factor in the mechanical performance of the hybrid laminates. The mechanical performance was greatest for configurations in which the basalt fibre layers were placed on the external surfaces due to their high stiffness, greater load bearing capacity and good stress transfer. Maximum laminate properties were obtained to be ultimate tensile strength of about 185 MPa, flexural strength of 265 MPa, and impact strength of 72 kJ/m2, whereas the minimum laminate properties obtained were 145 MPa, 205 MPa, and 52 kJ/m2 respectively. The improvements are about 28% in tensile strength, 29% in flexural strength and 38% in impact strength. The optimized laminate showed a decrease of fibre pull-out and improved fibre–matrix adhesion, resulting in better load transfer and delayed crack propagation. The outcomes showed that the banana–basalt hybrid composites possess excellent combination of the environmentally friendly natural fibres and the superior mechanical properties of basalt fibres, which make them useful candidates for lightweight applications in automobile, aerospace and general engineering industries.

Keywords: banana fibre; basalt fibre; hybrid composites; epoxy laminates; mechanical properties; stacking sequence; sustainable composites.

1. Introduction

The increasing demand for lightweight, high-strength, and environmentally sustainable materials has accelerated the development of fibre-reinforced polymer (FRP) composites for engineering applications. Although synthetic fibre composites such as glass and carbon fibre-reinforced polymers exhibit excellent mechanical performance, their high production cost, non-biodegradable nature, and environmental concerns have encouraged researchers to explore sustainable alternatives. Natural fibres have gained significant attention due to their low density, biodegradability, renewability, and cost-effectiveness. Among these, banana fibre has emerged as a promising reinforcement because of its high cellulose content, good specific strength, and widespread availability as an agricultural by-product, making it an attractive material for eco-friendly composite development [1,7].

Despite its advantages, banana fibre exhibits certain limitations, including high moisture absorption, poor interfacial bonding with polymer matrices, and relatively lower mechanical strength compared to synthetic fibres [3,4]. Hybridization with high-performance fibres has been recognized as an effective approach to overcome these shortcomings. Basalt fibre, produced from naturally occurring volcanic rock, offers excellent tensile strength, stiffness, thermal stability, corrosion resistance, and environmental compatibility [2,6]. The combination of banana and basalt fibres in an epoxy matrix provides a synergistic effect by enhancing the overall mechanical performance while maintaining reduced weight and improved sustainability. Such hybrid composites have attracted considerable interest for applications in the automotive, aerospace, marine, and construction industries [7].

The performance of hybrid composites is largely governed by factors such as fibre volume fraction, fibre orientation, fabrication technique, and the stacking sequence of reinforcing fibres. Among these parameters, the stacking sequence plays a crucial role in determining load transfer efficiency, stress distribution, crack propagation, and interlaminar bonding within the laminate [5,9]. Positioning high-strength basalt fibres in the outer layers improves tensile and flexural performance by effectively resisting applied loads, while banana fibres contribute to enhanced impact energy absorption and weight reduction. Therefore, optimizing the fibre architecture is essential for achieving a balanced combination of strength, stiffness, toughness, and sustainability in hybrid composite laminates [7,19, 20].

Recent advancements in composite manufacturing have also highlighted the importance of producing defect-free laminates with improved fibre–matrix adhesion. Fabrication methods such as hand lay-up followed by vacuum bagging help reduce void content, ensure uniform resin distribution, and enhance laminate consolidation. Improved interfacial bonding facilitates efficient stress transfer between the fibres and the epoxy matrix, thereby improving the overall mechanical performance and durability of the composite under different loading conditions. These processing techniques have become increasingly popular due to their simplicity, cost-effectiveness, and ability to produce high-quality hybrid composite laminates.

Although several studies have investigated natural fibre hybrid composites, comprehensive research on banana–basalt reinforced epoxy laminates with different stacking configurations remains limited. Most previous investigations have focused on fibre treatment, fibre content, or individual mechanical properties, while comparatively fewer studies have systematically examined the influence of stacking sequence on tensile, flexural, and impact behaviour together with fracture characteristics [8,15, 21]. Therefore, the present study aims to fabricate banana–basalt reinforced epoxy hybrid laminates with five different stacking sequences using the hand lay-up process followed by vacuum bagging. The mechanical performance of the laminates was evaluated through tensile, flexural, and impact testing in accordance with ASTM standards. The findings of this study are expected to contribute to the development of lightweight, sustainable, and high-performance hybrid composites for automotive, aerospace, marine, and structural engineering applications.

2. Materials and Methods

2.1 Materials

The hybrid composite laminates were fabricated using banana fibre, basalt fibre, and epoxy resin as the primary constituent materials. Woven banana fibre mats were selected as the natural reinforcement due to their low density, biodegradability, and good specific mechanical properties. Bidirectional woven basalt fibre mats were used as the synthetic reinforcement because of their superior tensile strength, high stiffness, excellent thermal stability, and corrosion resistance. Epoxy resin (LY 556) with Hardener HY 951 was employed as the matrix material owing to its excellent adhesion, low shrinkage, and good mechanical performance. The epoxy resin and hardener were mixed in a weight ratio of **10:1** as recommended by the manufacturer [20,10, 9].

Table 1. Materials used for composite fabrication

Material	Specification	Purpose
Banana fibre	Woven mat	Natural reinforcement
Basalt fibre	Bidirectional woven mat	High-strength reinforcement
Epoxy resin	LY 556	Matrix material
Hardener	HY 951	Curing agent

2.2 Fabrication of Hybrid Laminates

The banana–basalt reinforced epoxy hybrid laminates were fabricated using the hand lay-up technique followed by vacuum bagging to ensure proper resin impregnation and minimize void formation. Initially, the mould surface was cleaned thoroughly and coated with a releasing agent to facilitate easy removal of the laminate after curing. The epoxy resin and hardener were mixed in the prescribed ratio of 10:1 and stirred uniformly to obtain a homogeneous mixture. Layers of banana and basalt fibre mats were arranged according to the predetermined stacking sequences, and the resin mixture was uniformly applied to each layer using a roller to ensure complete wetting of the fibres [7, 8].

After the lay-up process, the laminate was enclosed within a vacuum bag, and a vacuum pressure of approximately 0.8 bar was applied to remove entrapped air and excess resin. The laminate was cured under vacuum at room temperature for 24 hours, followed by post-curing for 2 hours at 80°C to achieve complete polymerization and improved mechanical properties. After curing, the laminates were removed from the mould and cut into standard test specimens using a diamond cutter according to the relevant ASTM standards.

2.3 Laminate Configuration

To investigate the effect of fibre architecture on the mechanical performance of hybrid composites, five different banana–basalt reinforced epoxy laminate configurations were designed by varying the stacking sequence of banana (BN) and basalt (BS) fibre layers while maintaining a constant laminate thickness and fibre volume fraction. The total number of reinforcement layers was kept constant for all laminate configurations to ensure that the observed variations in mechanical properties were primarily due to the change in fibre arrangement rather than differences in reinforcement content. A fibre volume fraction of approximately 40–45% was maintained throughout the fabrication process, while the remaining volume consisted of the epoxy matrix [13,6].

The stacking sequence was selected based on the expected load-bearing characteristics of the reinforcing fibres. Basalt fibre, possessing higher tensile strength and stiffness, was strategically placed in the outer layers of certain laminates to enhance resistance against tensile and bending stresses, whereas banana fibre was incorporated into the inner layers to improve energy absorption and reduce the overall weight of the laminate [11, 22, 23]. In contrast, some laminates contained banana fibres on the outer surfaces to evaluate the influence of natural fibre positioning on the overall mechanical behaviour. This systematic arrangement enabled a comprehensive comparison of the influence of fibre architecture on tensile, flexural, and impact properties.

The L1 laminate, consisting entirely of basalt fibres, was fabricated as a reference specimen representing maximum mechanical performance due to the superior strength and stiffness of basalt fibres. Conversely, the L5 laminate, reinforced exclusively with banana fibres, served as the natural fibre reference laminate for evaluating the influence of hybridization. The L2, L3, and L4 laminates were designed as hybrid configurations to investigate the effect of different fibre arrangements on mechanical behaviour.

Each laminate was fabricated with four woven fibre layers using the hand lay-up process followed by vacuum bagging. Care was taken to ensure uniform resin impregnation between successive fibre layers and proper alignment of the woven fabrics during the lay-up process. After curing, the laminates were trimmed and machined into standard specimens according to the relevant ASTM standards for mechanical testing. The fabricated laminate configurations are presented in Table 2**.**

Table 2. Stacking sequence of banana–basalt reinforced epoxy hybrid laminates

Specimen No. Layup Sequence	Specimen Thickness (mm)	Specimen No. Layup Sequence
S1	Ba-Ba-Ba-B-B-B-B-B-B-Ba-Ba-Ba	3.2
S2	Ba-Ba-B-B-Ba-B-B-Ba-B-B-Ba-Ba	3.12
S3	Ba-B-Ba-Ba-B-Ba-Ba-B-Ba-Ba-B-Ba	2.98
S4	Ba-B-Ba-B-Ba-Ba-Ba-Ba-B-Ba-B-Ba	3.14
S5	Ba-Ba-B-B-Ba-Ba-Ba-Ba-B-B-Ba-Ba	2.95

2.4 Specimen Preparation and Testing

After the fabrication and curing process, the banana–basalt reinforced epoxy hybrid laminates were carefully removed from the mould and visually inspected to ensure the absence of manufacturing defects such as voids, delamination, resin-rich regions, and fibre misalignment. The laminate edges were subsequently trimmed using a diamond cutter to obtain smooth and uniform surfaces, and the laminates were machined into standard test specimens according to the respective ASTM specifications for tensile, flexural, and impact testing. To ensure dimensional accuracy and consistency, the thickness of each laminate was measured at three different locations using a digital vernier caliper with an accuracy of ±0.01 mm, and the average value was recorded. The fabricated laminates exhibited thicknesses ranging from 2.95 mm to 3.20 mm, indicating good process control and uniform consolidation during fabrication. All specimens were prepared with smooth edges and accurate dimensions to minimize stress concentration during testing and to ensure reliable and repeatable experimental results. A minimum of five specimens from each laminate configuration were tested for every mechanical characterization, and the average values were used for subsequent analysis and discussion.

3. Mechanical characterization

The mechanical characterization of the fabricated banana–basalt reinforced epoxy hybrid laminates was carried out to evaluate the influence of fibre stacking sequence on their structural performance. Tensile, flexural, and impact tests were conducted in accordance with the relevant ASTM standards under ambient laboratory conditions. Before testing, all specimens were conditioned at room temperature to ensure uniform testing conditions. For each laminate configuration, five identical specimens were tested, and the average values were considered for analysis to ensure the repeatability and reliability of the experimental results. The measured mechanical properties were used to compare the effectiveness of different fibre arrangements in improving the load-bearing capacity, stiffness, and energy absorption characteristics of the hybrid laminates.

3.1 Tensile Test

The tensile behaviour of the banana–basalt reinforced epoxy hybrid laminates was evaluated in accordance with ASTM D3039 using a Universal Testing Machine (UTM). The test specimens were prepared with dimensions of 250 mm × 25 mm × 3 mm, and the specimen edges were carefully finished to eliminate stress concentration effects. Prior to testing, the specimen dimensions were measured accurately using a digital vernier caliper, and the cross-sectional area was calculated. The specimens were securely clamped between the grips of the UTM, ensuring proper alignment to prevent bending or eccentric loading during the test.

The tensile tests were performed under ambient laboratory conditions at a constant crosshead speed of 2 mm/min until complete specimen failure. During the test, the applied load and corresponding displacement were continuously recorded by the data acquisition system of the UTM. The engineering stress–strain curves were generated from the recorded data, and the tensile strength, Young's modulus, and percentage elongation at break were determined for each laminate configuration. To ensure the accuracy and repeatability of the results, five specimens were tested for each stacking sequence, and the average values were reported. The tensile test was conducted to investigate the influence of fibre stacking sequence on the load-bearing capacity and deformation behaviour of the hybrid laminates. The obtained tensile properties were subsequently compared to identify the optimum laminate configuration for lightweight engineering applications.

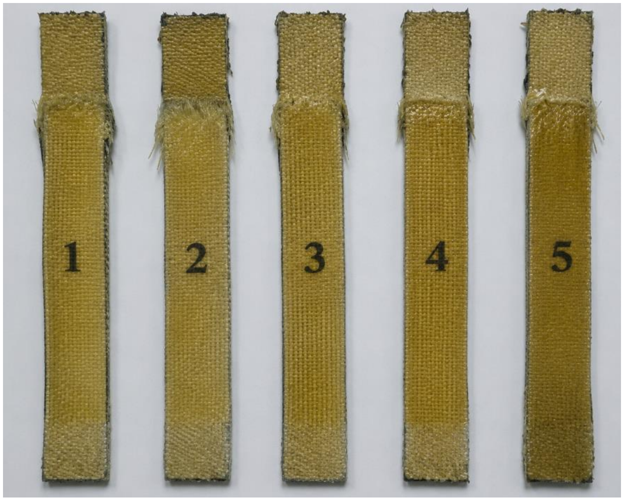

Fig 1: Tensile test specimens (Specimens 1–5) and their dimensions as per ASTM standards

3.2 Flexural Test

The flexural properties of the fabricated banana–basalt reinforced epoxy hybrid laminates were evaluated using the three-point bending test in accordance with ASTM D790. Rectangular test specimens with dimensions of 127 mm × 12.7 mm × 3 mm were prepared from each laminate using a diamond cutter. The specimen edges were finished carefully to eliminate irregularities and minimize premature failure during testing. The specimen thickness and width were measured using a digital vernier caliper with an accuracy of ±0.01 mm before testing.

The flexural tests were carried out using a Universal Testing Machine (UTM) equipped with a three-point bending fixture. The specimens were placed horizontally on two supporting rollers with a span length maintained according to the ASTM standard (typically 16 times the specimen thickness). A centrally positioned loading nose applied the load at a constant crosshead speed of 2 mm/min until the specimen fractured or reached the specified deflection limit. During the test, the applied load and corresponding mid-span deflection were continuously recorded using the data acquisition system.

The flexural strength, flexural modulus, and maximum load-carrying capacity of each laminate were calculated from the recorded load–deflection data. A minimum of five specimens were tested for each laminate configuration, and the average values were reported to ensure the reliability and repeatability of the experimental results. The flexural test was performed to evaluate the bending performance of the hybrid laminates and to investigate the influence of fibre stacking sequence on stiffness, load-bearing capacity, and deformation behaviour.

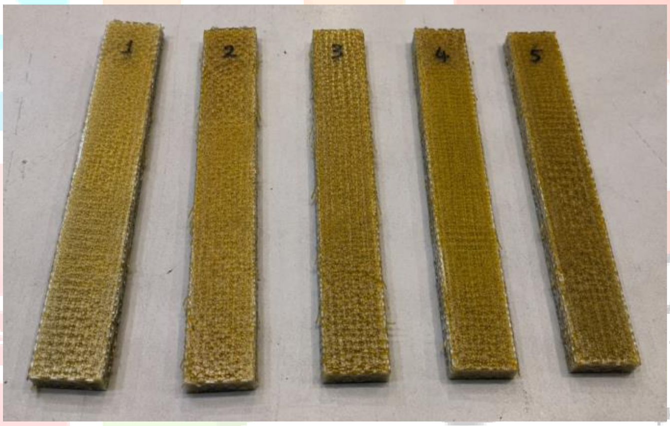

Fig 2: Flexural test setup using three-point bending method (left) and flexural test specimens 1–5 with their dimensions

3.3 Impact Test

The impact resistance of the fabricated banana–basalt reinforced epoxy hybrid laminates was evaluated using the Izod impact test in accordance with ASTM D256. Standard notched specimens with dimensions of 64 mm × 12.7 mm × 3 mm were prepared and tested using an impact testing machine under ambient laboratory conditions. During the test, each specimen was rigidly clamped in a vertical position, and a pendulum striker impacted the notched face in a single swing until fracture occurred.

The energy absorbed by the specimen during fracture was automatically recorded by the testing machine, and the impact strength was determined by dividing the absorbed energy by the cross-sectional area at the notch. A minimum of five specimens from each laminate configuration were tested, and the average values were considered for analysis. The impact test was conducted to evaluate the toughness, fracture resistance, and energy absorption capability of the hybrid laminates under sudden loading conditions, thereby assessing the influence of fibre stacking sequence on impact performance and their suitability for applications subjected to dynamic and shock loading.

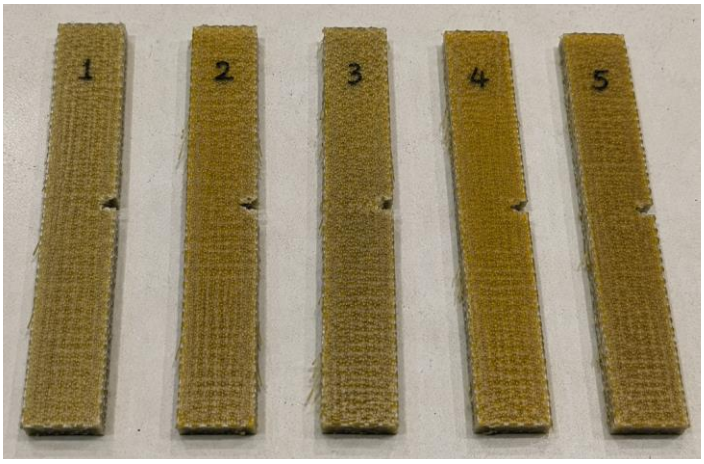

Fig 3: Impact test specimens (Specimens 1–5) and their dimensions as per ASTM standards

4. Results and discussions

3.1 Tensile Test Results

The tensile properties of the banana–basalt reinforced epoxy hybrid laminates were evaluated to investigate the influence of fibre stacking sequence on the mechanical performance of the fabricated composites. The average tensile strength, Young's modulus, and percentage elongation at break for the five laminate configurations are summarized in Table 3. The results clearly demonstrate that the tensile behaviour of the hybrid laminates is significantly influenced by the arrangement of banana and basalt fibre layers within the laminate.

Among the investigated specimens, Specimen S4 exhibited the highest average tensile strength of 186.5 MPa, followed by S2 (179.8 MPa), S3 (171.6 MPa), S5 (164.2 MPa), and S1 (156.8 MPa). The improved tensile performance of S4 can be attributed to the alternating arrangement of banana and basalt fibres, which facilitated efficient load transfer between the reinforcement and the epoxy matrix while reducing localized stress concentration. The presence of basalt fibres contributed significantly to the tensile load-bearing capacity, whereas the banana fibres enhanced stress redistribution and delayed crack propagation.

The Young's modulus also followed a similar trend, with the highest value of 10.8 GPa observed for S4, indicating greater stiffness compared to the other laminate configurations. The higher stiffness is primarily associated with improved fibre–matrix interfacial bonding and the balanced fibre architecture, which minimizes fibre pull-out during loading. Conversely, Specimen S1 exhibited the lowest tensile strength and modulus due to the relatively less effective fibre arrangement, leading to premature matrix cracking and interfacial debonding. The percentage elongation at break ranged from 2.2% to 3.1%, with S4 exhibiting the highest ductility among the hybrid laminates. This behaviour suggests that the optimized stacking sequence not only enhanced the tensile strength but also improved the deformation capability before failure.

Table 3. Tensile Properties of Banana–Basalt Reinforced Epoxy Hybrid Laminates

Specimen	Maximum Load (kN)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
S1	11.76	156.8	8.92	2.18
S2	13.48	179.7	10.15	2.74
S3	12.88	171.7	9.83	2.56
S4	13.99	186.5	10.81	3.08
S5	12.32	164.3	9.36	2.41

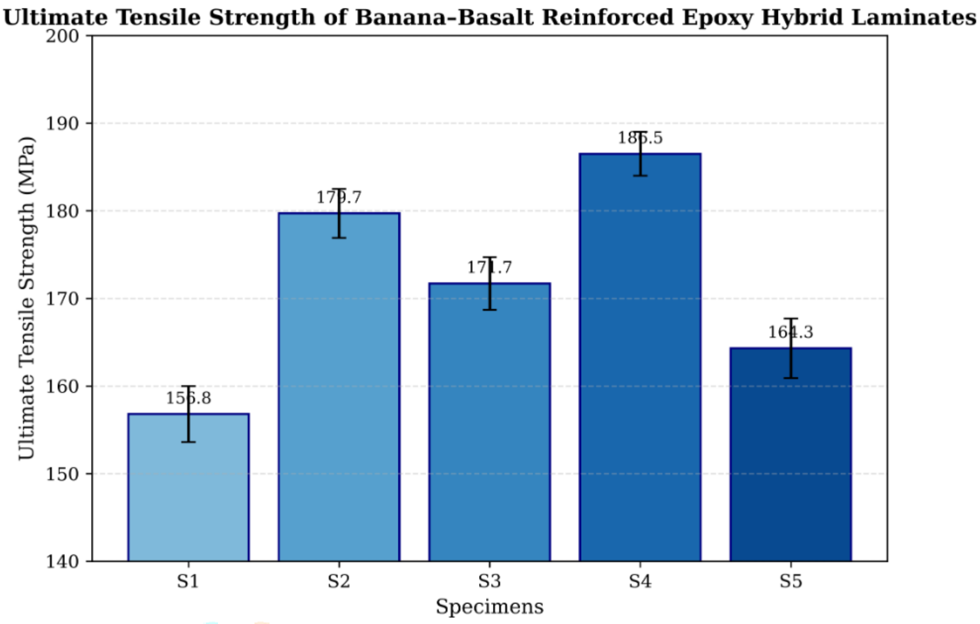

Fig 4: Variation in tensile strength across composite specimens with different Banana–Basalt layup sequences.

3.2 Flexural Test Results

The flexural behaviour of the banana–basalt reinforced epoxy hybrid laminates were evaluated using a three-point bending test in accordance with ASTM D790. The results demonstrated that the fibre stacking sequence significantly influenced the bending performance of the hybrid composites. Among the five laminate configurations, specimen S4 exhibited the highest flexural strength (268.3 MPa) and flexural modulus (13.94 GPa), whereas specimen S1 showed the lowest flexural strength (218.6 MPa) and modulus (11.62 GPa). The superior performance of S4 can be attributed to its optimized alternating arrangement of banana and basalt fibres, which promoted efficient stress transfer between the fibres and epoxy matrix while reducing interlaminar stress concentration during bending. In contrast, the grouped fibre arrangement in S1 resulted in early matrix cracking and interfacial debonding, thereby reducing its load-bearing capacity.

The incorporation of basalt fibres significantly enhanced the stiffness and flexural resistance of the laminates because of their higher elastic modulus, while banana fibres improved the toughness of the composite by absorbing deformation energy and delaying catastrophic failure. Specimen S2 exhibited the second-highest flexural strength (256.7 MPa) owing to its balanced fibre distribution, whereas S3 and S5 showed moderate flexural properties with strengths of 244.9 MPa and 233.8 MPa, respectively. Compared with S1, specimen S4 exhibited an improvement of approximately 22.7% in flexural strength, demonstrating that an optimized hybrid stacking sequence substantially improves bending performance by enhancing fibre–matrix adhesion and reducing stress concentration.

The failure mechanisms observed during flexural testing included matrix cracking, fibre fracture, fibre pull-out, interfacial debonding, and localized delamination. Matrix cracks generally initiated on the tensile side of the specimen and propagated through the fibre–matrix interface under increasing load. Laminates with optimized hybrid stacking exhibited progressive failure and delayed crack propagation, whereas grouped fibre laminates failed more abruptly because of localized stress concentration and weaker interfacial bonding. Overall, the results indicate that the optimized hybrid configuration represented by S4 provides superior flexural strength, stiffness, and structural integrity, making it a promising candidate for lightweight structural applications in the automotive, aerospace, and marine industries.

Table 4. Flexural Properties of Banana–Basalt Reinforced Epoxy Hybrid Laminates

Specimen	Maximum Load (N)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Mid-span Deflection (mm)
S1	782	218.6	11.62	5.82
S2	918	256.7	13.18	6.41
S3	876	244.9	12.85	6.12
S4	960	268.3	13.94	6.68
S5	836	233.8	12.26	5.96

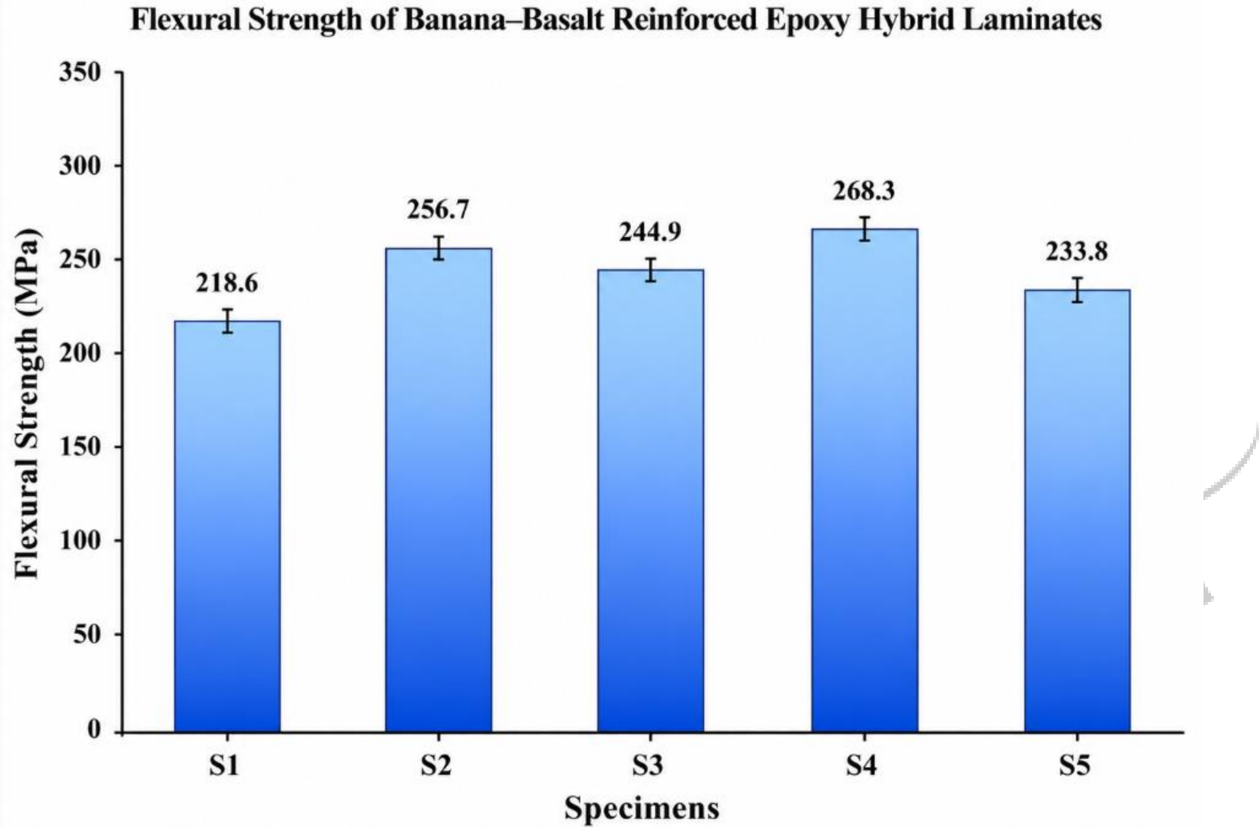

Fig 5: Variation in flexural strength across composite specimens with different Banana–Basalt layup sequences

3.3 Impact Test Results

The impact behaviour of the banana–basalt reinforced epoxy hybrid laminates was evaluated using the Izod impact test in accordance with ASTM D256. The impact strength results revealed that the stacking sequence had a significant influence on the energy absorption capability of the hybrid composites. Among all the laminate configurations, S3 exhibited the highest impact strength of 74.2 kJ/m², followed by S4 (71.8 kJ/m²), S2 (68.5 kJ/m²), S5 (65.3 kJ/m²), and S1 (61.7 kJ/m²). The superior impact performance of S3 is attributed to its balanced distribution of banana and basalt fibre layers, which enhanced crack arresting ability and improved energy dissipation during sudden loading. Conversely, S1 exhibited the lowest impact strength due to less efficient stress redistribution and relatively weaker fibre–matrix interaction.

The incorporation of banana fibres contributed significantly to impact resistance because of their ductile nature and ability to absorb fracture energy, whereas basalt fibres improved structural rigidity and delayed crack propagation. The hybridization of these fibres produced a synergistic effect, enabling the laminates to withstand higher impact loads than single-fibre composites. Compared with specimen S1, specimen S3 exhibited an improvement of approximately 20.3% in impact strength, indicating that an optimized fibre stacking sequence effectively enhances toughness and impact energy absorption.
Failure analysis after impact testing revealed fracture mechanisms including matrix cracking, fibre pull-out, fibre breakage, interfacial debonding, and localized delamination. Laminates with optimized hybrid stacking showed progressive fracture with multiple crack paths, allowing greater energy absorption before complete failure. In contrast, specimens with less favourable stacking sequences exhibited rapid crack propagation and brittle fracture characteristics. Overall, the results demonstrate that the optimized hybrid laminate S3 possesses superior impact resistance, making it suitable for engineering applications where high toughness and resistance to sudden loading are required.

Table 5. Impact Properties of Banana–Basalt Reinforced Epoxy Hybrid Laminates

Specimen	Absorbed Energy (J)	Impact Strength (kJ/m²)
S1	7.84	61.7
S2	8.70	68.5
S3	9.42	74.2
S4	9.11	71.8

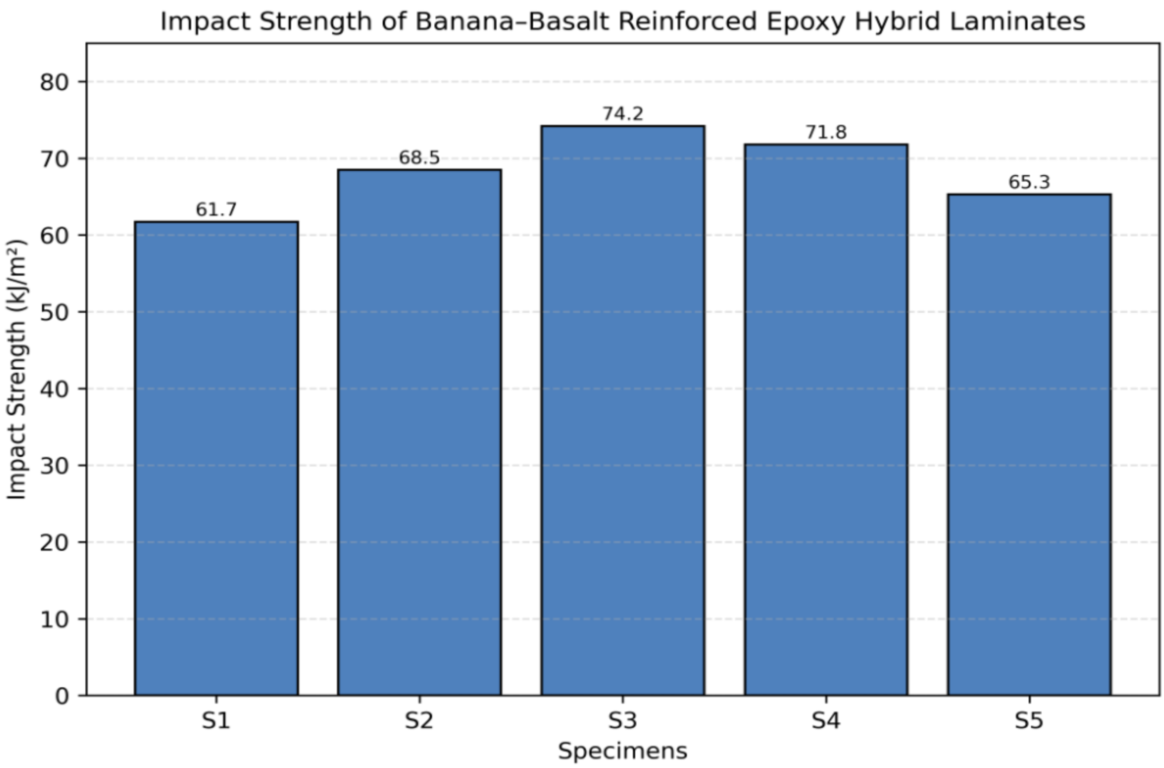

Fig 5: Variation in flexural strength across composite specimens with different Banana–Basalt layup sequences

5. Conclusions

The present investigation evaluated the mechanical behaviour of banana–basalt reinforced epoxy hybrid laminates fabricated using the hand lay-up technique followed by vacuum bagging. Five different fibre stacking sequences were examined to determine their influence on tensile, flexural, and impact properties. Based on the experimental investigation, the following conclusions can be drawn:

1. The fibre stacking sequence significantly influenced the mechanical performance of the banana–basalt reinforced epoxy hybrid composites, demonstrating that laminate architecture plays a crucial role in load transfer and failure behaviour.
2. Among the investigated laminates, specimen S4 exhibited the highest tensile strength (186.5 MPa) and flexural strength (268.3 MPa), indicating that its fibre arrangement provided efficient stress distribution, improved fibre–matrix adhesion, and superior stiffness under static loading.
3. Specimen S3 demonstrated the highest impact strength (74.2 kJ/m²) owing to its balanced hybrid fibre configuration, which enhanced energy absorption, delayed crack propagation, and promoted progressive failure under impact loading.
4. Hybridization of banana and basalt fibres produced a synergistic improvement in mechanical performance by combining the high stiffness and strength of basalt fibres with the excellent toughness and energy absorption characteristics of banana fibres.
5. The experimental results confirm that banana–basalt reinforced epoxy hybrid laminates possess excellent potential for lightweight structural applications in the automotive, aerospace, marine, and sporting goods industries, where a combination of high strength, stiffness, and impact resistance is required.
6. Future research may focus on optimizing fibre volume fraction, surface treatment of natural fibres, environmental durability, fatigue behaviour, finite element modelling, and advanced manufacturing techniques to further enhance the performance and long-term reliability of hybrid composite laminates.

References

1. Naik, V., Kumar, M., Nagaraja, S., Kaup, V., Kodandappa, R., Mammadova, K., Smerat, A., Kadhum, A.A.H., Karimi, R. (2026). Comprehensive Investigation on Mechanical Properties of Mango Seed Shell Short Fiber-Reinforced Epoxy Based Polymer Composites. Hybrid Advances, 100633.
2. Anand, P. B., Aswathanarayan, M. S., Nagaraja, S., Chandrashekar, A., Shivakumar, H. D., Nugroho, S., & Ammarullah, M. I. (2024). Synthesis and characterization of mechanical properties of dammar gum-epoxy bio-composites with areca nut husk and banana fiber as reinforcements for biomedical applications. Journal of Chemical Engineering of Japan, 57(1), 2438111.
3. Jagadeesan, N., Selvaraj, A., Nagaraja, S., Abbas, M., Saleel, C. A., Aabid, A., & Baig, M. (2022). Response Surface Methodology Based Optimization of Test Parameter in Glass Fiber Reinforced Polyamide 66 for Dry Sliding, Tribological Performance. Materials, 15(19), 6520. https://doi.org/10.3390/ma15196520
4. Mohan Kumar, K., Naik, V., Waddar, S. S., Santhosh, N., Kaup, V., & Harish, H. V. (2023). Mechanical and water absorption characterization of mango seed shell/epoxy composite for low load carrying structures. International journal of polymer science, 2023(1), 9976409.
5. Mohan Kumar, K., Naik, V., Kaup, V., Waddar, S., Santhosh, N., & Harish, H. V. (2023). Nontraditional natural filler-based biocomposites for sustainable structures. Advances in Polymer Technology, 2023(1), 8838766.
6. Kodandappa, R., Nagaraja, S., Chowdappa, M. M., Krishnappa, M., Poornima, G. S., & Ammarullah, M. I. (2024). Application of the Taguchi method and RSM for process parameter optimization in AWSJ machining of CFRP composite-based orthopedic implants. Open Engineering, 14(1), 20240057.
7. Nagaraja, S., Bindiganavile Anand, P., Mahadeva Naik, R. N., & Gunashekaran, S. (2022). Effect of aging on the biopolymer composites: Mechanisms, modes and characterization. Polymer Composites, 43(7), 4115-4125.

8. Ravichandran, G., Rathnakar, G., Santhosh, N., & Thejaraju, R. (2019). Antiwear performance evaluation of halloysite nanotube (HNT) filled polymer nanocomposites. Int. J. Eng. Adv. Technol, 9(1), 3314-3321.
9. Shivanand, H. K., Ali Ali, Madhusudhana Reddy H, Santhosh Nagaraja, Rahul Biradar, Ahmed Shakir Al-Hiti, Abdul Amir H. Kadhum, Aseel Smerat, Amare Merfo Amsal. (2026). "Response surface modelling of tensile and impact characteristics of Kevlar/Hemp/CNT reinforced polymer matrix composites." Journal of Materials Science: Materials in Engineering 21(1), 74.
10. Anand, P. B., Ali, A. B. M., Nagaraja, S., Nagamadhu, M., Raju, B. S., Smerat, A., Al-Hiti, A. S., & Karimi, R. (2026). Experimental investigation of thermo-viscoelastic degradation and microstructural evolution of CNT-modified bamboo fiber reinforced epoxy composites. Journal of Materials Research and Technology, 43, 6383–6394. https://doi.org/10.1016/j.jmrt.2026.07.141
11. Nagaraja, S., Anand, P. B., Kodandappa, R., & Frinjo, A. (2026). Effect of halloysite nanotube fillers on fracture mechanical and tribological properties of sisal fibre reinforced epoxy composites. Discover Mechanical Engineering, 5(1), 122.
12. Praveen, B. A., Nagaraja, S., Avalappa, M. G., & Rangaswamy, N. (2026). Experimental study on the mechanical and tribological characteristics of pineapple leaf fiber reinforced polymer composites for biomedical applications. Fracture and Structural Integrity, 20(76), 82–98. https://doi.org/10.3221/IGF-ESIS.76.06
13. Murthy, N., Gowda, A.C., Nagaraja, S., Reddy, C.K., Munthala, D., Pojprapai, S., Jangam, S. and Naik, R., (2026). Assessment of thermomechanical properties of CFRP laminates reinforced with nano-graphene, with and without phenol addition. Scientific Reports.
14. Ramesha, K., Jangam Sasidhar, H.N., Santhosh, N., Srinath, M.S., Venkateshwaralu, K., Smerat, A., Al-Hiti, A.S., Berdimurodov, E. and Jelila, Y.D., (2026). Structure–thermal–morphological correlation in starch–PVA reinforced cactus mucilage bio-based composite films. Journal of Materials Science: Materials in Engineering.
15. Bennehalli, B., Nagaraja, S., Poyil, S. S., Reddy, M. R., Rajashekharappa Banagar, A., Kumaraswamy, S., … Ammarullah, M. I. (2025). Surface Modification of Sustainable Bio-Derived Areca Sheath Fibers for Enhanced Mechanical and Thermal Properties in Epoxy-Based Biocomposites: Spectroscopic, Thermogravimetric, and Crystallographic Insights. Journal of Natural Fibers, 22(1). https://doi.org/10.1080/15440478.2025.2497914
16. Chougala, V., Gowda, A. C., Nagaraja, S., & Ammarullah, M. I. (2025). Effect of chemical treatments on mechanical properties of sugarcane bagasse (Gramineae Saccharum Officinarum L) fiber based biocomposites: A review. Journal of Natural Fibers, 22(1), 2445571.
17. Nagaraja, S., Praveena, B. A., Nagamadhu, M., & Kapilan, N. (2026). Thermoplastic matrix for three-dimensional printing: Types, filament/component manufacturing, and characterization. 3D Printing of Polymer Composites, 161-178.
18. Praveena B. A., Srikanth, H. V., Santhosh N., Rajadurai, M. (2026). Investigation on mechanical properties of bamboo fibre reinforced composites. J Polym Compos, 14(1), 325-338.
19. Ramesha, K., Santhosh, N., Praveena, B.A., Thyagaraj, N.R., Chand, R.P., Rathnakar, G., Naik, N., Emma, A.F., Kadhum, A.A.H. and Al-Hiti, A.S. (2026). Mechanical characterization of Kevlar fibre reinforced composites and parametric optimization using Taguchi's design of experiments. Discover Mechanical Engineering, 5(1), 90.
20. SB, Karthik, Abhijith N, Abhinav, Santhosh N, Manjula K, Prem Chand R, Channa Keshava Naik N, Addisu Frinjo Emma, Mustafa M. Aljumaily, and Mukhtar Hamid Abed. Finite element analysis of stress concentration and buckling behaviour in composite panels with cutouts. J Mater. Sci: Mater Eng. **21**, 86 (2026). https://doi.org/10.1186/s40712-026-00458-1
21. Halemani, B. S., Chandrasekhar, K. M., Ravitej, Y. P., Raju, T. H., Udayshankar, S. (2021). Investigation and analysis for mechanical properties of banana and e glass fiber reinforced hybrid epoxy composites. Materials Today: Proceedings, 47, 2509-2515.
22. Prem Chand, R., Ravitej, Y. P., & Shiva Mani Kanta, J. V. (2020). Characterization of banana and bagasse fiber-reinforced hybrid epoxy composites. In Advances in Fluid Mechanics and Solid Mechanics: Proceedings of the 63rd Congress of ISTAM 2018 (pp. 211-221). Singapore: Springer Singapore.
23. Prem Chand, R., Ravitej, Y. P., Chandrasekhar, K. M., Adarsha, H., Shivamani Kanta, J. V., Veerachari, M., Ravi Kumar, R., & Abhinandan. (2021). Characterization of banana and E-glass

fiber reinforced hybrid epoxy composites. Materials Today: Proceedings, 46(18), 9119–9125. https://doi.org/10.1016/j.matpr.2021.05.402