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Investigation of the Mechanical and Morphological Behavior of Hybrid PALF-Kenaf Composites Reinforced with Hydroxyapatite and Zinc Oxide Nanoparticles

Shilpa B. Sahare[1], P. Satishkumar[2*], Sivakumar Ramamurthy[3], D. S. Vijayan[4], Azhagu Saravana Babu Packirisamy[5], R. Prakash[6] and P. Krishnakumar[6]

[1]Department of Mechanical Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, MH, India
[2]Department of Mechanical Engineering, Rathinam Technical Campus, Coimbatore, TN, India
[3]Department of Physics, Easwari Engineering College, Ramapuram, Chennai, TN, India
[4]Department of Civil Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission Research Foundation (VMRF), Chennai, TN, India
[5]Department of Biotechnology, Vel Tech Rangarajan Sagunthala R & D Institute of Science and Technology, Chennai, TN, India
[6]Department of Science & Humanities, Rathinam Technical Campus, Coimbatore, TN, India
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*sp.sathishkumar10@gmail.com

ABSTRACT

This research examines the mechanical, biodegradable, and morphological properties of pineapple leaf fiber (PALF), kenaf fiber (KF), and hybridized PALF-KF composites reinforced with hydroxyapatite and zinc oxide nano-fillers. The composites were fabricated using the hand lay-up technique followed by compression molding. Mechanical properties such as tensile, impact, flexural, and hardness were evaluated in accordance with ASTM standards. The PALF–kenaf hybrid composite achieved a maximum tensile strength of 55.38 MPa, impact strength of 7.68 kJ/m^2, and hardness of 84.62, while the neat PALF composite exhibited the highest flexural strength of 106.56 MPa. Biodegradability assessments indicated that natural fiber composites degraded more significantly than nano-reinforced composites, with PALF-rich variants showing greater weight loss over time. SEM analysis revealed strong fiber–matrix bonding in the hybrid composites. However, the agglomeration of nano-fillers resulted in lower strength values for PALF-KF hybrid composites. These findings offer valuable insights into optimizing hybrid natural fiber composites to enhance their mechanical and morphological behavior.

Keywords: PALF; Kenaf; Nano-hydroxyapatite; Mechanical properties; Biodegradability.

1. INTRODUCTION

The increasing significance of environmentally friendly materials has driven the growing use of natural fiber-reinforced composites (NFRCs). They are highly regarded for their overall performance, chemical resistance, and strength. Additionally, they offer significant benefits, such as environmental sustainability and biodegradability. Unlike traditional composites made from carbon, glass, or aramid fibers, NFRCs are an eco-friendlier alternative, as they break down naturally. Glass/jute hybrid epoxy laminates were fabricated through hand lay-up to assess the impact of cyclic loading on vibration characteristics. Free vibration and fatigue tests revealed that the stacking sequence has a significant impact on the dynamic behavior. Optimal stacking achieved balanced tensile, flexural, and vibrational performance (Murugan *et al.* 2023). Areca–carbon and areca–basalt fiber composites were fabricated using epoxy/bio-epoxy matrices and three different stacking sequences. Carbon–areca composites showed superior tensile, flexural, and impact properties, while SEM confirmed better interfacial bonding. These bio-based laminates are suitable for medium-load structural applications (Yashas *et al*. 2022a).

Flax, Kevlar, and carbon fiber-based hybrid epoxy laminates were fabricated with varying stacking sequences. Carbon–flax hybrids (CFFCs) achieved the highest tensile (178.48 MPa) and flexural (378.86 MPa) strengths and the lowest water absorption. Outer synthetic fiber layers significantly improved interlaminar and impact properties (Yashas *et al.* 2022b). Jute–wool hybrid epoxy laminates were stacked in four sequences and tested for flexural strength (FS), interlaminar shear strength (ILSS), impact strength (IS), and fracture toughness. JW1 (Jute/Wool/Wool/Jute) outperformed others with a tensile strength of 40 MPa and an ILSS of 3.09 MPa due to outer jute and core wool synergy. JW1 showed an 82% mechanical improvement over other configurations (Shivayogi *et al.* 2024). Buri palm fiber treated with 5% NaOH for 24 h yielded the highest single-strand tensile strength of 159.16 MPa. Composite laminates with a 5-layer stacking achieved a flexural strength of 56.72 MPa. Alkali treatment and increased layering improved mechanical performance for lightweight automotive interiors (Zalinawati *et al.* 2020).

PALF-strengthened epoxy composites were fabricated with 1.5 and 3 wt. % nanoclay using hand lay-up and compression molding. The maximum mechanical strength was observed with 30 wt. % PALF and 1.5 wt. % nanoclay; however, 3 wt. % caused agglomeration and reduced bonding. SEM analysis showed strong interfacial bonding with 1.5 wt. % nanoclay (Muralishwara *et al.* 2023). PALF/epoxy composites were fabricated with varying fly ash filler (3–9 wt. %) and PALF (10–30 wt. %) contents. Optimal mechanical results were observed at 6 wt. % fly ash with a 65.3% tensile and a 31.9% flexural strength improvement, and water absorption decreased with higher filler. SEM confirmed uniform dispersion and improved interfacial bonding (Nagaraja *et al.* 2024). Epoxy Lapox L-12 composites with 40 wt. % PALF and boron carbide (5–15 wt. %) were fabricated by hand lay-up. The 15 wt. % B_4C composite showed maximum improvements: 61.7% in tensile, 34.6% in flexural strength, and 51.6% in hardness. Mechanical performance increased in the composites, while elongation slightly decreased (Devi *et al*. 2025). Epoxy composites with 5–10 vol. % graphite and 30 vol. % PALF were prepared using hand lay-up. Mechanical testing showed enhanced tensile and flexural strengths, though elongation was slightly reduced. FEM simulation validated the experimental findings (Reddy *et al.* 2022). PALF with epoxy composites were prepared with various fiber types, orientations (0°, 45°, and 90°), and contents (5–25 wt. %). Long fibers at 5 wt. % achieved the highest tensile (35.72 MPa) and flexural (56.19 MPa) strengths, while 0° orientation yielded the best impact and flexural properties. FTIR and SEM confirmed chemical treatment and failure modes (Singh *et al*. 2024).

PALF/epoxy composites were modified with 1.5 wt. % surface-treated nanoclay to reduce seawater absorption. Nanoclay addition decreased the diffusion coefficient by 54% and saturation uptake by 74%, minimizing strength degradation. Mechanical tests and SEM revealed better retention of tensile and flexural properties under wet conditions (Ambekar *et al*. 2023). Kenaf/Kevlar-29 hybrid composites (with 0.5–1.5 wt. % graphene) were fabricated using hand lay-up. Flexural strength and hardness increased significantly at 1–1.5 wt. % graphene due to enhanced bonding, while lower concentrations reduced hardness. The layering sequence influenced the performance, with alternating layers yielding optimal properties (Hombal *et al.* 2025). Areca/kenaf hybrid epoxy laminates were fabricated with different stacking sequences using LY556-HY951 matrix. Kenaf-as-skin laminates showed better tensile, flexural, and hardness properties, while areca-as-skin offered higher compressive and impact strength. SEM analysis revealed fiber pull-out and matrix cracking patterns (Sathyaseelan *et al.* 2024). Kenaf-reinforced ABS (Acrylonitrile Butadiene Styrene) composites with a six-layer arrangement were analyzed for water uptake and strength. The 0°/45°/−45°/90° configuration yielded the best TS (35.3 MPa) and FS (85.4 MPa) and the lowest water absorption. The ±45° plies improved multi-directional strength and minimized fiber pull-out (Fitri *et al*. 2024).

Indian almond and kenaf (KF) composites with different stacking sequences were evaluated for dynamic mechanical behavior. The Kenaf/Kenaf/Indian almond configuration showed the maximum storage and loss moduli due to high stiffness and better bonding. Thermal stability of the composites followed the order: Kenaf > Kenaf/Almond > Almond/Kenaf > Almond (Jeyaraman *et al.* 2022). Hybrid laminates of aloe vera, roselle, and glass fibers showed improved thermal and mechanical behavior. Adding aloe vera between roselle layers enhanced tensile strength by 30.2%, while three roselle layers resulted in a 12.6% higher impact strength. Hybrid sequencing led to 6.1% thermal degradation up to 800 °C (Vijayan *et al.* 2023). In-situ synthesis of hydroxyapatite (HAp) on cellulose fibers was carried out using microwave irradiation for the development of a dental resin composite. Characterization confirmed HA deposition, and mechanical testing showed improved strength as cellulose/HAp content increased from 30 to 50 wt. %. Biocompatibility tests revealed over 90% cell viability, indicating the material's suitability for dental restorations (Sabir *et al.* 2020). A composite of cellulose nanocrystals (CNCs), HAp, and natural fibers was developed to simulate real bone behavior for surgical training. Mechanical tests showed a cutting force of approximately 4 N, matching human bone properties, while CNCs enhanced fracture toughness and surface irregularity. 3D X-ray imaging confirmed uniform CNC dispersion, enabling realistic bone-cutting simulation (Jeon and Kim, 2024).

Epoxy composites, reinforced with wood dust and varying ZnO nanoparticle (0.1–1 vol. %) content, were prepared by casting. Mechanical tests, such as FS and hardness, improved up to 0.5 vol. % ZnO, then declined due to likely agglomeration. SEM analysis confirmed morphological characteristics supporting this trend (Al-Lhaibi and Shabander, 2022). Ixtle and henequen fiber biolaminates with ZnO (1–3 wt. %) in bio-epoxy resin were fabricated using vacuum-assisted infusion. Mechanical and viscoelastic behavior varied by fiber type and filler loading, with optimal performance in henequen laminates at >2 wt. % ZnO. Excessive filler led to reduced interlaminar bonding and toughness (Torres *et al.* 2022*)*. Kenaf fiber/epoxy composites treated with 6% NaOH and reinforced with 3 wt. % TiO_2, MgO, or ZnO nanoparticles showed enhanced mechanical strength. Vacuum bagging and ultrasonication ensured uniform dispersion, resulting in improved mechanical properties. NaOH treatment combined with nanofiller addition optimized fiber-matrix bonding (Sathish Kumar *et al.* 2023).

30% of pineapple leaf fiber (PALF) and 2.5–10% of chemically treated pineapple micro-particulates were combined in hybrid polymer composites. The 7.5% particulate loading offered peak tensile, flexural, and hardness properties, while 2.5% loading maximized impact strength. TGA, SEM, and biodegradability tests confirmed improved interfacial bonding, thermal stability, and eco-performance (Saha *et al.* 2021). Polylactic acid (PLA) reinforced with *Pennisetum setaceum* fiber underwent marine and disintegration biodegradability tests. Composites degraded faster than neat PLA, especially in disintegration conditions, with higher mass loss and mechanical property reduction. Fiber addition significantly improved the biodegradability of PLA, highlighting its potential for reducing plastic waste in marine environments (Cabrera *et al.* 2024).

This study investigated the fabrication of epoxy composites reinforced with natural fibers, namely pineapple leaf fiber (PALF) and kenaf (KF), incorporating nano-hydroxyapatite (n-HAp) and nano-zinc oxide (n-ZnO) as innovative additives. Bioactivity and high stiffness were introduced by incorporating n-HAp. The composites are suitable for multifunctional applications due to the filler system's enhanced antibacterial and UV-resistant properties when combined with n-ZnO. For the first time, PALF and kenaf, two sustainable and under-utilized natural fibers, were hybridized in a woven form to capitalize on their complementary mechanical properties. This hybridization is anticipated to result in enhanced tensile, flexural, and impact properties, as well as improved biodegradability and lightweight performance. Compression molding was carried out after the hand lay-up of composites. Seven composite variants were fabricated, both with and without nano-fillers. Mechanical testing was conducted following ASTM standard procedures. A biodegradability test was conducted to assess the environmental impact. The SEM investigation revealed the filler dispersion and the quality of the fiber-matrix bonding. The study illustrated the potential of PALF–Kenaf/n-HAp/n-ZnO composites in biomedical and structural applications that are lightweight.

2. MATERIALS AND METHODS

2.1 Materials

The PALF and KF woven bi-directional mats were employed as reinforcement in the composites, and they were obtained from Go Green Products, Chennai, India. The matrix material was supplied by Covai Cheenu Enterprises, Coimbatore, India, and it was composed of an epoxy resin (LY556) and a hardener (HY951). The Matrics Enterprises, Nagercoil, Tamilnadu, India, provided the nano-fillers, zinc oxide (ZnO) and hydroxyapatite (HAp), each with an average particle size of 30 nm.

2.2 Fabrication of Composites

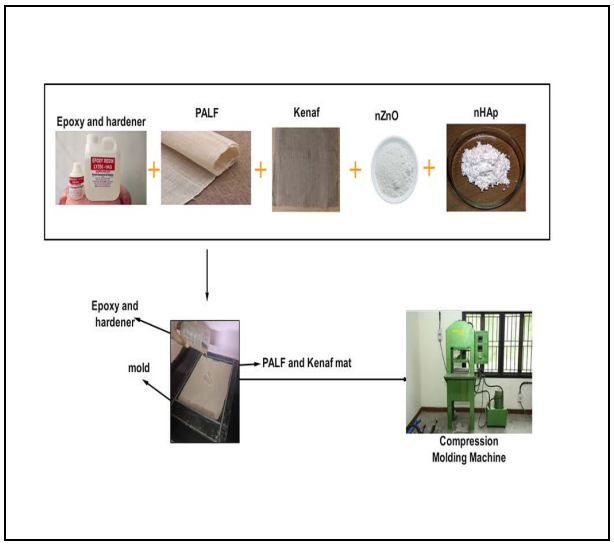


Fig. 1: Fabrication process of the composite

Fig. 1 presents the schematic of the composite fabrication process. Initially, fiber mats were sectioned into uniform dimensions of 300 mm × 250 mm. The hybrid composites were fabricated using five layers of woven PALF and KF, arranged according to the designated layer arrangement (A, B, C, D, E, F, and G). All composite laminates were fabricated to maintain a consistent thickness of 3 mm, ensuring uniform mechanical comparison. The epoxy resin and hardener were mixed manually in a 10:1 weight ratio for approximately 5–8 minutes to obtain a homogeneous matrix (Gaddala *et al.* 2025). To ensure a controlled fiber-to-matrix ratio of approximately 25:75, mild steel (MS) plates were placed on both sides of the mold. To ensure the cured composites could be removed easily and without surface damage, a mold release agent was applied to the plates before processing.

The hand lay-up process was subjected to uniform pressure at ambient temperature for 24 hours to allow complete curing (Kumar *et al.* 2025). This procedure was repeated identically for all subsequent composite variants. For hybrid composite configurations, fiber stacking was conducted based on the laminate sequences detailed in Table 1. In the case of nano-filled hybrid composites, the appropriate quantity of nano-fillers was first added into the epoxy resin and manually stirred for 30 minutes to ensure uniform dispersion prior to hand lay-up. Following the curing process, the composite laminates were sectioned and conditioned for mechanical testing. Fig. 2 depicts the Universal Testing Machine (UTM) setup and the composite specimens for testing TS, FS, and IS. Mechanical testing, including tensile, flexural, impact, and hardness tests, as well as the biodegradability test, was conducted following relevant ASTM standards to evaluate the structural performance of the fabricated composites.

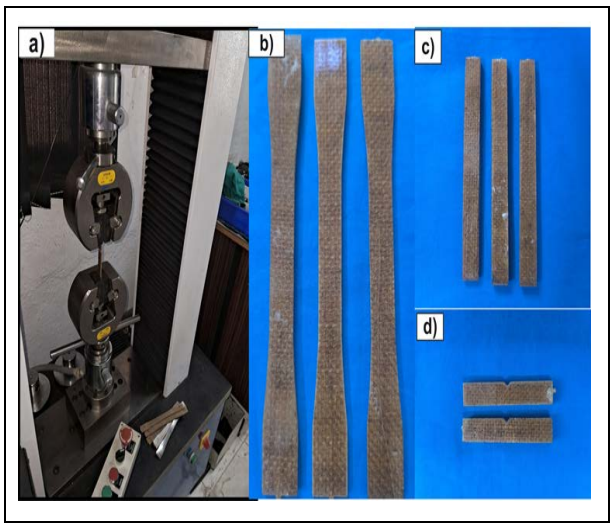


Fig. 2: (a) Universal Testing Machine, and (b-d) Specimens for tensile, flexural, and impact strength tests

Table 1. Composite Specimens

Speci-men	Stacking Order	Epoxy (wt. %)	Fiber (wt. %)	Nano-HAp filler (wt. %)	Nano-ZnO filler (wt. %)
A	PPPPP	75	25	-	-
B	KKKKK	75	25	-	-
C	PKPKP	75	25	-	-
D	PKPKP + HAp	74	25	1	-
E	PKPKP + ZnO	74	25	-	1
F	PKPKP + HAp	73	25	2	-
G	PKPKP + ZnO	73	25	-	2

P-PALF, K-Kenaf, ZnO-Zinc oxide, HAp- Hydroxyapatite

2.3 Analysis of Mechanical Properties

The mechanical performance of the composites was examined as per ASTM standards. In accordance with ASTM D638-03, dumb bell-shaped specimens measuring 175 mm × 25 mm × 3 mm were used at a constant displacement rate to measure tensile characteristics on a UTM (Mayakannan *et al.* 2023). As per ASTM D790, flexural testing was conducted on specimens measuring 125 × 12 × 3 mm. The crosshead speed of 2 mm/min and 5 kN load was maintained for both tests. Utilizing an Izod impact tester, the impact resistance of the specimen was assessed in accordance with ASTM D256. The specimen had a V-shaped notch and measured 127 mm x 10 mm x 3 mm. Specimens measuring 30 mm x 10 mm were subjected to hardness testing according to ASTM D2240, with a dwell time of 15 s.

2.4 Biodegradation of Composites

The composites underwent biodegradation in soil under natural burial conditions. A uniform mass was formed by initially eliminating inert components and subsequently removing dirt from the surface layer (Ejaz *et al.* 2020). To achieve a depth of approximately 4 cm in a plastic pot, 100 g of soil was incorporated. The samples, with dimensions of 30 mm × 10 mm × 3 mm, were buried to a depth of 1 cm in pots following meticulous weighing, and then dried for 24 hours at 50 °C. To maintain moisture, water was misted daily. Each specimen was weighed weekly for four weeks after being dried for one day at 50 °C and subsequently washed with distilled water. The biodegradation process was repeated three times for each sample.

2.5 SEM Analysis

SEM analysis was employed to examine the surface morphology and fiber–matrix interfacial bonding of the fractured composite specimens, which were sputter-coated with a thin gold layer. SEM images were captured at various magnifications to investigate fracture mechanisms and filler dispersion. The testing was conducted at the Bannari Amman Institute of Technology, Sathyamangalam, Tamilnadu, India.

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

Fig. 3 depicts the tensile behavior of the tested composites. The hybridized sample (C) demonstrated the highest TS at 55.38 MPa, whereas the pure PALF sample (A) recorded a strength of 54.62 MPa. This appears to be a synergistic effect between KF and PALF fibers, as approximately a 1.3% increase in the strength of composite C was observed compared to A. Utilizing more robust fibers in the outermost layers enabled the hybrid composite to attain its maximum strength. The superior characteristics of PALF, including its ability to effectively transmit stress and its strong interfacial bonding with the matrix, contribute to its mechanical performance. Furthermore, the hybrid composite demonstrates enhanced strength as a result of the combination of PALF's high aspect ratio and KF's reduced microfibril angle.

The composite showed the minimum TS at 29.27 MPa compared to the pure PALF and the PALF–KF hybrid composite. This indicates that the tensile strength is highest when PALF layers are combined with

kenaf fibers, particularly when PALF is used in the inner layers. The primary reasons for the enhancement of tensile and flexural strengths by PALF are its high rigidity and strong bonding with the matrix. The addition of nano-fillers (HAp and ZnO) resulted in a substantial decrease in the tensile strength of the hybrid composites (D, E, F, and G) in comparison to the unfilled hybrid composite (C).

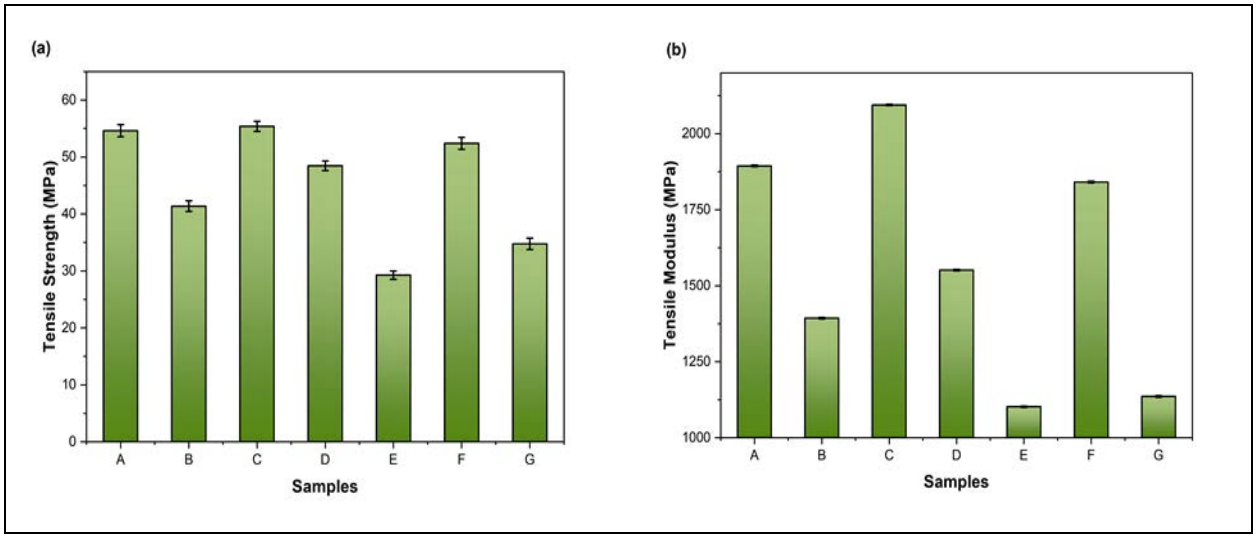


Fig. 3: (a) Tensile strengths and (b) Tensile moduli of the composite samples

The TS of the composite F was 52.40 MPa, reflecting a 5.38% decrease compared to the hybrid composite C. Composite G exhibited a notable reduction of 37.26% in TS (34.75 MPa) compared to the other composites. Similarly, kenaf/glass/polyester composites were reinforced with 1–5 wt. % pistachio shell particles (PSP) and stacked in various sequences (KGKG, GKKG, etc.). The KGKG configuration with 5% PSP exhibited the best tensile strength (127.35 MPa), while 3% PSP provided the highest flexural (112.42 MPa) and impact strength (Mohapatra *et al.* 2024). The addition of nano-fillers leads to non-uniform stress distribution within the composite due to filler agglomeration, which negatively affects the strength. The variations in tensile modulus among the composites indicate variances in fiber rigidity, fiber–matrix bonding, and filler distribution. The pure PALF composite (A) and hybrid composite (C) exhibited elevated tensile moduli, signifying effective stress transfer attributable to the high aspect ratio of PALF fibers and their robust interfacial adhesion with the epoxy matrix. In the hybrid composites, kenaf fibers enhanced stiffness, while PALF layers preserved structural rigidity, yielding balanced modulus values. The incorporation of nano-fillers in composites D–G resulted in a reduced tensile modulus relative to the unfilled hybrid (C), mostly attributable to nano-filler agglomeration and void formation, which serve as stress concentrators and impede uniform load distribution.

3.2 Flexural Properties

Samples (A–G) had their flexural characteristics determined using the three-point bending test. Fig. 4 shows that composite A, made entirely of PALF fibers, had the maximum average flexural strength of 106.56 MPa, emphasizing the extraordinary bending capability of PALF fibers. The inclusion of kenaf fibers resulted in a reduction in the FS of composite B (71.20 MPa). Meanwhile, a hybrid of kenaf and PALF fibers (composite C) exhibited a flexural strength of 64.30 MPa. The FS values for the nano-filled hybrid composites (D, E, F, and G), which included HAp and ZnO fillers, were 50.52, 54.05, 56.80, and 58.35 MPa, respectively. These values are slightly lower than those of the unfilled composites, primarily due to nano-filler agglomeration and the formation of voids, which weaken the composite structure. Thus, the PALF fiber composites (A) showed the best flexural characteristics The trends in flexural modulus correspond to the stiffness and bending resistance of the fiber architecture. Composite A, composed only of PALF fibers had the highest modulus attributable to PALF's elevated cellulose content and comparatively low microfibril angle, which augment its bending rigidity. The reduced modulus in hybrid composites (C) and kenaf samples (B) indicates that, although kenaf fibers have commendable flexural strength, they exhibit diminished resistance to bending deformation. Nano-filled hybrids (D–G) demonstrated marginally diminished flexural moduli, ascribed to filler agglomeration that interrupts the continuity of the load transfer and induces premature local deformation under bending stresses..

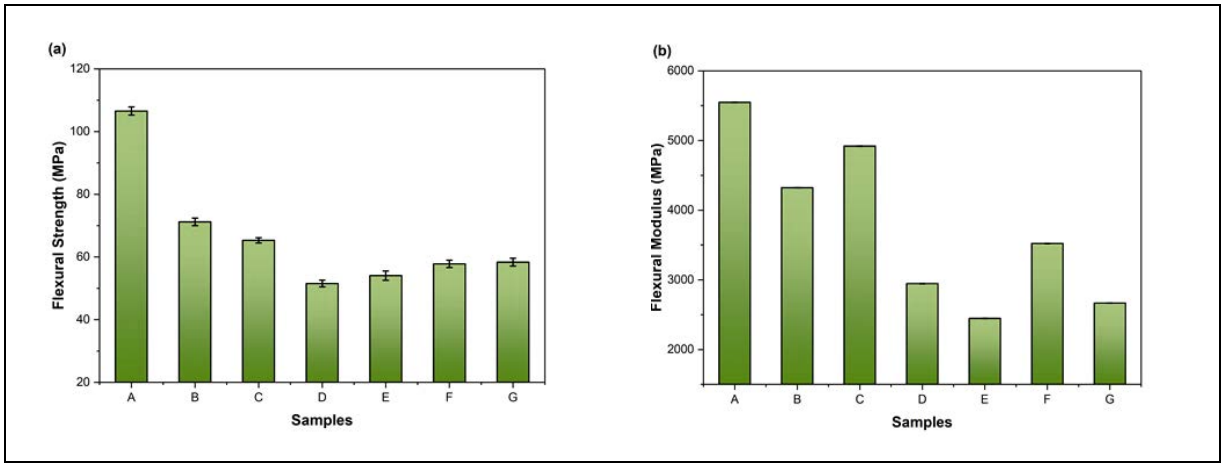


Fig. 4: (a) Flexural strengths and (b) Flexural moduli of the composite samples

3.3 Impact Properties

The impact strengths of the composites (A–G) were assessed to evaluate their ability to absorb energy and resist fracture. Typical data for impact intensity and average absorbed energy are shown in Fig. 5. The PALF–kenaf hybrid composite (C) exhibited the maximum impact strength of 7.68 kJ/m^2, which highlights the effective energy absorption resulting from the combination of PALF and kenaf fibers, outperforming the pure composites A and B. In contrast, the HAp nano-filled hybrid composites (D and F) exhibited impact strengths of 7.14 and 7.17 kJ/m^2, respectively. The incorporation of HAp nano-fillers slightly improved toughness and fracture resistance. Compared to the PALF composite (A), which had an IS of 6.41 kJ/m^2, the kenaf composite (B) showed a lesser value of 5.79 kJ/m^2. The ZnO nano-filled hybrid composites (E and G) demonstrated even lower impact strength values, 5.57 and 5.56 kJ/m^2, respectively, due to weaker interfacial bonding and increased filler agglomeration. Likewise, a composite reinforced with jute, glass fibers, and kenaf, filled with multi-walled carbon nanotubes (MWCNTs), exhibited superior flexural strength (136 MPa) and impact resistance (169 J/m). These improvements were attributed to uniform nanoparticle dispersion and strong fiber–matrix interfacial bonding (Arunachalam *et al.* 2025). This variation in energy absorption and impact resistance among the composites highlights the influence of nanofiller dispersion, hybridization strategy, and fiber type on overall performance. The combination of additives and the synergistic use of different fibers enhances the impact resistance of hybrid composites**.** The hybrid composite (C) exhibited the highest energy absorption owing to the synergistic effects of PALF and kenaf fibers, with PALF contributing stiffness and kenaf giving enhanced elongation prior to failure, resulting in optimal toughness. The slight enhancement in HAp-filled hybrids (D and F) indicates that the ceramic properties of HAp facilitate fracture deflection and microcrack bridging. In contrast, ZnO-filled hybrids (E and G) exhibited reduced absorbed energy, presumably due to filler aggregation and inferior interfacial adhesion, which favor brittle fracture over energy-absorbing failure mechanisms.

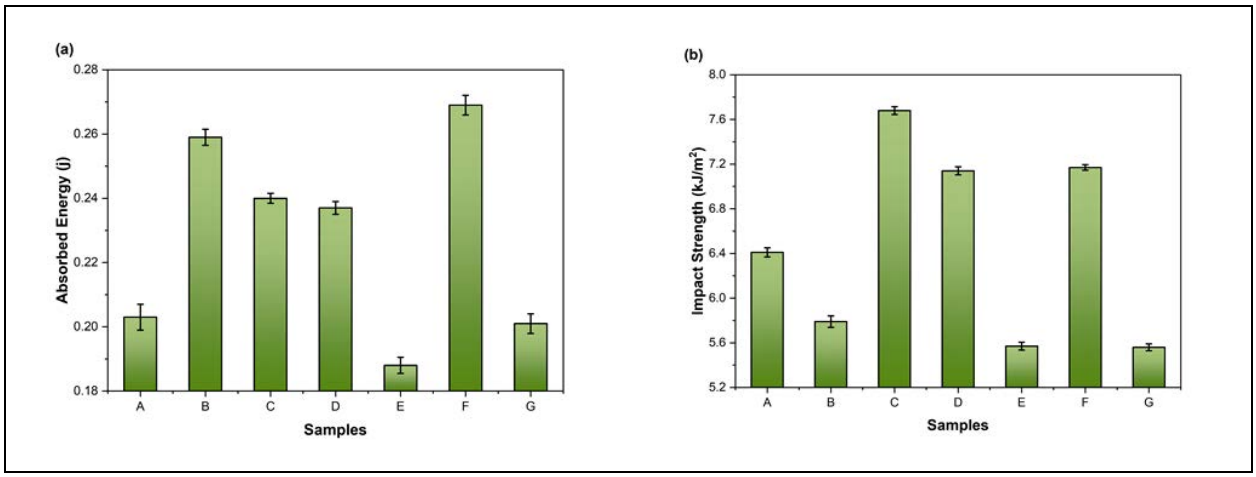


Fig. 5: (a) Impact energy absorbed by the composite samples and (b) Impact strengths of the composite samples

3.4 Hardness

Samples with relatively high hardness values required the use of the Shore durometer hardness test, specifically the Shore D scale. By evaluating the depth of indentation of a calibrated indenter under standardized load conditions, the hardness of the manufactured samples (A to G) was determined according to the ASTM D2240 standard. All of the composites had Shore D hardness values ranging from 79.02 to 84.62 (Fig. 6). On average, the hybrid composite (C) exhibited the highest hardness value (84.62), followed by the pure kenaf composite, B (83.18), and the pure PALF composite, A (82.76). The composites containing nano-fillers (D–G) showed slightly lower hardness values than the pure and hybrid fiber composites, likely due to the presence of voids and filler agglomeration. The superior hardness of the PALF–kenaf hybrid composite (C) can be attributed to the complementary properties of both fibers: KF provides excellent energy absorption, while PALF contributes stiffness and structural rigidity. As demonstrated by previous results, this combination improves both hardness and impact resistance.

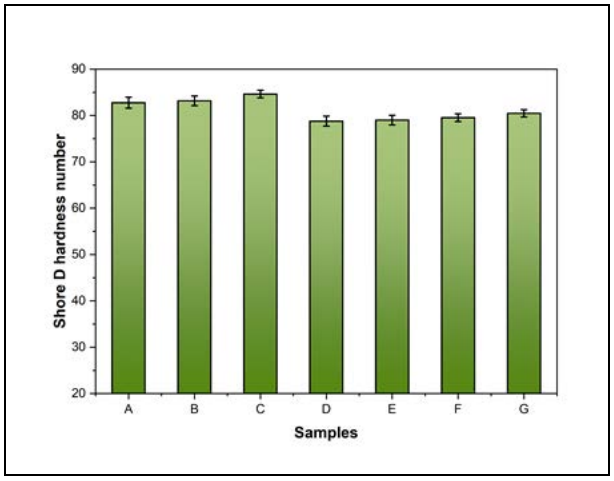


Fig. 6: Hardness of the composite specimens

3.5 Biodegradability Test

The usage of natural fibers such as PALF and KF offers significant benefits in terms of environmental sustainability and end-of-life disposal due to their intrinsic biodegradability. Both fibers are lignocellulosic, primarily composed of hemicellulose, cellulose, and lignin materials that are naturally broken down by microbial activity in soil and composting environments. The hybridization of PALF and KF in the current study further supports biodegradability by maintaining a 100% bio-based reinforcement system. The fiber content, maintained at 25 wt. % in all composite variants, ensures that a significant portion of the material remains bio-derived. PALF is particularly recognized for its high cellulose content, which accelerates microbial degradation, while KF, with its favorable fibrillar structure and lower microfibril angle, promotes moisture absorption, a factor that can enhance biological breakdown in suitable environments.

Regarding the nano-fillers, both HAp and ZnO are inorganic and do not degrade biologically. However, these materials are considered non-toxic and biocompatible, particularly in biomedical and environmental contexts. Their incorporation at low levels (1–2 wt. %) is unlikely to significantly hinder the overall biodegradability of the composite and assist partial breakdown due to the creation of microstructural discontinuities. As shown in Fig. 7, Composite A (pure PALF) showed the highest biodegradation, reaching approximately 42% mass loss after 12 weeks, due to its high cellulose content and absence of inorganic fillers. Composite B (pure KF) followed, with around 37% degradation. Composite C (PALF–KF hybrid) exhibited slightly lower biodegradation (~33%) due to the mixed fiber configuration. Nano-filled hybrid composites (D to G) demonstrated further reductions in biodegradability, attributed to the presence of non-degradable inorganic particles. In a similar approach, polyvinyl chloride was reinforced with untreated and treated areca sheath fibers using injection molding. A fiber loading of 18 wt. % provided optimal mechanical properties, with TS and FS of 42.38 MPa and 18.22 MPa, respectively. Biodegradability improved with increasing fiber content, supporting the use of natural fibers in partially degradable composites (Nayak *et al.* 2020).

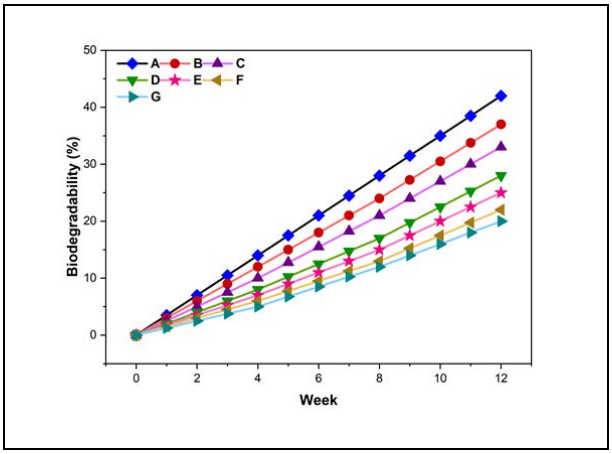


Fig. 7: Biodegradability of various composites

3.6 SEM Analysis

SEM was used to examine the surface characteristics of a fractured tensile specimen of the PALF–KF hybrid (C) composite. Fig. 8 shows SEM images indicating a reduced number of cavities and slight fiber–matrix separation. The uniform resin distribution enhances durability by enabling efficient load transfer from the matrix to the fibers. This robust interfacial bonding also helps to reduce fiber pull-out. SEM observations support the potential use of the composites

in automotive and sports equipment applications (Sathyaseelan *et al.* 2022). Kenaf fibers contribute compressive strength and rigidity, while PALF fibers provide excellent tensile strength. Incorporating them together results in improved mechanical performance. SEM analysis validated improved bonding and minimal void formation, indicating suitability for medium-load structural applications (Raghunathan *et al*. 2022).

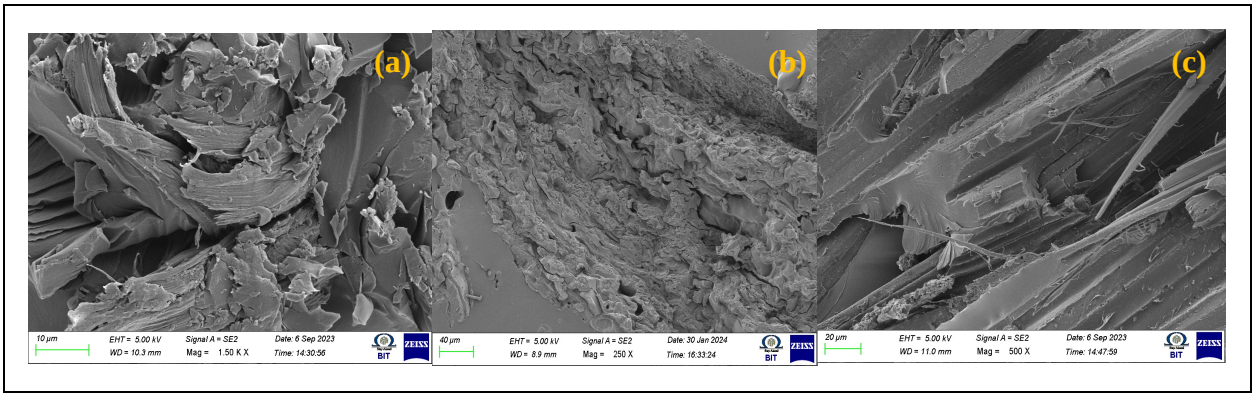


Fig. 8: SEM micrographs of the fractured tensile specimen C: (a) Fiber-matrix delamination, (b) Voids, and (c) Fiber pull-out

Fig. 9 depicts the SEM images of the hybrid composite specimen with ZnO nano-fillers (E). Fig. 9 (a) clearly shows nanoparticle aggregation, which results from the non-uniform distribution of ZnO nanoparticles in the epoxy matrix. This agglomeration is primarily caused by the high surface area of the nano-fillers and intensified by strong Van der Waals forces. These forces lead to nanoparticle clustering instead of uniform dispersion. Nanoparticle clusters serve as stress concentrators under mechanical loading, resulting in localized stress zones that weaken the composite's mechanical properties. This prolonged stress concentration accelerates crack initiation and propagation, ultimately reducing the strength and durability of the composite. Moreover, nano-fillers possess higher density, which increases their tendency to settle at the bottom of the matrix during mixing. This sedimentation, combined with poor dispersion and limited interfacial bonding due to their large surface area, results in compromised mechanical performance and increased agglomeration. Fig. 9 (b) depicts fiber fragmentation caused by premature failure. The reduction in strength is further attributed to weak interfacial bonding, causing inadequate bonding between the ZnO nano-fillers and the epoxy matrix. Fig. 9 (c) shows evidence of fiber breakage. This further confirms the inadequate interaction between the nano-fillers and the matrix, thereby hindering effective load transfer within the composite.

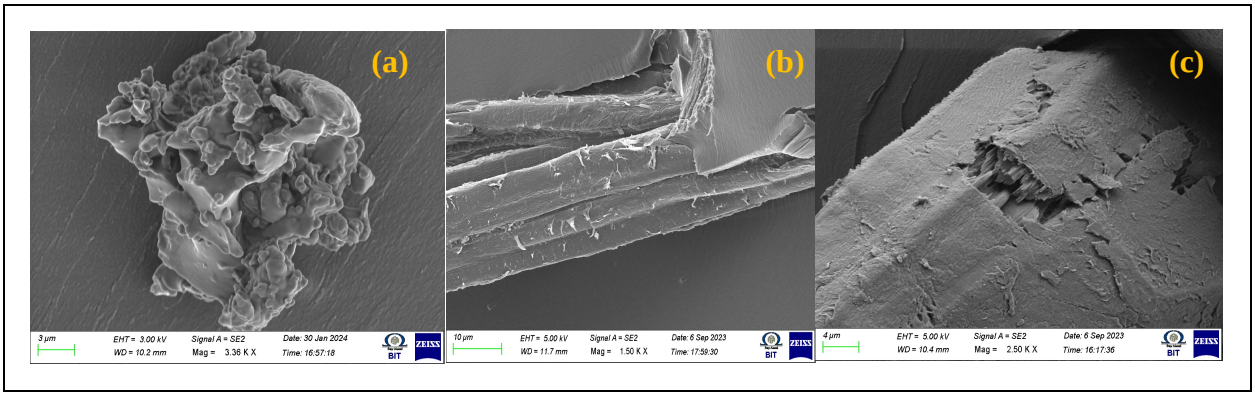


Fig. 9: SEM images of the fractured tensile specimen E (ZnO nano-filled composite): (a) Accumulation of nano-fillers, (b) Fiber-matrix bonding, and (c) Fiber breakage

4. CONCLUSION

The main objective of the study is to examine the mechanical properties of woven PALF and kenaf composites that have been subjected to varying layering sequences and the addition of HAp and ZnO nano-fillers. Surface morphology of the composites was analyzed using SEM. The following conclusions can be drawn from the study:

Among all tested composite specimens—pure PALF (A), pure kenaf (B), hybrid PALF–kenaf

composite (C), the nano-filled variants HAp-filled (D, F), and ZnO-filled (E, G), specimen C exhibited the highest TS (55.38 MPa), IS (7.68 kJ/m^2), and Shore D hardness (84.62). The pure PALF composite (A) exhibited the maximum FS at 106.56 MPa, surpassing both B (71.20 MPa) and C (64.30 MPa). Compared to the pure kenaf composite (B), this reflects a 41.37% improvement in flexural strength. Furthermore, the nano-filled composites C (hybrid), D, E, F, and G showed up to a 33.9% increase in strength compared to composite B, depending on the filler and layering configuration. In general, the mechanical properties of the nano-filled composites (HAp-filled D and F, and ZnO-filled E and G) were lower than those of the pure PALF (A), pure Kenaf (B), and hybrid PALF–KF (C) composites. The agglomeration of nano-fillers (HAp and ZnO) is the primary reason for this reduction, as it results in voids and microstructural flaws within the matrix, reducing the strength of the material. The biodegradation behavior of the composites confirms that the natural fiber-reinforced variants (A to C) degrade more significantly over time compared to the nano-filled composites. Composites with higher PALF content exhibited the greatest weight loss, indicating higher environmental compatibility. These findings support the suitability of PALF-KF composites as sustainable alternatives for semi-biodegradable structural applications. The SEM analysis of the ZnO nano-filled composite (E) revealed micro-pores, agglomeration, and cavities in the fractured tensile specimen. These structural defects acted as stress concentrators, leading to premature failure and directly contributing to the observed reduction in mechanical performance.

AUTHOR CONTRIBUTION STATEMENT

Shilpa B Sahare - Conceptualization, Methodology, Experimental Design, Writing, Original Draft. Satishkumar P - Materials Preparation, Mechanical Testing, Data Collection, Funding Acquisition. Sivakumar Ramamurthy - SEM Analysis, Visualization, Morphological Studies. D. S. Vijayan - Biodegradability Assessment, Data Curation, Validation. Azhagu Saravana Babu Packirisamy - Formal Analysis, Literature Review, Writing, Review & Editing. R. Prakash - Supervision, Project Administration, Technical Guidance. Krishnakumar P - Resources, Final Manuscript Review and Approval.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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