Research Article

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Investigation on the Physical and Mechanical Properties of Banana/Ramie Hybrid Composites Reinforced with Graphene Oxide Nanoparticles

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ABSTRACT

In this study, hybrid composites reinforced with graphene oxide nanoparticles and woven banana/ramie fibers were fabricated and their physical and mechanical characteristics were examined. Graphene oxide nanoparticles in varying weight percentages (0, 2, 4, 6, and 8 wt%) and three different fiber layering sequences (BRBR, BRRB, and RBBR) were used to fabricate hybrid composites using the hand layup method. The physical properties evaluated include density and moisture absorption, and their mechanical properties assessed are tensile strength (TS), flexural strength (FS), hardness, impact resistance, and interlaminar shear strength (ILSS). Reduced void content (19.7%) and limited moisture absorption (4.7%) were observed in the banana/ramie composite with RBBR stacking sequence and 6 wt% graphene oxide nanoparticles. Peak tensile modulus was measured at 27.61 MPa and peak tensile strength was recorded at 37.35 MPa when RBBR composites were combined with 4 wt% graphene oxide nanoparticles. The addition of 6 wt% graphene oxide nanoparticles to RBBR hybrid composites increased the flexural modulus by 4.91% and the FS by 170.35 %. Fiber pullout, failure modes, and other fissures inside the hybrid composite were investigated through surface morphological investigation of the specimens using SEM.

Keywords: Hybrid composite; Mechanical properties; Graphene oxide nanoparticles; Natural fibers; Stacking sequences.

1. INTRODUCTION

Natural fibers have emerged as promising alternatives to synthetic fibers in composite materials due to their biodegradability, sustainability, low cost, and abundant availability. Commonly used fibers such as banana, jute, ramie, flax, coir, and sisal are increasingly being explored in various hybrid and reinforced composites, either alone or in combination with synthetic fibers like Kevlar and glass. Loganathan *et al.* (2024) analyzed surface modification effects on natural fiber hybrid composites including jute, coir, ramie, banana, and others to improve mechanical characteristics. Fiber/degradable epoxy hybrid composites were modified with NaOH to enhance moisture resistance and mechanical characteristics. Composites showed best performance with shear strength (Geng and Cai, 2024). Fiber/epoxy hybrid composites were prepared by hand layup method and treated with NaOH to improve thermal and mechanical characteristics (Rahman *et al.* 2025). Fiber bio-composites were prepared and tested for biodegradability and mechanical characteristics. Tensile and impact strength improved with 20 wt.% ramie fiber (Behera, 2025). Banana/ramie epoxy composites reinforced with nanoparticles showed improved mechanical characteristics like hardness, impact resistance, and reduced water absorption (Sathish *et al.* 2024). Ramie hybrid composites with NaOH-treated Ramie layers showed enhanced physical and mechanical characteristics substantiated by vibrational and tensile tests (Thiyagu and Narendrakumar, 2022).

Banana fiber hybrid composites were fabricated using hand layup method and tested for physical and mechanical characteristics, including tensile, flexural, water absorption, and void content. The optimal combination showed superior strength (Raghavendra *et al.* 2025). Fiber epoxy hybrid composites with nano clay were fabricated by hand layup method and tested for mechanical characteristics. Alkali-treated fiber with 6% nano clay particles showed peak performance (Krishna *et al.* 2024). Fiber epoxy hybrid composites modified with graphene oxide were fabricated by hand layup method, improving mechanical characteristics (Chowdhury *et al.* 2025). Ramie/polyester composites with filler showed improved physical and mechanical characteristics, especially in tensile and flexural tests (Raja *et al.* 2024). Fiber-based hybrid composites with SiO_2 nanoparticles showed improved wear and mechanical characteristics (tensile, flexural, impact). Mechanical mixing and sonication ensured nanoparticle dispersion; and its water absorption and density were studied (Mayakannan *et al.* 2023). Ramie hybrid composites were fabricated using hand layup method with 0° and 90° fiber orientations and

tested for physical and mechanical characteristics. Maximum tensile, flexural, and impact strengths were achieved at 90° (Kemparaju *et al.* 2024). Ramie hybrid composites with nanodiamond fillers were tested for physical and mechanical characteristics. The composites showed good tensile and flexural strengths (Kumar *et al.* 2024).

Hybrid composites were fabricated using hand layup method and tested for physical and mechanical characteristics. Increased tensile and flexural strength were observed with fiber-matrix reinforcement (Vedanarayanan *et al.* 2022). Fiber epoxy hybrid composites were developed with varied fiber/filler ratios and tested for mechanical characteristics. Best results were found for high-fiber-content sample (Raja *et al.* 2023). Banana fiber hybrid composites with ZrC fillers (0–2 wt%) were fabricated and tested for physical and mechanical characteristics. The 1.5 wt% filler showed optimal results; FESEM revealed matrix-fiber interaction (Muniyan *et al.* 2024). Banana epoxy composites with fly ash filler showed best mechanical characteristics at 3% due to enhanced bonding, with strength reducing at 5% due to filler agglomeration. Scanning electron microscopy confirmed poor adhesion at high filler content (Kannan *et al.* 2022). Banana fiber composites with red mud filler were fabricated using hand layup method. Best physical and mechanical characteristics were observed with specific fiber lengths and NaOH treatment (Prabu *et al.* 2013). GO-PPDA (graphene oxide - p-phenylenediamine) was used to enhance tensile and compressive strength in fiber composites through improved interfacial interactions and crystallinity. The physical and mechanical characteristics improved significantly, supporting real-world composite applications (Zhang *et al.* 2025). Graphene hybrid composites were developed with different graphene oxide particle sizes and weight percentage, showing peak performance at 5 wt% and 25 µm. Enhanced mechanical characteristics were noted, correlating filler size with flexural strength (Kamatchi *et al.* 2023). Fiber epoxy composites incorporated with graphene oxide were tested for mechanical characteristics by tensile, impact, bending, and compression tests. Improved interface due to GO, and reducing delamination were revealed by SEM (Neuba *et al.* 2025).

Natural fiber granulated hybrid composites using banana, ramie, and others were fabricated by a novel additive method and tested for mechanical characteristics (Anandkumar *et al.* 2021). Hybrid composites with recycled PET and banana fiber were fabricated using hand layup method and tested for mechanical characteristics like tensile, compression, and flexural strength (Nkomo *et al.* 2025). Banana fiber hybrid composites reinforced with unsaturated polyester were prepared using hand layup method, and stacking orientation effects on mechanical characteristics and water absorption were evaluated (Asyraf *et al.* 2025). Banana hybrid composites with nano-graphene oxide and epoxy were developed, showing enhanced mechanical and physical characteristics at 0.50 wt.% GO. Graphene oxide was ultrasonically dispersed and stacking sequences were varied. Scanning electron microscopy confirmed uniform dispersion of the GO nanoparticles (Shubham *et al.* 2025). Ramie fiber and nano Al_2O_3 reinforced epoxy biocomposites were fabricated using hand layup method. Scanning electron microscopy showed dispersion of the nanofiller (Samuel *et al.* 2021). Hybrid composites made from banana fibers with epoxy and nano SiO_2 fabricated *via* hand layup method showed enhanced physical and mechanical characteristics (tensile, flexural, impact). Scanning electron microscopy revealed the morphology and delamination of the composites (Harak *et al.* 2024).

This study utilized graphene oxide nanoparticles as an innovative filler to improve the mechanical and physical properties of banana/ramie epoxy composites. Fifteen distinct sets of laminated banana/ramie composites were fabricated, integrating varied weight percentages of graphene oxide nanoparticle fillers. Scanning electron microscopy was utilized to analyze the surface morphology of the composite specimens.

Table 1. Chemical compositions and mechanical characteristics of banana and ramie fibers

Properties	Banana Fiber	Ramie Fiber
Cellulose (%)	60-65	68-76
Hemicelluloses (%)	15-20	13-16
Lignin (%)	4-12	0.6-0.7
Density (kg/m^3)	1.35-1.50	1.50-1.55
Tensile strength (MPa)	350-600	500-938
Young's modulus (GPa)	5-12	25-128
Elongation at break	1.0-3.5	1.2-3.8
Diameter (μm)	80-250	20-80
Microfibrillar angle θ (degrees)	14-25°	7-12°

2. MATERIALS AND METHODS

2.1 Materials

Banana and ramie mat fibers were sourced from Go Green Products, Chennai, India. The epoxy matrix with a density of 1.5 g/cc was procured from Kovai Seenu Enterprises, Coimbatore, Tamil Nadu. Graphene oxide

nanoparticles were supplied by Matrics Enterprises, Nagercoil, Tamil Nadu. Tables 1 and 2 present the chemical compositions and mechanical properties of banana fibers and ramie fibers, and graphene oxide nanoparticles, respectively.

Table 2. Properties of graphene oxide nanoparticles

Properties	Values
Purity (%)	>98
Average particle size (nm)	10-500 nm
Specific surface area (m^2 g^{-1})	200-800 m^2/g
pH value	3-5
True density (g/cm^3)	1.8-2.2 g/cm^3
Morphology	Wrinkled
Melting point (°C)	200-250 °C

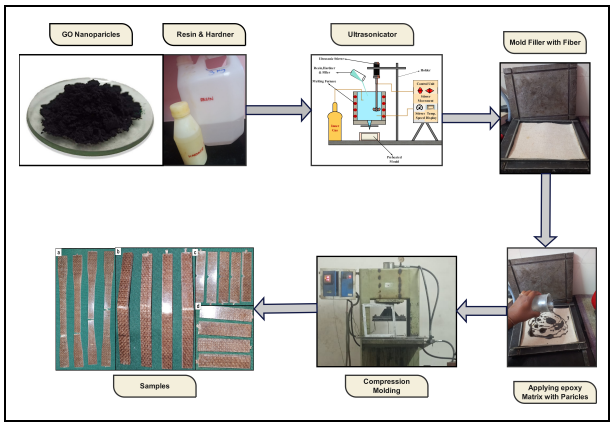


Fig. 1: Fabrication process of the composite specimens

2.2 Fabrication of Specimens

To achieve uniform integration of the matrix and filler, graphene oxide nanoparticles and epoxy resin (LY 556) were first blended using an ultrasonicator operating at 150 rpm for 10 minutes. Subsequently, the epoxy-graphene oxide mixture was combined with the hardener (HY 951) in a 1:10 ratio and stirred for 5 minutes. This step is crucial to ensure complete homogeneity and to minimize void formation in the hybrid composite. Composite specimens were prepared with varying GO nanoparticle weight percentages (0 2, 4, 6, and 8wt %). A four-layer fiber structure was fabricated using different sequences of ramie (R) and banana (B) fibers, arranged as BRBR, BRRB, and RBBR. Each composite laminate maintained a constant fiber content of 20 wt% (9 wt% banana and 11 wt% ramie). Table 3 presents the weight percentages of all components, including ramie fiber, banana fiber, graphene oxide nanoparticles, and the epoxy matrix. The prepared homogeneous mixture was poured onto the mold's bottom layer, followed by a fabric layer, and this process was followed for all four layers. For fabrication, the prepared homogeneous mixture was poured onto the mold surface, pre-coated with mold release spray to facilitate easy demolding. Fabric layers were placed successively, and the process was followed for all four layers. A uniform pressure of 50 kg was applied to the mold to achieve a consistent laminate thickness of 4 mm, promote effective bonding between layers, and minimize void formation. The complete fabrication process is shown in Fig. 1.

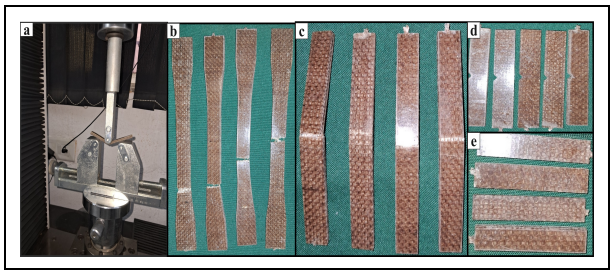


Fig. 2: (a) Universal testing machine, composite samples of (b) Tensile, (c) Flexural, (d) Impact and (e) ILSS

2.3 Testing of Physical Properties

Following the steps outlined in Equation (1), the theoretical densities of the composite samples were determined using the Agarwal and Broutman method.

$$\rho_{ct} = \frac{1}{(W_b/\rho_b)+(W_r/\rho_r)+(W_g/\rho_g)+(W_e/\rho_e)} \quad \ldots (1)$$

In this context, W represents the weight fraction and ρ denotes the density. The subscripts b, r, g, and e correspond to banana fiber, ramie fiber, graphene oxide nanoparticles, and matrix, respectively. The actual density of the fabricated composite specimens was determined based on the buoyancy principle, in accordance with ASTM D792-91. The void volume fraction was subsequently calculated using Equation (2).

$$V_v = \frac{\rho_{ct}-\rho_{ca}}{\rho_{ct}} \quad \ldots (2)$$

In accordance with the ASTM D570-99 standard, specimens with dimensions of 60 mm × 10 mm × 4 mm were used to evaluate the moisture absorption behavior of the fabricated composites. Prior to immersion in distilled water, the initial weight of each sample was recorded. After immersion, the samples were removed, gently dried using tissue paper, and then reweighed. A precision balance with an accuracy of 0.001 g was used to measure the sample weights. The percentage of moisture absorption was calculated based on the difference in mass using Equation (3).

$$\text{Moisture absorption } (\%) = \frac{(W_f-W_i)}{W_i} \times 100 \quad \ldots (3)$$

Table 3. Experimental parameters along with their compositions

Stacking Sequence	Sample Code	Banana (wt%)	Ramie (wt%)	Graphene Oxide Nanoparticles (wt%)	Total Reinforcement	Wt% of Matrix
BRBR	S1	9	11	0	20	80
	S2			2	22	78
	S3			4	24	76
	S4			6	26	74
	S5			8	28	72
BRRB	S6	9	11	0	20	80
	S7			2	22	78
	S8			4	24	76
	S9			6	26	74
	S10			8	28	72
RBBR	S11	9	11	0	20	80
	S12			2	22	78
	S13			4	24	76
	S14			6	26	74
	S15			8	28	72

2.4 Testing of Mechanical properties

Before testing, the composite laminates were precisely cut to the required dimensions using a saw cutter, adhering to ASTM standards. The edges of the specimens were subsequently smoothed using an emery sheet to ensure uniformity. An ASTM-compliant composite specimen prepared for mechanical testing is depicted in Fig. 2. The mechanical properties, including tensile and flexural behavior, were evaluated using a Instron testing machine. Tensile testing was performed on specimens with dimensions of 153 mm in length, 12.7 mm in width, and 4 mm in thickness, in accordance with ASTM D3039-76, to determine the tensile strength and modulus. Flexural characteristics were assessed through a three-point bending test, following ASTM D790-07, using specimens measuring 125 mm × 12.7 mm × 4 mm. A constant crosshead speed of 2 mm/min was maintained during the flexural testing. The impact strength of the hybrid composite specimens was determined using an Izod impact tester in accordance with ASTM D256. Specimens measuring 64 mm in length, 12.7 mm in width, and 4 mm in thickness were subjected to pendulum impact until fracture occurred. Surface hardness measurements were conducted using a Vickers hardness tester, conforming to ASTM D785 standards. For each composite category, mechanical property values were calculated as the geometric mean of measurements obtained from a minimum of three individual specimens. Furthermore, the surface morphology and fracture behaviour of the tested specimens were analyzed using a GEMINI scanning electron microscope.

3. RESULTS AND DISCUSSION

3.1 Volume and Density of the Void Content

The density of polymer composites is significantly influenced by the weight ratio between the reinforcement and the matrix. Table 4 presents the actual and theoretical density values, along with the corresponding void volume percentages, for the fabricated banana/ramie hybrid composites with and without graphene oxide (GO) nanoparticle fillers. The results clearly indicate that, the experimentally measured densities are consistently lower than the theoretically

calculated values, primarily due to the presence of voids introduced during the fabrication process. The void volume percentage in the banana/ramie composite samples was determined by comparing the actual and theoretical density values. Notably, the composites containing 6 wt% GO nanoparticles exhibited reduced void percentages of 19.5%,19.3% and 19.7%% for the BRBR, BRRB, and RBBR layering sequences, respectively, when compared to other filler concentrations. This reduction is attributed to the enhanced interfacial compatibility among the epoxy matrix, GO filler, and banana/ramie fibers, which promotes better dispersion and matrix wetting.

In contrast, the unfilled composite laminates (0 wt% GO) displayed the highest void content, likely due to the hydrophilic nature of banana and ramie fibers, which can hinder effective matrix impregnation. Furthermore, the results suggest that increasing the GO nanoparticle content beyond the optimal level leads to a progressive rise in void percentage, potentially due to nanoparticle agglomeration and reduced matrix-fiber interaction.

Table 4. Theoretical density, actual density and void percentages of the hybrid composites

Sample	Theoretical density (g/cm^3)	Actual density (g/cm^3)	Void percentage (%)
S1	1.482	1.200	19.0
S2	1.468	1.185	19.3
S3	1.460	1.175	19.5
S4	1.450	1.150	20.7
S5	1.450	1.145	21.0
S6	1.452	1.200	19.0
S7	1.468	1.185	19.3
S8	1.460	1.175	19.5
S9	1.450	1.160	20.0
S10	1.450	1.155	20.3
S11	1.482	1.200	19.0
S12	1.468	1.185	19.3
S13	1.460	1.175	19.5
S14	1.450	1.165	19.7
S15	1.450	1.160	20.0

The observed increase in void content at higher filler loadings attributed to inadequate interfacial adhesion between the fillers and the matrix. However, when 6 wt% of GO nanoparticles was incorporated, a substantial reduction in void volume was achieved compared to the unfilled composites. Specifically, the void content decreased by 58.83% in the BRBR stacking sequence, 58.7% in the BRRB sequence, and 59.1% in the RBBR sequence. Void content is a critical parameter influencing the mechanical performance of composite materials, particularly their tensile and flexural strengths. Among the three stacking configurations, the RBBR sequence exhibited the lowest void content. This outcome can be attributed to the finer lumen structure of ramie fibers and their improved wettability by the epoxy matrix, which facilitates better fiber-matrix interaction.

3.2 Absorption of Moisture

Moisture absorption is a critical factor influencing the mechanical performance and dimensional stability of banana/ramie fiber-reinforced composites. This study examined hybrid composites incorporating varying concentrations of GO nanoparticles (2, 4, 6, and 8 wt%) across three different stacking sequences: BRBR, BRRB, and RBBR, as illustrated in Fig. 3a–c. Due to their inherently hydrophilic nature and the presence of microcracks, both banana and ramie fibers facilitate moisture uptake, which increases with prolonged immersion time. The intrinsic porosity of these natural fibers permits the ingress of water molecules through capillary action.

Initially, the rate of moisture absorption was rapid and linear; however, it gradually decreased and reached equilibrium after approximately 5 days. Among the unfilled composites (0 wt% GO), the maximum moisture absorption was recorded as 4.7 % for the BRBR configuration, 4.7% for BRRB, and 4.8% for RBBR. The RBBR sequence consistently exhibited the lowest moisture absorption, indicating better resistance to water ingress, which can be attributed to improved interfacial bonding and reduced fiber exposure. The incorporation of GO nanoparticles at an optimal concentration of 4 wt% significantly reduced moisture uptake. In contrast, increasing the filler concentration to 8 wt% led to particle agglomeration, thereby increasing the composite's void content and facilitating moisture penetration. The high surface area and barrier-forming ability of GO nanoparticles contribute to improved filler dispersion, reduced interfacial gaps, enhanced matrix-fiber adhesion, and limited water permeation. After 5 days of immersion, composites reinforced with 4 wt% GO nanoparticles demonstrated substantial reductions in moisture absorption compared to unfilled composites specifically, reductions of 112% for BRBR, 89% for BRRB, and 145% for RBBR stacking sequences. These findings underscore the critical role of filler content and stacking sequence in optimizing the moisture resistance of natural

fiber-based hybrid composites. In a literature work, banana fiber epoxy composites with SiO_2 fillers showed improved mechanical characteristics, wear resistance, and reduced moisture absorption (Sengottaiyan *et al.* 2025).

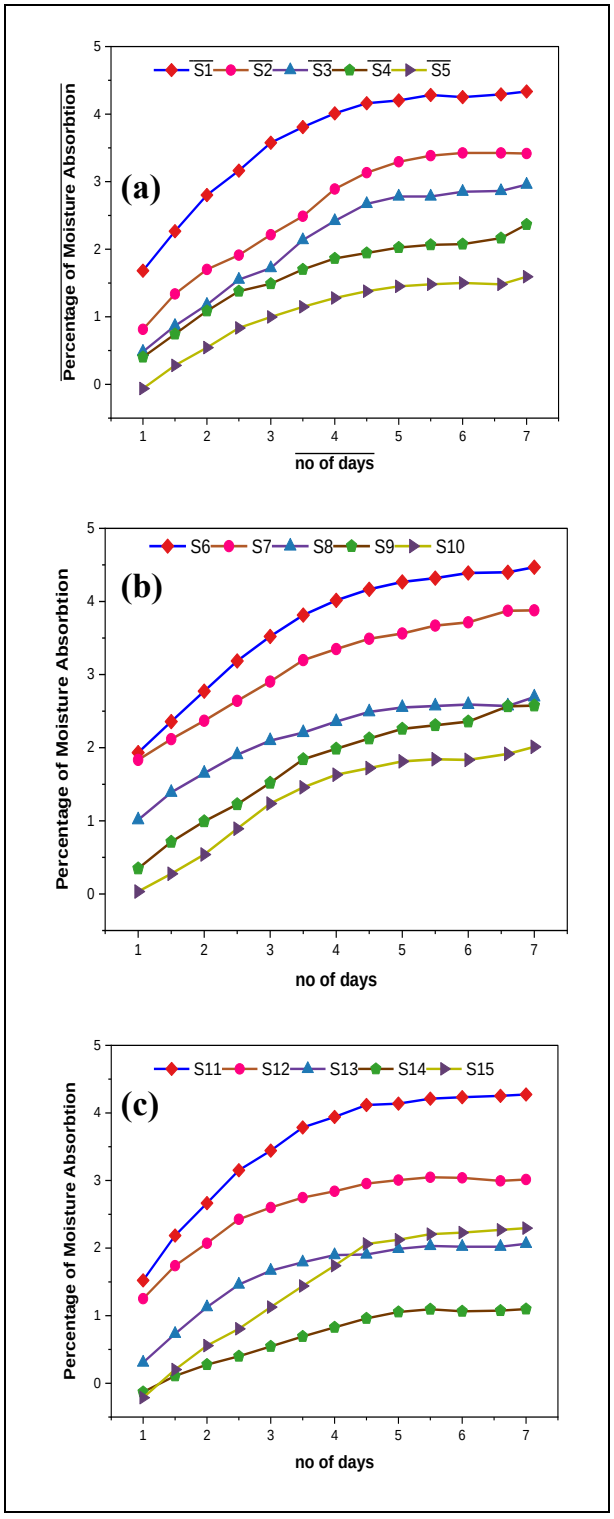


Fig. 3: Moisture absorption behaviour of the composite specimens are (a) BRBR, (b) BRRB and (c) RBBR

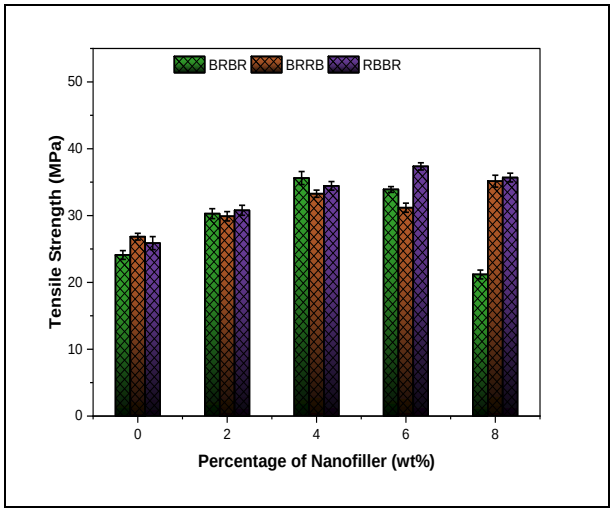


Fig. 4: Impact of GO nanoparticles and stacking pattern on the tensile strength

3.3 Tensile Properties

The tensile strength and modulus of banana/ramie hybrid composites were markedly affected by the addition of GO nanoparticle fillers, as demonstrated in Fig. 4 and 5. Tensile tests were performed following ASTM standards on hybrid composites composed of different GO weight percentages (0 2, 4, 6, and 8wt%) and organized in three specific stacking sequences: BRBR, BRRB, and RBBR. The presented values denote the mean ± standard deviation derived from three separate specimens for each setup. The unaltered epoxy matrix demonstrated a tensile strength of 37.35 MPa and a tensile modulus of 27.61MPa. The use of GO fillers up to 6 wt% led to a significant improvement in tensile strength and modulus for all stacking sequences. This enhancement is mainly ascribed to the uniform distribution of GO nanoparticles achieved through mechanical stirring, which fosters improved stress transfer between the fiber and matrix, augments interfacial bonding, and diminishes void formation, thereby improving the structural integrity of the composite. The RBBR stacking sequence with 6 wt% GO filler exhibited optimal performance, with a maximum tensile strength of 37.35 MPa among the assessed configurations. In comparison, BRBR and BRRB sequences demonstrated maximum tensile strengths of 33.91 MPa and 31.17 MPa, and 37.35 MPa respectively, at identical filler concentrations. These numbers denote percentage increases of 20.0%,16.7% and 22.6%, respectively, relative to the tensile strength of the unmodified epoxy matrix. In earlier study, the hybrid composite of laminated Ramie/silk/silk/Ramie with 3% montmorillonite nanoclay produced the highest tensile strength (Sadashiva *et al.* 2023). Nevertheless, above the ideal concentration of GO, a deterioration in tensile characteristics was noted. This decrease is likely because of filler agglomeration and interfacial debonding, where

high particle loading impairs the stress transfer process, resulting in early failure. The failure of agglomerated particles to adequately bond with the matrix or support load leads to a decline in mechanical characteristics.

As illustrated in Fig. 5, the tensile modulus of unfilled banana/ramie hybrid composites with BRBR, BRRB, and RBBR stacking sequences exhibits a progressive increase with the addition of GO nanoparticles at concentrations of 2, 4, 6, and 8 wt%. The initial tensile modulus values for the unfilled composites were 28.14 MPa (BRBR), 29.35 MPa (BRRB), and 31.35 MPa (RBBR). Upon incorporation of 6 wt% GO nanoparticles, the corresponding tensile modulus values reached peak values of 31 MPa. This can be attributed to the increased stiffness of the composite matrix, improved interfacial bonding between the fibers and the matrix, and reduced polymer chain mobility due to effective GO nanoparticle reinforcement. For composites containing 30 wt% fiber, the percentage increase in tensile modulus from the unfilled samples to those containing 6 wt% GO was calculated as 27.61 % for BRBR, 25.27 % for BRRB, and 26.44 % for RBBR stacking sequences. However, a further increase in GO nanoparticle concentration to 8 wt% resulted in a decline in tensile modulus across all configurations. This reduction is likely due to nanoparticle agglomeration, which disrupts stress transfer and creates stress concentration zones within the matrix. These findings confirm that 6 wt% GO represents the optimal filler concentration for maximizing tensile modulus in banana/ramie fiber-reinforced composites.

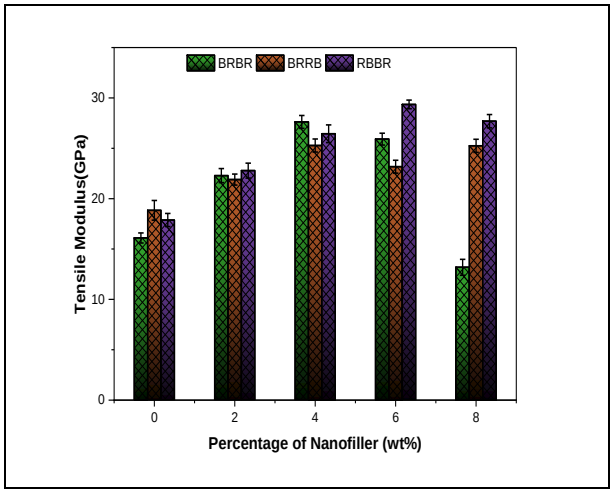


Fig. 5: Impact of GO nanoparticles and stacking pattern on the tensile modulus of the composite samples

3.4 Flexural Properties

Fig. 6 and 7 present the flexural strength and modulus of banana/ramie hybrid composites reinforced with varying weight percentages of GO nanoparticles. The flexural properties of the composites showed a marked improvement with increasing GO content up to an optimal concentration of 4 wt%, beyond which a decline was observed. The enhancement in flexural performance at lower filler concentrations can be attributed to improved matrix-reinforcement bonding and increased shear resistance, which together contribute to better stress transfer and energy absorption under bending loads. Conversely, the decline in flexural properties at 8 wt% GO is likely due to filler agglomeration within the epoxy matrix, leading to the formation of stress concentration sites that weaken the overall composite structure. At 6 wt% GO, the composites achieved peak flexural strength values of 166.91 MPa for BRBR, 164.17 MPa for BRRB, and 170.35 MPa for RBBR stacking sequences.

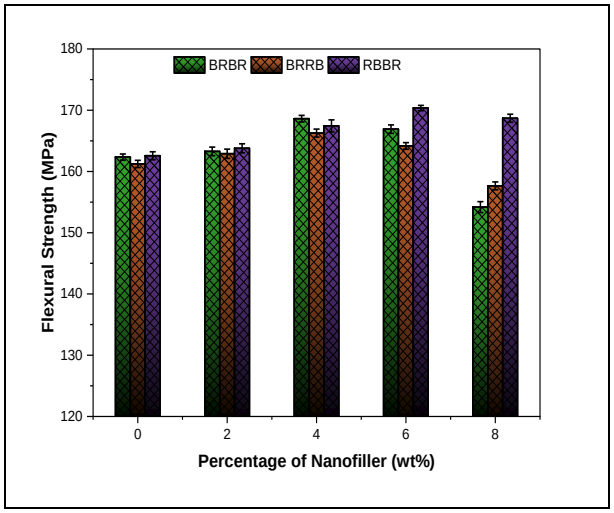


Fig. 6: Impact of GO nanoparticles and stacking pattern on the flexural strength of the composite samples

Among the stacking sequences, the RBBR configuration consistently exhibited superior flexural strength, underscoring the influence of fiber arrangement on mechanical performance. The improved flexural behavior in this configuration is attributed to the outer placement of ramie fibers, which possess higher strength and stiffness, thereby contributing significantly to load-bearing capacity during bending. These findings align with existing literature, which emphasizes the critical role of layer architecture in determining the flexural properties of hybrid laminates (Kim *et al*. 2021). In terms of flexural modulus, the composites incorporating 6 wt% GO nanoparticles exhibited values of 167 MPa (BRBR), 164 MPa (BRRB), and 171 MPa (RBBR). When compared to the unfilled composites, these values reflect percentage increases of 3.09 % (BRBR), 1.23% (BRRB), and 4.91% (RBBR). The increase in flexural modulus is attributed to the high stiffness of GO nanoparticles, when uniformly dispersed within the epoxy matrix, mimicking the mechanical behavior of the natural fibers and enhance matrix rigidity. Additionally, the nanoparticles improve fiber-matrix interfacial adhesion and contribute to greater resistance against deformation by providing supplementary energy absorption during compression loading. Specifically, in the RBBR stacking sequence, the

flexural modulus increased linearly with the addition of GO nanoparticles: from 480 MPa at 2 wt% to 580MPa (4 wt%), 650MPa (6 wt%), and 590 MPa (8 wt%). However, a slight decline to 650 MPa was observed when the filler content increased to 6 wt%, reaffirming the optimality of 6 wt% GO for maximizing flexural performance. Banana fiber composites with nanofillers showed improved mechanical characteristics (flexural strength of 420 MPa) (Sundeep and Varadharaj, 2024).

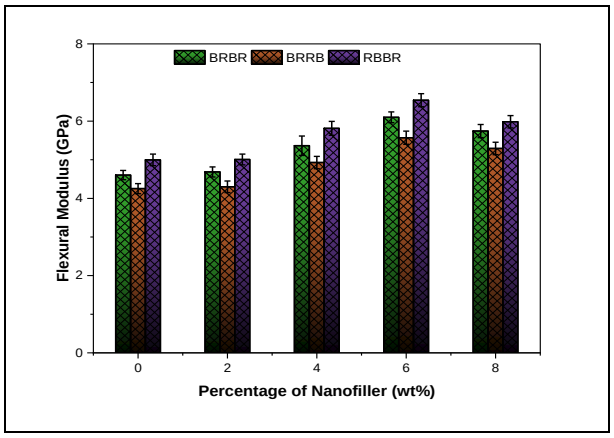


Fig. 7: Impact of GO nanoparticles and stacking pattern on the flexural modulus of the composite samples

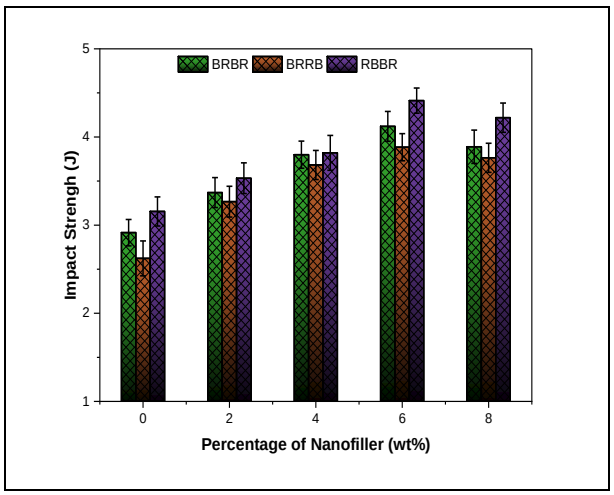


Fig. 8: Impact of stacking pattern and GO nanoparticles on the impact strength of the composite samples

3.5 Impact Energy

The main aim of an impact test is to evaluate a material's capacity to absorb energy under conditions of high strain rate. This study experimentally assessed the Izod impact energy of the fabricated banana/ramie hybrid composites, with and without GO nanoparticle fillers, in compliance with ASTM D256 standards. Fig. 8 depicts the fluctuation in impact energy relative to the fiber stacking sequence and the weight percentage of GO nanoparticles. The organized epoxy matrix demonstrated an impact energy of 4.3 J. The hybrid composites containing 6 wt% GO nanoparticles attained markedly elevated impact energies: 4.12 J for the BRBR stacking sequence, 3.84 J for BRRB, and 4.412 J for RBBR. The results indicate percentage enhancements of 284%, 263%, and 309%, respectively, in comparison to the unreinforced epoxy system. The RBBR stacking sequence exhibited the greatest impact resistance among the evaluated configurations. In a reported work, a hybrid composite of ramie fibers and filler achieved high impact strength (35.88 kJ/m²) (Mary *et al.* 2024). The enhanced performance is ascribed to the positioning of ramie fibers on the outer layers, recognized for their improved energy absorption capacity relative to banana fibers. The increased impact energy noted in the RBBR configuration highlights the effect of fiber orientation on dynamic mechanical performance, especially under high-velocity impact scenarios.

3.6 Interlaminar Shear Strength

Fig. 9 illustrates the Interlaminar Shear Strength (ILSS) values of the banana/ramie hybrid composite specimens, with and without GO nanoparticle fillers. A continuous improvement in ILSS was noted with the integration of GO nanoparticles, while preserving a uniform weight fraction of banana and ramie fibers in all configurations. The polished epoxy resin demonstrated an ILSS of 59.01 MPa, establishing a benchmark for comparison. Notable enhancements were observed in composites using 6 wt% GO nanoparticles. The improved ILSS results from enhanced interfacial adhesion between the epoxy matrix and the reinforcing fibers, enabled by the uniformly disseminated GO nanoparticles. These nanoparticles function as interfacial bonding, enhancing efficient stress transfer and reducing interfacial debonding. The incorporation of GO nanoparticles diminishes thermal induced stresses at the fiber-matrix interface, thus improving the structural integrity of the composites. At 6 wt% GO concentration, the peak ILSS values observed were 63 MPa for BRBR, 58 MPa for BRRB, and 66 MPa for the RBBR stacking sequence. These represent ILSS increases of roughly 40.0%, 38.1%, and 32.0%, respectively, in comparison to the pure epoxy system. Among the stacking sequences, RBBR demonstrated the maximum interlaminar shear strength (ILSS) followed by BRBR and BRRB. In previous study, the optimal fibre orientation that enhances the interlaminar shear strength of sisal fibre-reinforced epoxy composites (Subbiah *et al*. 2024).

The enhanced performance of the RBBR design is ascribed to the positioning of ramie fibers in the outer layers, which exhibit improved stiffness and interlaminar strength compared to banana fibers. The higher ILSS in this configuration results from the inherent mechanical superiority of ramie fibers and their greater compatibility with the matrix due to the presence of GO nanoparticles. The BRBR and BRRB sequences, including alternating layers of banana and ramie fibers, exhibit synergistic

effects, albeit to a lesser degree compared to that of RBBR.

3.7 Hardness of the Surface

Fig. 10 illustrates the surface hardness of hybrid composites with BRBR, RBBR, and BRRB stacking sequences, both with and without the addition of GO nanoparticle fillers. The results reveal a consistent increase in surface hardness across all stacking configurations as the GO content increases from 0 to 6 wt%, followed by a decline at 8 wt%. The enhancement in surface hardness is attributed to the increased stiffness imparted by the banana and ramie fibers and the restricted mobility of polymer chains due to effective filler reinforcement. At the optimal concentration of 4 wt% GO, the BRBR, BRRB, and RBBR composites exhibited surface hardness values of 44, 39, and 42, respectively. This indicates that the RBBR stacking sequence achieved the highest hardness among the tested configurations. The inclusion of fillers such as GO nanoparticles typically contributes to an increase in both surface hardness and elastic modulus of fiber-reinforced composites. However, exceeding the optimal filler concentration (e.g., 6 wt%) led to a reduction in surface hardness. This decline may be due to filler agglomeration and the resultant poor stress transfer efficiency, as well as the matrix becoming excessively constrained, which may cause internal stresses or compromise the interface, leading to premature material failure. These findings underscore the importance of optimizing filler content to achieve superior mechanical properties without inducing structural instability or interfacial degradation.

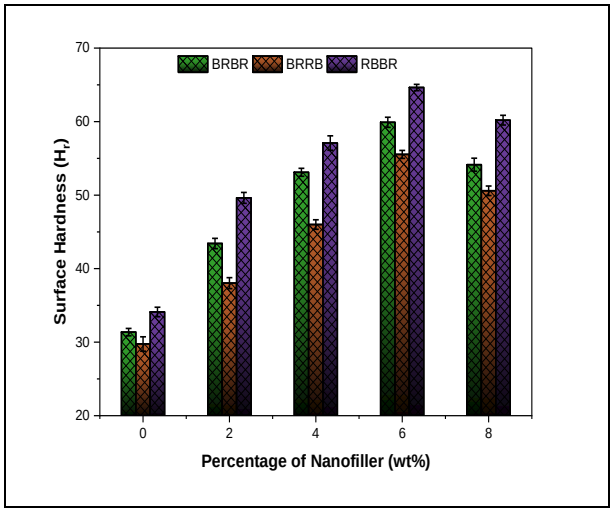


Fig. 9: Impact of stacking pattern and GO nanoparticles on the interlaminar shear strength of the composite samples

3.8 SEM Analysis of the Composite Specimens

Scanning electron microscopy was employed to analyze the tensile fracture surfaces of banana/ramie hybrid composites to investigate fiber failure mechanisms, fiber pull-out, and the quality of interfacial bonding between fibers and the matrix. The analysis revealed cracks and pull-out of the matrix in the composites. The SEM images provide critical insights into the microstructural changes caused by the inclusion of 6 wt% GO and the influence of stacking sequence. Fig. 11(a) shows the BRBR stacking sequence, without GO particles where the clean and smooth fiber surfaces indicate weak interfacial bonding. Minimal matrix residue on the fiber surface implies poor adhesion, contributing to inferior tensile strength. Fig. 11(b) corresponds to the BRBR sequence filled with GO. The presence of matrix debris adhered to the fiber surfaces reveals enhanced matrix-fiber interaction. However, signs of fiber pull-out and matrix cracking remain visible, suggesting partial improvement in bonding. Fig. 11(c) represents the BRRB configuration with GO reinforcement. Although there is better matrix bonding than the sample, without GO particles the presence of microcracks, voids, and fiber breakage points to moderately improved bonding, with stress concentrations still evident. Fig. 11(d) depicts the RBBR sequence reinforced with GO, which demonstrates the most effective fiber-matrix interface. Matrix material is clearly seen clinging to the fractured fiber ends, and the reduced presence of voids or pulled-out fibers implies strong interfacial bonding and superior load transfer capabilities. Overall, the SEM observations align with mechanical testing outcomes, highlighting that GO addition and optimal fiber stacking significantly enhance interfacial bonding and tensile performance. Optimal stacking sequence enhanced the tensile and impact strength, with voids and bonding observed by SEM analysis. The RBBR configuration, in particular, shows minimal void formation and improved structural coherence, making it the most mechanically robust composite arrangement among those studied.

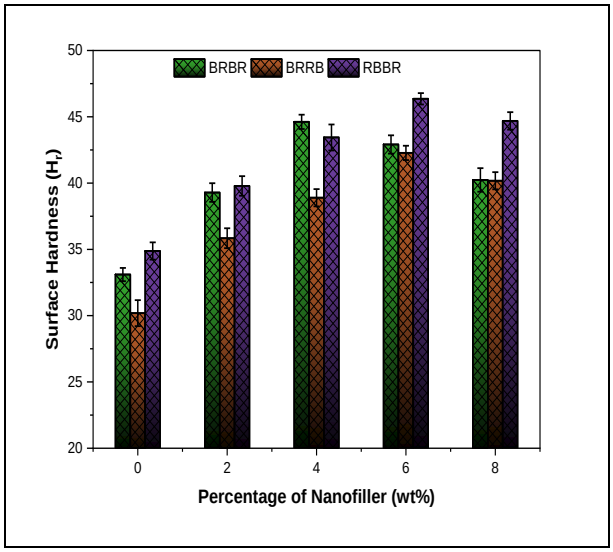


Fig. 10: Impact of GO nanoparticles and layering sequence on the surface hardness of the composite samples

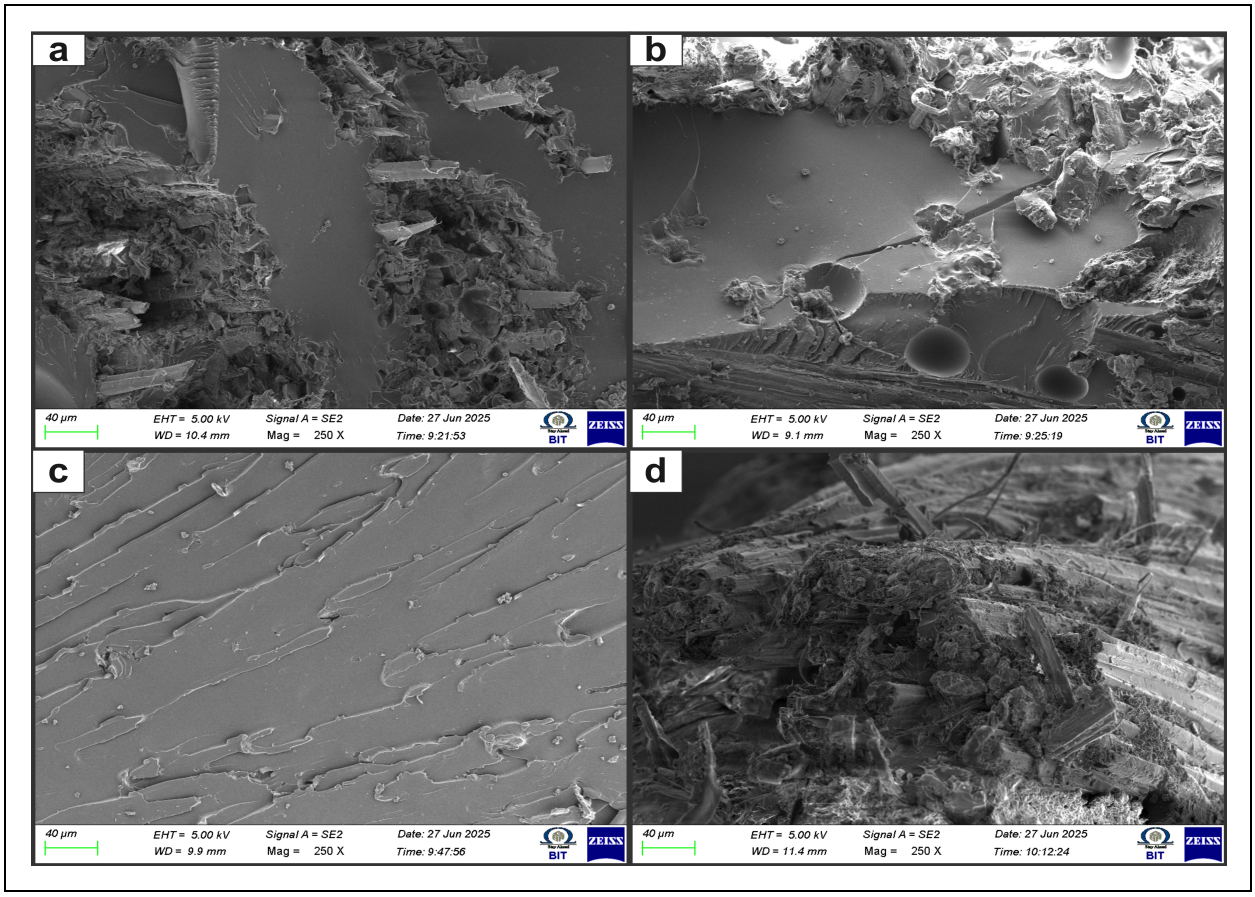


Fig. 11: Fracture surface of the tensile test specimens (a) Composites without filler. Composites with filler (b) BRBR, (c) BRRB, and (d) RBBR

4. CONCLUSIONS

This work thoroughly examined the mechanical, physical, and morphological properties of banana/ramie hybrid composites reinforced with different concentrations of graphene oxide nanoparticles. The composites were produced using the traditional hand layup method, incorporating ramie and banana fibers inserted in an epoxy matrix and uniformly distributed with GO nanoparticles. Improvements in tensile and flexural characteristics were noted in all three stacking sequences BRBR, BRRB, and RBBR with the increasing proportion of GO nanoparticles. The enhancements are mainly ascribed to the optimized filler distribution and improved interfacial adhesion between the epoxy matrix and the natural fibers. Among the fabricated laminates, the composite containing 6 wt% GO nanoparticles and arranged in the RBBR stacking sequence exhibited exceptional mechanical performance. Increasing the GO nanoparticle level to 6 wt% led to agglomeration and inadequate dispersion, thereby impacting fiber-matrix adhesion and overall composite efficacy. Thus, a 6 wt% GO nanoparticle reinforcement is considered ideal for banana/ramie epoxy-based hybrid composites. The enhanced mechanical and morphological characteristics at this concentration render the composites suitable for semi-structural and structural applications, such as printed circuit boards, electronic enclosures, and car dashboards.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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