Research Article

Journal of Environmental Nanotechnology

Experimental Investigation of the Behavior of Hybrid Natural Fiber-reinforced, Nano-filled HDPE Composites for Lightweight Automotive Components

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Received: 10.10.2025 Accepted: 11.11.2025 Published: 30.12.2025

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ABSTRACT

Due to the increasing demand for sustainable and lightweight materials in the automotive sector, there has been a renewed interest in natural fiber-reinforced polymer composites. In this work, the mechanical behaviour of hybrid composites composed of banana, kenaf, and coir fibers reinforced with high-density polyethylene (HDPE) containing nano-fillers is examined. The composite was prepared with 70% epoxy resin. The contents of fibers and HDPE were varied in three different proportions: (1) 10% banana, 10% kenaf, 5% coir and 5% HDPE; (2) 7.5% banana, 10% kenaf, 7.5% coir and 5% HDPE; and (3) 7.5% banana, 7.5% kenaf, 10% coir and 5% HDPE. Nanoparticles were incorporated into the HDPE matrix to enhance the mechanical and physical characteristics of the composites. Experimental results showed that compositions with higher banana and kenaf fiber contents exhibited improved tensile strength, compressive strength, and impact resistance. Conversely, formulations containing a higher coir fiber content exhibited enhanced flexural strength, hardness, and water absorption performance. Scanning electron microscopy (SEM) analysis of fracture surfaces provided insights into fiber–matrix adhesion and fracture mechanism. Overall, the incorporation of nano-fillers significantly improved the behaviour of hybrid natural fiber/HDPE composites, making them suitable for lightweight and eco-friendly automotive components. These enhanced mechanical properties demonstrate the strong potential of the developed hybrid nano-filled composites for lightweight automotive components, contributing to vehicle weight reduction, improved fuel efficiency, and lower emissions.

Keywords: Hybrid natural fiber composites; Nano-fillers; HDPE reinforcement; Automotive applications; Mechanical properties.

1. INTRODUCTION

Natural fiber-reinforced composites are gaining popularity in the automotive, marine, and aerospace sectors owing to their environmental friendliness, high specific strength, and low cost. Kenaf, banana, and coir fibers are promising natural alternatives to synthetic fibers such as glass fiber. This research investigates hybrid composites with different proportions of banana, kenaf, and coir fibers and HDPE, while maintaining a constant epoxy content of 70%. Mechanical and morphological studies indicate that fiber composition has a great impact on strength, impact resistance, and water absorption characteristics.

Natural fiber–reinforced polymer composites have attracted increasing attention in the automotive industry due to their biodegradability, low cost, and high strength-to-weight ratio. (Al-Oqla and Sapuan, 2014) showed that date palm fibers can be used as the constituent of polymer composites to provide sustainable automotive parts. (Al-Oqla *et al.* 2016) developed a decision-making framework to choose the appropriate natural fiber-polypropylene composites for vehicle manufacturing. Hybridization approaches have also demonstrated an increase in mechanical performance. (Palanikumar *et al.* 2016) indicated an increase in tensile and flexural properties of sisal-glass fiber composites, whereas (Hanan *et al.* 2020) found that oil palm/kenaf fiber hybrids can be used in lightweight car parts with a positive mechanical performance. (Marichelvam *et al.* 2020) demonstrated that palm sheath and sugarcane bagasse fiber hybrids could be used for automotive interiors.

Detailed studies by (Mochane *et al.* 2019; (Nurazzi *et al.* 2021) and (Suriani *et al.* 2021) highlighted that hybrid natural fiber composites were found to provide a balance between the mechanical performance, low cost, and sustainability, which could be used as structural and semi-structural parts of the automotive industry. Specifically, natural and glass fiber-reinforced penta-layered hybrid composites proved to be considerably better in terms of impact and wear-resistance properties, and thus, can be used in the load-bearing parts of the vehicles (Mochane *et al.* 2019).

(Athith *et al.* 2018) showed that hard fillers like tungsten carbide can be used to increase tribological and mechanical characteristics of natural fiber hybrid composites significantly, which can satisfy the requirements of high-performance automotive engineering. The functional capability of natural fiber composites has also been increased further with the integration of nanotechnology. According to (Saba *et al.* 2014), nano-fillers are also important in enhancing fiber-matrix interfaces and durability and thermal stability. As demonstrated by (Tang *et al.* 2016) and (Zhang *et al.* 2011), nano-enhanced polymer composites such as HDPE can be used in automotive electronics, engine, and body panel industries owing to their superior thermal and dielectric behavior. In the overall automotive design, polymer matrix nanocomposites play an important role in lightweighting efforts with no adverse effect on environmental sustainability (Naskar *et al.* 2016). (Boland *et al.* 2016) found through life cycle assessment that natural fiber composites could mitigate environmental impacts, thereby supporting lightweighting and renewable energy policies. Other recent research has also pointed to progress in lightweight materials and forming technologies, such as aluminum, magnesium, and composite systems (Czerwinski, 2021; Rosenthal *et al.* 2020), and sustainable manufacturing methods such as wire arc additive manufacturing of lightweight automotive parts (Omiyale *et al.* 2022). Hybrid polymer composites have shown considerable advances in the mechanical performance, especially in the multi-layered glass-natural fiber composites, which are applicable in structural automotive applications (Karthick *et al.* 2022). The use of recycled fiber composites has been shown to reduce life-cycle environmental impacts while promoting automotive lightweighting (Meng *et al.* 2017). Also, nano-engineered polymer composites have better dielectric and functional characteristics that broaden their application in the future in the development of sophisticated automotive and electronic items (Zhang *et al.* 2016).

This paper presents a novel hybrid composite made of banana, kenaf, and coir fibers with HDPE and augmented with nano-fillers, designed as an automotive lightweight component. Although previous studies have concentrated on single or dual fiber systems, the present study aims to explore a three-fiber hybrid with different ratios and provide an understanding of the synergistic behavior of mechanical and physical characteristics. The application of the nano-filled HDPE in strengthening the fiber-matrix bonding is not examined extensively, especially in environmentally friendly car materials. Also, there are relatively few studies that present comparative performance information among composites in tensile, flexural, and impact strengths. This paper fills this void by combining the variability of natural fibre with nano-enhancement and subsequent SEM analysis to extend the work on sustainable composites.

2. MATERIALS AND METHODS

2.1 Materials

The natural fibers (banana, kenaf, and coir), nano-enhanced high-density polyethylene (HDPE), and unsaturated polyester resin, which are used as the matrix in this study, are natural fibers. Other materials needed during the fabrication process are cobalt naphthalate (used as an accelerator), methyl ethyl ketone peroxide (MEKP) (catalyst), cellophane leather (sealing agent of the mold), and rollers, scissors, water, containers, and molds used in specimen preparation.

2.2 Banana Fiber

Banana Fiber (Figure 1) has high specific strength, similar to glass fiber, with a low weight, moderate elongation, fire resistance, and good moisture absorption. These characteristics make it an eco-friendly bio-reinforcement for use in automotive composite materials.



Fig. 1: Banana fibers sample

2.3 Kenaf Fiber

Kenaf is a cellulose-based natural fiber that grows rapidly (Figure 2). It is relatively inexpensive and sustainable. Its mechanical characteristics and the fiber yield depend on cultivar, planting time, climate, and maturity stage. They are extensively used in composite products because of their power and renewability.

2.4 Coir Fiber

Coir is a natural, durable fiber extracted from the coconut husk and was traditionally used in products such as mats, brushes, and mattresses (Figure 3). The increasing application of sustainable composite materials is motivated by their broad availability, durability, and environmental compatibility.



Fig. 2: Kenaf fiber sample



Fig. 3: Coir fiber sample

2.5 High-density Polyethylene (HDPE)

HDPE is a high-strength-to-density ratio thermoplastic polymer made of petroleum, with high chemical resistance. Nano-fillers were used to reinforce HDPE in this study to enhance its mechanical strength, toughness, and thermal performance. To enhance interfacial bonding and overall composite behavior, the nano-enhanced HDPE is incorporated into the fiber matrix, which makes it appropriate for lightweight automotive parts (Figure 4).

2.6 Selection of Epoxy Resin

Although unsaturated polyester was preferred as the primary matrix owing to its good flowability, moldability, and low cost, alternative materials such as epoxy resin were also considered due to their high tensile strength (80–120 MPa), high thermal resistance (up to 200 °C), and excellent chemical stability. These binders are used in composite fabrication to produce materials suitable for automotive manufacturing.

2.7 Specimen Fabrication

The hybrid composite laminates were made through the hand lay-up method. A pre-weighed amount of unsaturated polyester resin was combined with 4% cobalt naphthalate (accelerator) and 1% MEKP (catalyst). This was cast into a mold and left to dry pre-harden in 10 minutes. A sheet of cellophane leather was put on top of the composite, followed by a mold cover. A concrete block was taken to press it for 24 hours to cure properly. To eliminate air entrapment between layers, a roller was used to increase adhesion between the fibers and the matrix. The laminates were subsequently machined to ASTM standard dimensions for mechanical testing.



Fig. 4: Nano-filled HDPE



Fig. 5: Epoxy resin

2.8 Specimen Preparation

The fabricated composite laminates were cut into standard sizes with a hacksaw after the curing period in order to attain uniformity and precision in specimen dimensions in various mechanical tests.

2.9 Mechanical Testing of the Specimens

Mechanical tests (impact strength, flexural strength, and compressive strength tests) were done on different laminate samples as per ASTM in the Structural Laboratory, Civil Engineering Department, Abubakar

Tafawa Balewa University, Bauchi State, Nigeria. Table 1 presents the matrix reinforcement ratio. Figure 6 shows the fiber images.

2.10 Matrix–Reinforcement Ratio

Table 1. Matrix–reinforcement ratio

Composition Ratio	Epoxy Resin	Banana Fiber	Kenaf Fiber	Coir Fiber	Nano-filled HDPE
R1	70% / 210 g	10% / 30 g	10% / 30 g	5% / 15 g	5% / 15 g
R2	70% / 210 g	7.5% / 22.5 g	10% / 30 g	7.5% / 22.5 g	5% / 15 g
R3	70% / 210 g	7.5% / 22.5 g	7.5% / 22.5 g	10% / 30 g	5% / 15 g

2.11 Compression Molding

Choosing a suitable processing technique is the key to the desired quality, performance, and cost-efficiency of natural fiber composites. The compression molding process (Figure 7) is characterized by low cycle time, high reproducibility, and low fiber damage. Other variations, such as sheet molding compounds (SMCs) and extrusion-compression blends, are even more efficient and cost-effective to manufacture.



Fig. 6: Fiber images after weight calculation

2.12 Hardness Testing

The Brinell, Rockwell, and Vickers tests are the most commonly used methods to measure metal hardness. These tests assess a metal's resistance to indentation by observing how deeply a ball or cone penetrates under a set load and time. Generally, harder metals also exhibit greater strength (Figure 9).

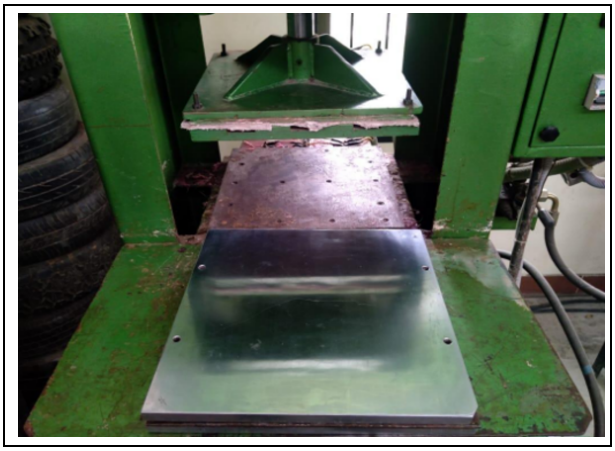


Fig. 7: Compression molding machine

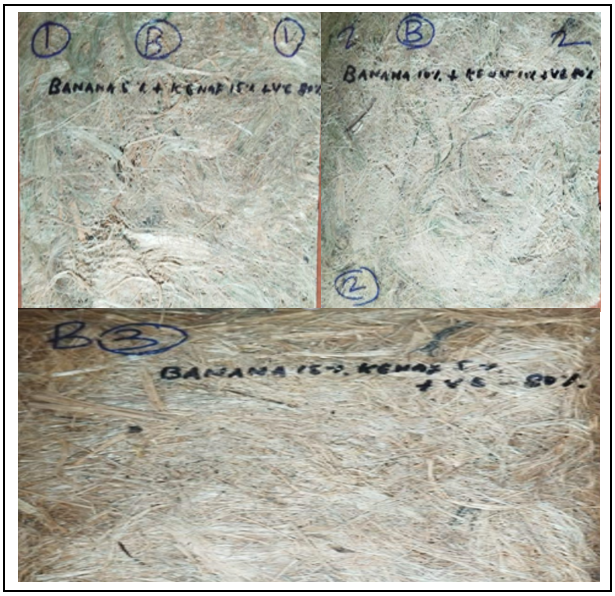


Fig. 8: Fabricated fiber sheets



Fig. 9: Hardness testing

2.13 Impact, Tensile, Compressive, and Flexural Tests

The Izod test is used to estimate the resistance of a material to sudden loads. An increase in the absorbed energy indicates an increase in toughness, which is important in impact-sensitive structures such as aircraft skins.



Fig. 10: Tensile and compression testing setup

Tensile and compressive strengths of composites were measured using an INSTRON 3369 universal testing machine (UTM). It was carried out on the basis of the standard ASTM 3039 (tensile test) and the compressive strength ASTM-D 3410. The speed of the cross-head was kept at 5 mm/min (Figure 10).

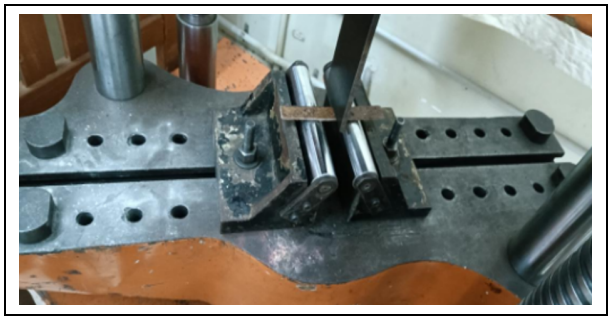


Fig. 11: Flexural test setup

The popular method of determining the flexural strength of a material is through a transverse bending test with a three-point flexural test method. Bending strength is also referred to as flexural strength, modulus of rupture, or transverse rupture strength. To determine the flexural properties (strength and modulus), the samples were made as per ASTM D 790 standard (Figure 11).

3. RESULTS AND DISCUSSION

3.1 Hardness Value

Table 2. Hardness value

Sample Code	Composite Composition (With nano-filled HDPE)	Hardness (HRM)
B1	Epoxy Resin 70% + Banana Fiber 10% + Kenaf Fiber 10% + Coir Fiber 5% + Nano-HDPE 5%	66
B2	Epoxy Resin 70% + Banana Fiber 7.5% + Kenaf Fiber 10% + Coir Fiber 7.5% + Nano-HDPE 5%	74
B3	Epoxy Resin 70% + Banana Fiber 7.5% + Kenaf Fiber 7.5% + Coir Fiber 10% + Nano-HDPE 5%	72

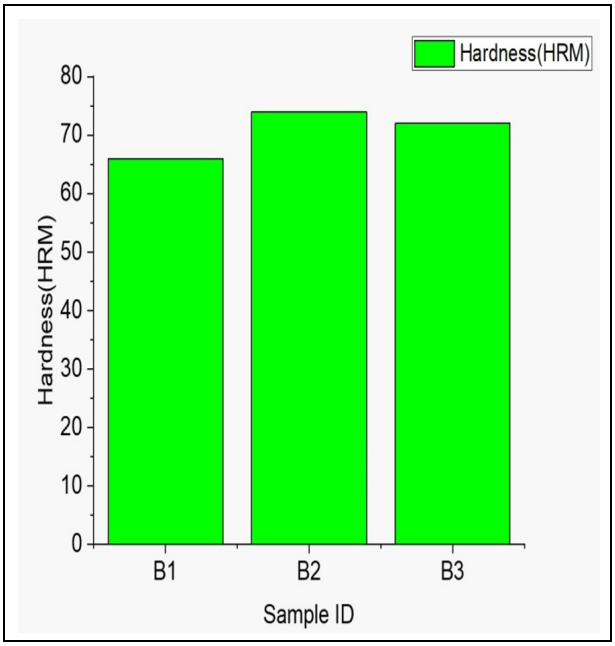


Fig. 12: Hardness strengths of samples

The results of the hardness tests (Figure 12 and Table 2) depict that the sample B2 has the highest hardness strength of approximately 74 HRM, followed by B3 with 72 HRM. But the sample B1, with the highest percentage of banana and kenaf coir fibers, exhibited reduced hardness (66 HRM).

3.2 Tensile Strength Values

Table 3. Tensile strength value

Sample ID	Thickness (mm)	Width (mm)	Cross-sectional Area (mm²)	Tensile Strength N/mm²)	Average TS (N/mm²)
B1	3.27	23.96	78.349	11, 81	46
B2	3.17	27.77	88.031	7, 14	10.5
B3	3.22	21.67	69.777	8, 6	7

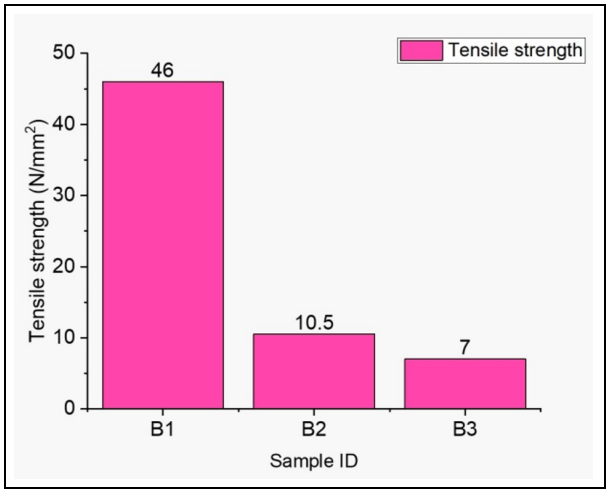


Fig. 13: Tensile strength graph

The results of the tensile test (Table 3 and Figure 13) indicate that the maximum proportion of banana and kenaf with the least coir fiber (B1) results in the highest average tensile strength of 46 N/mm^2.

3.3 Impact Test

The maximum impact load of 0.90 J was observed for sample B1 (Table 4 and Figure 14), which contains a higher percentage of banana and kenaf fibers and a lower percentage of coir fiber. The sample B2 exhibited an impact load of 0.80 J. In contrast, higher coir fiber contents resulted in a minimum impact load of 0.75 J.

Table 4. Impact energy of samples

S. No.	Sample	Impact value (J)
B1	ER-70%+BF-10%+KF-10%+CF-5%+HDPE-5%	0.90
B2	ER-70%+BF-7.5%+KF-10%+CF-7.5%+HDPE-5%	0.80
B3	ER-70%+BF-7.5%+KF-7.5%+CF-10%+HDPE-5%	0.75

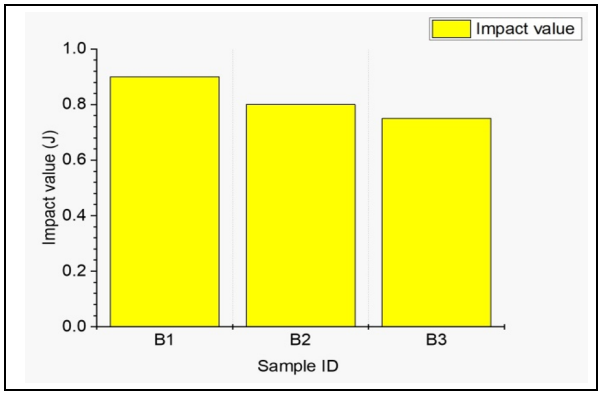


Fig. 14: Variation of Impact energy of samples

3.4 Flexural Strength

Table 5. Flexural strength value

Identification	Thickness (t), mm	Span length (l), mm	Flexural load (W), kN	Flexural Strength (N/mm²)
B1	3.71	50	0.08	51.28
B2	3.77	50	0.12	76.92
B3	3.49	50	0.09	57.69

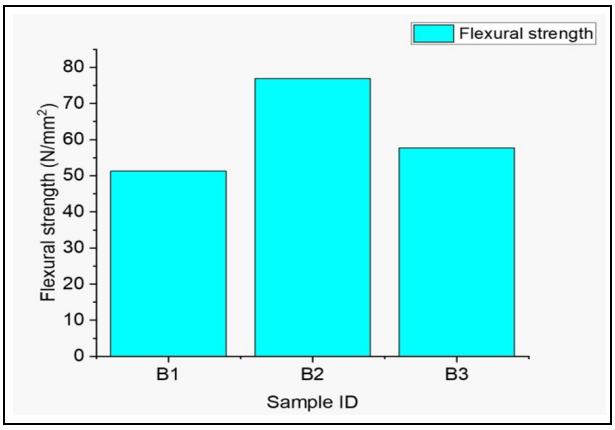


Fig. 15: Flexural strength graph

The results of the flexural strength test (Table 5 and Figure 15) indicate that a maximum flexural strength of approximately 76.92 N/mm² is achieved with sample B2. This is followed by the specimen (B3) with equal banana and kenaf fiber contents and a higher percentage of coir fiber, which exhibits a flexural strength of 57.69 N/mm².

3.5 Compression Load

As per the compressive load test results (Table 6 and Figure 16), the highest compressive load of approximately 0.24 kN is registered for the composite sample B1.

Table 6. Compressive loads of samples

S. No.	Sample	Compressive Load (kN)
B1	ER-70%+BF-10%+KF-10%+CF-5%+HDPE-5%	0.24
B2	ER-70%+BF-7.5%+KF-10%+CF-7.5%+HDPE-5%	0.10
B3	ER-70%+BF-7.5%+KF-7.5%+CF-10%+HDPE-5%	0.16

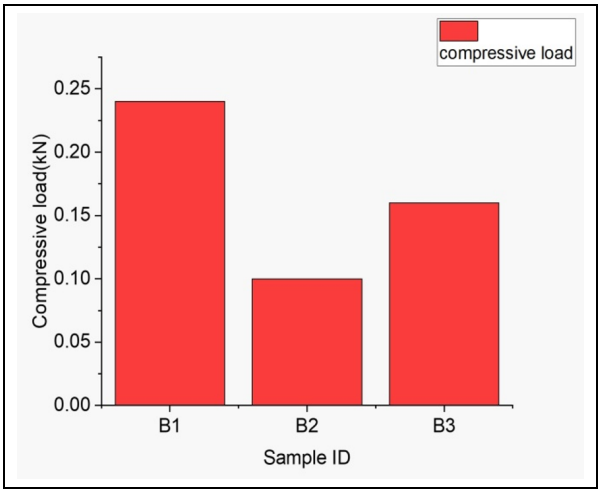


Fig. 16: Variation of Compressive loads of samples

3.6 Water Absorption Assessment

Water absorption of all hybrid fiber composites was assessed over a period of 3 days at 24-hour intervals. The results show that composites with higher coir fiber content exhibited lower water absorption, with a minimum value of 18%. In contrast, composites with higher kenaf fiber content showed a maximum water absorption of 47% (Figure 17).

The nature and percentage of natural fibers in the hybrid composite determine the water absorption behavior rather strongly. The one with more coir fibers had the lowest water absorption (18%) due to the fact that coir fibers have larger lignin content and a tighter cell structure that does not allow moisture diffusion. Conversely, composites with higher kenaf fiber content exhibited the highest water absorption (47%) because kenaf is hydrophilic, contains higher cellulose content, and has more micro-voids that absorb water. This trend clearly indicates that the choice of fiber type and ratio is crucial for controlling moisture resistance in automotive applications.

The performance trends were analyzed by comparing fiber ratios with specific mechanical properties. Results show that higher banana–kenaf content enhances structural performance, yielding maximum tensile, compressive, and impact resistance. In contrast, increased coir content improves hardness and reduces water absorption due to its denser, more moisture-resistant structure. Overall, the hybrid composites containing nano-fillers exhibit superior performance across multiple properties, demonstrating their potential for high-performance automotive applications.

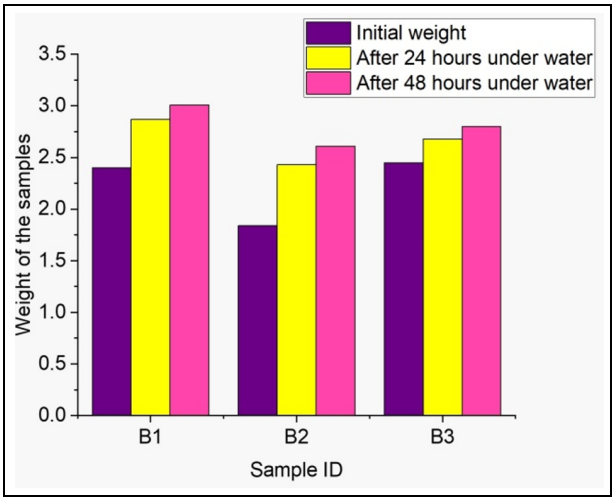


Fig. 17: Water absorption graph

3.7 SEM Analysis

Figures 18–20 show the SEM images of samples B1, B2, and B3, respectively.

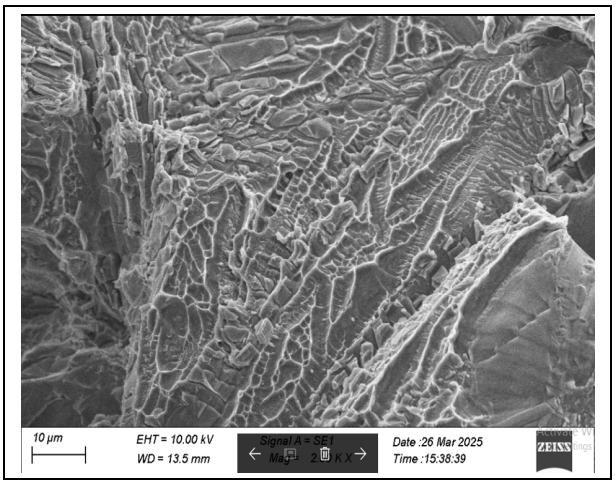


Fig. 18: SEM image of sample B1

Microfracture and fiber pullout were significantly reduced in the B1 sample (Figure 18). The smooth broken surface shows good adherence and interaction between the banana fiber, and kenaf fibers, and the polymer matrix. Tensile strength has also improved, according to the results.

Figure 19 shows the post-tensile fracture condition of sample B2. The fibers, fiber aggregation, and fiber-free matrix are all clearly evident. The air gaps are clearly evident in the image. The fiber orientation and dispersion are also visible, and the composite is weakened by the air gaps.

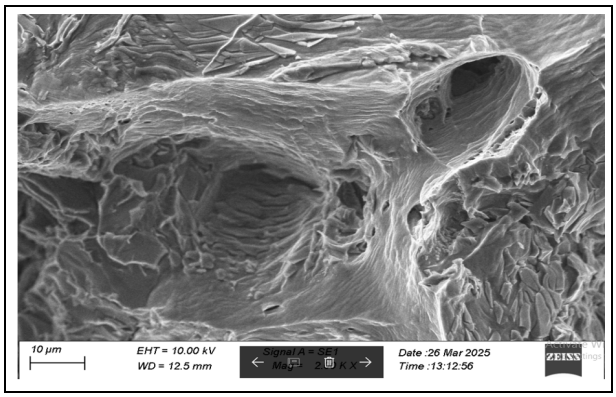


Fig. 19: SEM image of sample B2

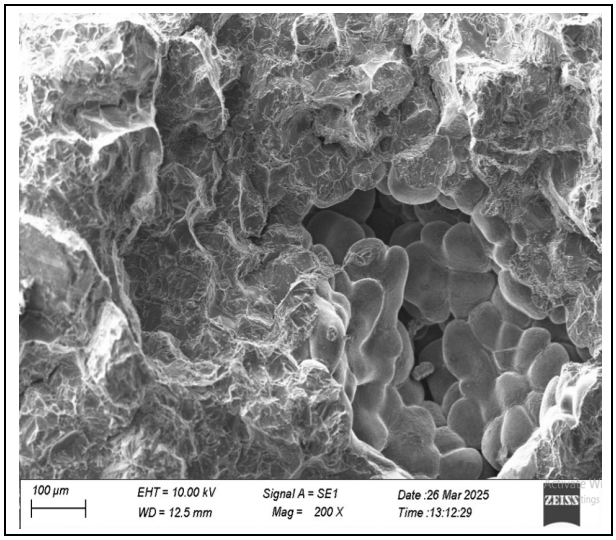


Fig. 20: SEM image of sample B3

Figure 20 depicts substantial fiber pullout on the tensile side of the fracture in sample B3, indicating inadequate fiber–matrix adhesion. This poor interfacial bonding significantly reduces composite strength, as evidenced by the minimal matrix resin adhering to the fibers.

4. CONCLUSION

Banana, kenaf, and coir fibers were demonstrated to be potential sustainable reinforcing fibers in epoxy matrix composites through the production of hybrid natural fiber–reinforced composites using the compression molding process.

Hardness test results indicated that composites with higher kenaf fiber content exhibited greater hardness (up to 75 HRM), suggesting that resistance to indentation is provided by the nano-fibrillar structure of kenaf fibers.

Higher banana fiber and kenaf fiber contents combined with a lower coir content resulted in maximum tensile strength (46 N/mm²), indicating strong interfacial adhesion and effective nano-scale stress transfer between the fibers and the matrix.

Composites with a balanced banana/kenaf ratio and reduced coir fiber content showed the highest impact strength (0.90 J), demonstrating that micro- and nano-level hybridization enhances energy absorption capacity without inducing brittle failure.

The maximum flexural strength (76.92 N/mm²) was obtained with sample B2, as the finer kenaf fibrils enabled improved load distribution and bending resistance, highlighting their structural role in green composites.

Water absorption experiments revealed that increasing coir content reduced water absorption (18%), whereas increasing kenaf content increased absorption (47%). These results indicate that fiber ratios can be optimized to improve environmental sustainability, which is a critical consideration for eco-friendly applications.

SEM fractography revealed voids and interfacial gaps in certain samples (B2 and B3), corroborating that nano-scale defects have a profound influence on tensile strength. In general, composites containing higher banana and kenaf contents and lower coir content exhibited superior tensile, compressive, and impact properties, making them promising materials for eco-friendly engineering applications with reduced reliance on synthetic reinforcements.

Overall, these results demonstrate strong practical potential for hybrid and nano-engineered polymer composites as lightweight, sustainable automotive materials capable of enhancing structural performance while reducing vehicle weight, fuel consumption, and environmental impact.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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