Research Article

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Development of High-performance Peepal Fiber/Epoxy Composites with ZrO_2 Nanofiller for Structural Applications

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ABSTRACT

Natural fiber reinforced polymer composites are increasingly favored for applications in both commercial and residential environments. This study seeks to improve the mechanical properties of peepal (P) fiber and epoxy resin (E) composites through the incorporation of zirconium oxide (ZrO_2) nanoparticles as a filler. The composites were fabricated using the compression molding process, with the filler used at varying amounts (0 wt%, 1 wt%, 3 wt%, 5 wt%, 7 wt%). Tensile, hardness, and impact tests were performed on the fabricated composites. The mechanical properties, including tensile strength, impact resistance, and hardness were enhanced in the S1 composite. The uniform dispersion of ZrO_2 nanoparticles and their enhancement of load transfer between the epoxy matrix and peepal fiber were the principal factors contributing to the improvement in hardness and strength. Infrared spectroscopy validated the beneficial effects of alkaline treatment on the peepal fiber. This experimental study seeks to improve peepal-epoxy composites through the use of fillers, aiming to produce lightweight and highly durable components for aerospace and automotive industries. Scanning electron microscopy was employed to analyze the fracture surfaces.

Keywords: Peepal fiber; Mechanical properties; Epoxy resin; Natural fibers; ZrO_2 nanofiller.

1. INTRODUCTION

As the importance of sustainability has grown in recent years, many researchers and industries have developed sustainable materials that either replace or at least enhance synthetic fibers. Common fibers are advantageous due to their high specific strength, low weight, affordability, and global availability. Natural fiber composites with banyan and peepal fibers were developed in various ratios using the hand layup technique. The banana-peepal-banana hybrid composite showed the best mechanical properties, lowest density, and lower water absorption. This lightweight, high-strength material shows potential for industrial applications (Velmurugan *et al.* 2022). Hybrid composites made with peepal and Indian almond fibers were fabricated for automotive applications. The epoxy with 40 wt% peepal fiber composite outperformed others in strength, wear resistance, and friction behavior. Peepal fiber composites demonstrate potential as alternatives to conventional industrial composites (Xavier *et al.* 2024). The inflorescence of *Ficus religiosa* was explored as an eco-friendly adsorbent for crystal violet dye removal from wastewater. With 94.15% efficiency in just 15 minutes and adherence to Langmuir isotherm and pseudo-second-order kinetics, the process proved highly effective. The adsorbent was reusable and effective in real wastewater, offering a sustainable solution (Jangir *et al.* 2024). Silver nanoparticles were synthesized using mixed extracts from *Ficus religiosa* bark, leaf, and root, showing a crystalline nature and spherical morphology (50–70 nm). These AgNPs exhibited strong antibacterial activity against multiple strains and scavenged up to 75% of free radicals. The study confirms their potential for pharmaceutical and biomedical applications (Yadav *et al.* 2025).

Hybrid composites using peepal and Veli karuvelam fibers were fabricated, with nanosilica added to enhance performance (Fig. 1). Among different layer sequences, the peepal/veli karuvelam/peepal (PVP) configuration showed superior strength, which improved further with 2 wt% nanosilica. The optimized PVP-SiO_2 composite showed high mechanical strength, making it suitable for engineering applications (Krishna *et al.* 2024). Jute fiber/ZrO_2-reinforced epoxy biocomposites were developed, with fibers treated using NaOH and fillers chemically activated. Mechanical and thermal analyses showed notable improvements in strength, stiffness, and degradation temperature, with tensile and impact properties enhanced by over 20–85%. The optimized composite displayed superior structure-property synergy and enhanced thermal resilience (Biswas *et al.* 2025). ZrO_2-modified fibers were used in cement composites to study aging durability under wet–dry cycles and alkali conditions. Modified fibers resisted

strength loss and mineral deposition, retaining high mechanical strength and interface compatibility. ZrO_2 coatings significantly improved alkali resistance, making these composites suitable for outdoor and infrastructure applications (Song *et al.* 2024). ZrO_2 alone or with graphene oxide offered superior interlaminar shear strength in basalt/epoxy systems. Nanoparticles improved moisture, thermal resistance, and crack mitigation (Siddiqui *et al.* 2024). Composites were fabricated using *Cissus quadrangularis* fiber and CaO nanoparticles as reinforcement and filler in an epoxy matrix. The XRD and FTIR analyses confirmed 58% amorphous content and hydrophobic nature, while SEM revealed good fiber–matrix interaction. The composite showed 23% improved tensile strength and antibacterial activity suitable for biomedical applications (Raja *et al.* 2023).

Water hyacinth fiber and eggshell powder were used to develop sustainable composites by compression molding. Mechanical, thermal, and FTIR/XRD analyses confirmed improved strength and structure, while SEM showed fiber clustering and fracture modes. These bio-waste-based composites are viable for eco-friendly particle boards and lightweight materials (Arivendan *et al.* 2022). Epoxy composites with pineapple/flax fiber and peanut oil cake filler were developed using a hand layup-compression molding process. Mechanical properties peaked at 20 wt.% fiber and 2 wt.% filler, and Taguchi–ANOVA optimization confirmed minimal wear and friction. Surface deformation was revealed by SEM, supporting the composite's improved tribo-mechanical performance (Sumesh *et al.* 2022). *Ipomoea carnea* fiber and bran particulates in an epoxy matrix enhanced mechanical, thermal, and antibacterial properties of composites. The XRD analysis showed a crystallinity index of 68.29%, and SEM confirmed uniform fiber distribution and reduced failure. The study supports its potential in automotive, construction, and aerospace sectors. Date seed powder (DSP) was added to carbon fiber epoxy composites at various weight ratios to enhance mechanical and tribological properties. A 15% DSP addition yielded a 28% tensile and 23% bending strength improvement, while 10% DSP minimized friction and surface wear. The DSP-filled composites offer sustainable and high-performance alternatives for industry (Abdelhussein *et al.* 2025). *Enset ventricosum* fibers and *Limonia acidissima* shell powder were alkali-treated and used to fabricate optimized epoxy-based biocomposites. Response surface methodology (RSM) analysis identified 3 mm fiber length and 38.3 wt% filler as ideal for maximizing strength and minimizing water absorption. These natural filler composites offer a sustainable alternative to synthetic polymer reinforcements (Ponnuswamy *et al.* 2024).

Wool fabric was combined with epoxy resin and hydrophobic nanosilica to enhance composite mechanical properties. Up to 0.5% nanosilica improved tensile and impact strength, reduced water diffusivity, and slightly increased hydrophobicity. Soil burial tests showed less than 1% degradation, with SEM and FTIR confirming filler presence and dispersion (Jose *et al.* 2023). Hybrid composites of *Prosopis juliflora* bark, banana, and coconut fibers in epoxy were studied in treated and untreated forms. Alkali-treated specimens showed superior tensile, flexural, and impact strength due to better fiber–matrix adhesion, confirmed by FTIR, AFM, and SEM. Optimal performance occurred with specific fiber weight combinations, especially for coconut content (Kumar and Raja, 2021). Microcrystalline cellulose fibers from sisal, modified with hyperbranched aromatic polyamide (HBAP), were used in epoxy composites. With only 2 wt% HBAP-MCF, tensile, impact, and thermal properties significantly improved (e.g., 83.4% increase in impact strength). Enhanced filler–matrix interaction and thermal stability were verified by FTIR, TGA, and SEM (Xiao *et al.* 2014). Dried leaves and metal fillers (Co, Ni, Fe) were reinforced in epoxy, vinyl-ester, and polyester using an ultrasonication-assisted layup technique. Cobalt-filled samples showed the best mechanical and thermal performance, supported by FTIR and SEM. Artificial neural network (ANN) modeling and ANOVA validated the optimized composite's reliability and predictability (Mohit *et al.* 2024).

Composites of filature silk waste in epoxy were analyzed in untreated, alkali-treated, and nanoclay-filled forms. These treatments enhanced Young's modulus and tensile strength, with nanoclay boosting performance further. The improved fiber-matrix bonding and removal of surface sericin layer were confirmed by SEM and FTIR (Nair *et al.* 2021). Epoxy hybrid composites with jute, banana stem leaves (BSL), and tamarind shell powder (TSP) were tested for mechanical and water absorption properties. The 20% jute–10% BSL combination yielded the best results, with up to 39.1% improvement in impact strength. The structure–property relationships and chemical bonding were confirmed by SEM and FTIR (Manickaraj *et al.* 2025).

A novel tannic acid–based bio-epoxy was developed for hybrid composites with *Holoptelea integrifolia* fiber and *Ziziphus jujuba* seed particles. Thermal analysis and FTIR confirmed resin quality, and a fuzzy model predicted mechanical properties with 87% accuracy. This model-driven approach aids efficient development of high-performance, bio-based composites (Kandavalli *et al.* 2025). Polyester composites with jute as the base and *Prosopis juliflora* bark and kenaf fibers as fillers were tested for mechanical and thermal properties. Mechanical strengths increased with added natural fillers, confirmed by SEM and FTIR. Thermal analysis confirmed thermal stability, suggesting the viability of multi-fiber reinforced natural composites (Muthalagu *et al.* 2021). Epoxy composites reinforced with sabai

grass and fly ash (1.5–5 wt.%) in two fiber orientations were evaluated. At 5 wt.% filler and 0° fiber orientation, the composite achieved 63.5 MPa tensile and 118.5 MPa flexural strength. Analyses such as FTIR, XRD, and FESEM confirmed enhanced bonding and structural performance (Kumar *et al.* 2025).

Existing research on peepal fiber/epoxy composites employing ZrO_2 nanofiller is scarce, despite the fact that there are numerous specimens with different fillers. With peepal fiber reinforcement, epoxy matrix, and ZrO_2 filler concentrations of 0 wt%, 1 wt%, 3 wt%, 5 wt%, and 7 wt%, the present study aims to fabricate five different laminates. Compression molding technique was utilized to fabricate the composite materials. According to ASTM criteria, mechanical parameters such as impact, hardness, and tensile strength were evaluated.

Table 1. Chemical composition of Peepal fiber

Composition	Mean Weight Percentage
Hemicellulose	14.22
Ash	1.07
Alpha cellulose	52.31
Lignin	21
Fat and wax	0.65

Table 2. Weight percentages of peepal fiber, epoxy matrix and ZrO_2 nanofiller

Material Coding	Material Expansion	Fiber (wt (%)	Matrix (wt %)	Filler (%)
S1	Peepal epoxy composites	40	60	0
S2	1 wt% ZrO_2 filled peepal epoxy composites	39	60	1
S3	3 wt% ZrO_2 filled peepal epoxy composites	37	60	3
S4	5 wt% ZrO_2 filled peepal epoxy composites	35	60	5
S5	7 wt% ZrO_2 filled peepal epoxy composites	33	60	7

2. MATERIALS AND METHODOLOGY

The peepal fibers were acquired from Matrix Enterprises, Nagercoil, Tamil Nadu, India, and the ZrO_2 filler from Fiber Source Enterprises in Chennai, Tamil Nadu, India, for the reinforcing phase. The hardener (HY951) and epoxy (LY556) were sourced from Kovai Seenu Enterprises Coimbatore, Tamil Nadu, India. The hardener possesses a specific gravity of 0.98 gm/cm^3 at 250°C, a flash point of 1100°C, and a mixing ratio of 10:1. It cures at ambient temperature, possesses low viscosity, and exhibits resistance to chemical and environmental degradation. The epoxy resin was utilized to fabricate the composite specimens in this investigation owing to its characteristic qualities, including excellent mechanical strength, electrical resistance, chemical inertness, and water insolubility. Epoxy resin exhibits a viscosity of 10,000 to 12,000 MPa at 25°C and a density of 1.20 g/cm^3. The composition of peepal fibers is presented in Table 1. Peepal fibers offer numerous advantages, including their lightweight nature, environmental sustainability, non-toxicity, and low maintenance requirements (Mehto and Shukla, 2025). The following is a summary of the assessed physical and mechanical properties of peepal fiber. The fiber's low density (0.77 g/cm^3) rendered it relatively lightweight, advantageous for lightweight composite applications. The fibers exhibited a coarse structure, with diameters between 287 and 300 µm. The fiber exhibited modest mechanical capability, demonstrated by its tensile strength of 165 MPa. The fiber demonstrated a commendable level of flexibility in its deformation characteristics, with a break elongation of 11.5%. The moisture content, determined to be 7%, influences both the dimensional stability of the fiber and its ability to bond with polymer matrices in composite manufacturing.

Peepal fibers were extracted by submerging cut plant parts in fresh water for 24 hours. Then, they were rinsed with freshwater to eliminate any contaminants. The chemical retting technique involved immersing the peepal fiber in a 4% NaOH alkali solution by volume for 24 hours at a temperature of 26 ± 2 °C (Gowrishankar *et al.* 2025). The alkali-treated husk was rinsed with distilled water to eliminate any chemical residues from the fibers. Sun drying the peepal fibers following a two-day washing period reduced their moisture absorption capacity. The fibers were sun-dried subsequently and stored in airtight containers to prevent saturation. The density varies from 3.96 to 4.05 g/cm^3, the molar mass is 101.96 g/mol, and it possesses a hardness of 9 on the Mohs' scale. It is a crucial substance in ceramic engineering because of its elevated melting point, exceptional hardness, and thermal and electrical insulating properties (Kumar *et al.* 2023).

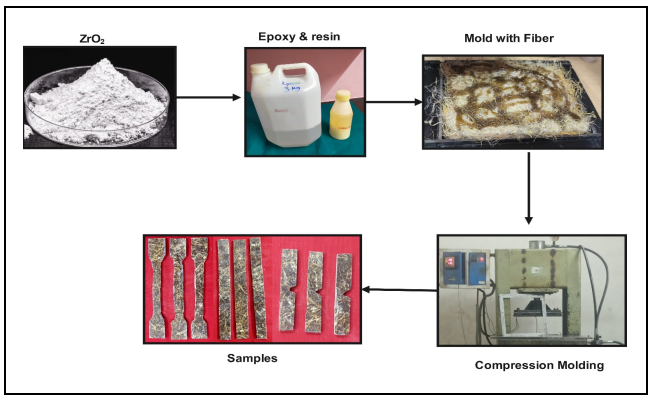


Fig. 1: Fabrication of the composite specimen

The hand layup technique was employed to fabricate the composites. Table 2 shows the placement of the specimens in molds. Fig. 2 illustrates the flowchart for specimen fabrication. The peepal fibers were precisely cut to fit the mold measurements (270 × 250 × 3 mm) prior to insertion. Both plates of the frame 250 mm top and 3 mm bottom were covered with wax. After thoroughly mixing the epoxy (LY556), hardener (HY551), and filler (ZrO_2), the fibers were arranged within the frame and positioned above the base plate, which was secured with a cover plate. The concluding phase in product fabrication involved the application of 33 bar of pressure by a compression molding apparatus. The temperature of the retrieved laminated materials was around 100°C. Subsequent to the sectioning of the specimens using a diamond-tipped cutter according to ASTM standards, they underwent automated testing.

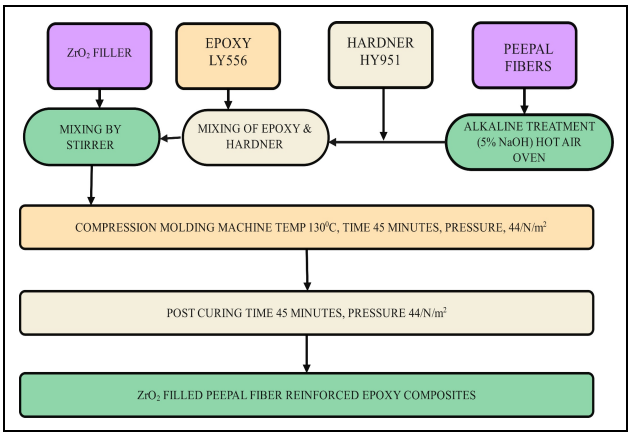


Fig. 2: Illustration of the composite production process

2.1 Mechanical Testing

In compliance with ASTM D2240, the hardness of the samples (Shore D hardness) was evaluated using a durometer. Izod impact tests were conducted in compliance with ASTM D256 utilizing an Instron testing apparatus (Raja & Devarajan, 2024). Under experimental settings, the specimens measured 60 mm × 12 mm × 5 mm, with a 2 mm notch at a 45° angle. The strain rate was established at 3.2 m/s. The strain rate necessary for the test was calculated as 3.2 times the impact strength, measured in J/m^2. The mean value was computed following the assessment of three samples. The tensile test findings of the specimens were evaluated using ASTM D638 standards with an Instron Universal testing machine (Mahapatra and Satapathy, 2022). Tensile testing was conducted on a rectangular specimen maintained at ambient temperature and subjected to a strain rate of 2 mm/min. The average of the outcomes was calculated from three trials after testing three different combinations. Fig. 3 shows the UTM and specimens for testing.

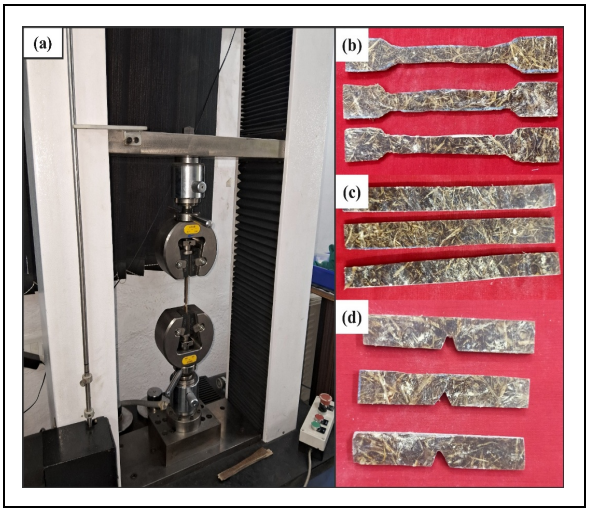


Fig. 3: (a) Universal testing machine; specimens for (b) tensile test (c) flexural test (d) impact test

2.2 Fourier Transforms Infrared Analysis (FTIR)

The FTIR spectra of the powder composite samples were recorded by KBr pellet method (Hui *et al.* 2020).

3. RESULTS AND DISCUSSION

3.1 Tensile Test

Fig. 4 illustrates the outcomes of the tensile testing conducted on five specimens. The tensile strength of the composite increased proportionally with the percentage of filler ingredient. The maximum value for composites containing 7 wt % ZrO_2 is 24.21 MPa. The tensile strength of unfilled composites is 17.2 MPa, which is lower than that of the filled composites. The enhancement in tensile strength results from the uniform incorporation of the ZrO_2 filler in the composites. A further consideration is the substantial influence of the filler's shape on augmenting tensile strength, which is crystalline or hexagonal close-packed. The incorporation of ZrO_2 filler, dispersed and integrated into the matrix, enhances both composite modulus and tensile strength.

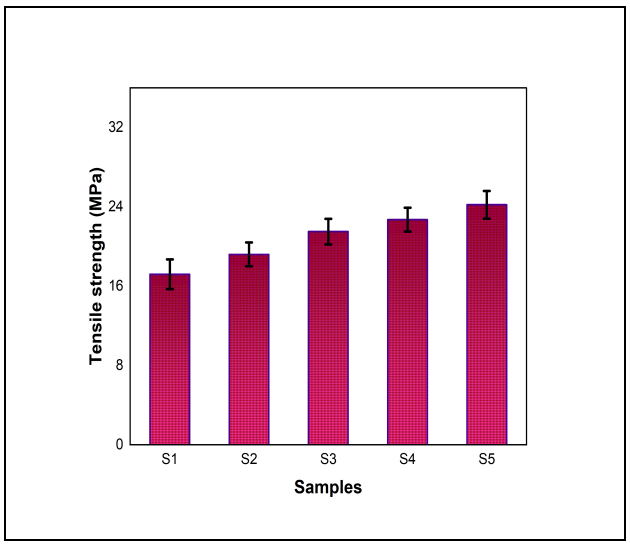


Fig. 4: Tensile strength of the composite specimens without (S1) and with (S2-S5) ZrO_2 nanoparticles

Ceramic fillers improve the mechanical interaction between the fiber and matrix, resulting in the distribution of the rubbing force between the epoxy and the fiber. This enhances the mechanical bonding of the two components. In comparison to other composites, the unfilled composites exhibit a lower tensile strength of 17.2 MPa. Similarly, graphene-reinforced nano-hybrid polypropylene composites with *Holoptelea integrifolia* and *Helicteres isora* fibers were optimized using RSM and MOPSO. The optimized blend achieved high tensile strength (45.4 MPa), flexural strength (62 MPa), and impact strength (147 J/m), with FESEM showing excellent interfacial bonding. These high-strength, lightweight composites are suitable for structural and automotive applications (Krishnasamy *et al.* 2025).

The composite specimen S5 exhibits a tensile strength of 24.21 MPa, surpassing that of the other specimens (Fig. 4). The load-bearing capacity and stress-transfer mechanisms result from the uniform dispersion of the filler ingredient and the strong bonding between the fibers and the matrix. The tensile strength is reduced due to less contact between the filler and the matrix. The epoxy matrix, peepal fiber, and ZrO_2 filler exhibit effective synergy. The peepal fibers are strengthened due to the filler-matrix interaction. The ability of the matrix and filler particles to transmit energy within the system is linked to alterations in tensile properties. The interaction between the matrix and the ZrO_2 filler particles facilitates a more efficient energy transfer mechanism. Compared to pure composites, peepal fibers treated with cellulose and lignin demonstrated significantly enhanced tensile strength. The graphs indicated an increase in tensile strength for specimens with a higher concentration of ZrO_2 filler. Compared to samples with 0%, 1%, 3%, and 5% ZrO_2 (S1), the value for 7 wt% ZrO_2 S5 composites is 24.21 MPa. The tensile strength exhibits improvements of 28%, 20%, 11%, and 6% relative to other samples. The addition of ZrO_2 particles primarily influences the elasticity of the epoxy specimen. While epoxies with a strongly cross-linked polymer structure predominantly exhibit an elastic response to loads, it is important to acknowledge that they can also experience viscous deformations. The incorporation of ZrO_2 particles, especially at elevated concentrations (7 wt% ZrO_2), markedly restricts atomic bond mobility, resulting in enhanced modulus.

3.2 Impact Test

Fig. 5 illustrates the correlation between impact strength and sample designation. The pattern is consistent with filler content percentages. As the percentage rises (from 0% to 7%), the impact strength correspondingly increases. This is the stress a material can withstand prior to failure. The 7 wt% ZrO_2 composites exert a greater influence on strength than pure composites due to the enhanced binding energy absorption by the ZrO_2 reinforcing particles. Similarly, peepal/Indian almond/ peepal fiber composites were enhanced with 7.5 wt% jujube fruit seed filler composite exhibited superior strength, impact resistance, and minimal water absorption (Srinivasan and Jayaraman, 2024). The energy necessary to surpass the material's resistance to crack propagation increases with an increase in filler concentration.

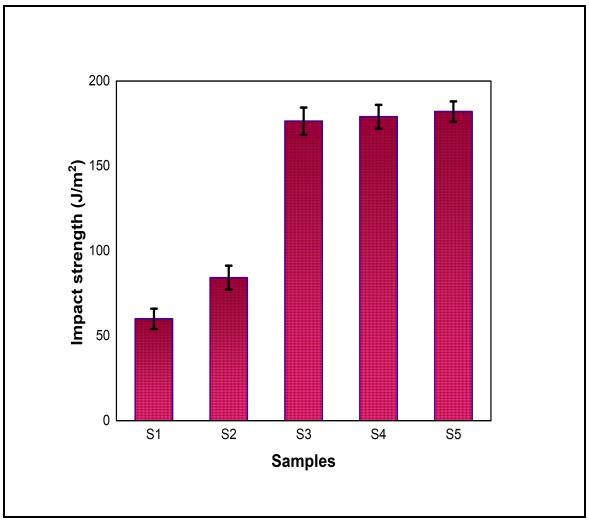


Fig. 5: Impact strength of the composite specimens without (S1) and with (S2-S5) ZrO_2 nanoparticles

The samples containing the nanofiller exhibited greater resistance to impact and fracture due to the strong bonding between the filler particles and the epoxy matrix. Here, the impact resistance of epoxy composites was improved by the use of reinforcing phases such as peepal fiber and ZrO_2 filler (crystalline structure). The enhanced dispersion of crystalline ZrO_2 particles within the matrix and the bonding between the peepal fiber and the epoxy matrix are the principal factors contributing to the improved impact strength.

As the reinforcing phases predominantly bear the load when bonding is strong, the energy absorption capacity of the epoxy matrix increases. No impediment exists to the propagation of the crack in pure composites. The propagation of the fracture is impeded when its trajectory alters upon encountering the firmly bound ZrO_2 particles in its path. The impact strength reduced for various composites, specifically those containing 0 wt%, 1 wt%, 3 wt%, and 5 wt% ZrO_2. The aggregation and inadequate matrix filler contact reduce the impact strength of these samples. Compared to 7 wt% ZrO_2 composites, 0 wt%, 1 wt%, 3 wt%, and 5 wt% specimens showed 67.03%, 53.68%, 3.07%, and 1.64% increase in impact strength. The incorporation of peepal fibers and ZrO_2 filler into the ZrO_2 specimens has improved their impact resistance.

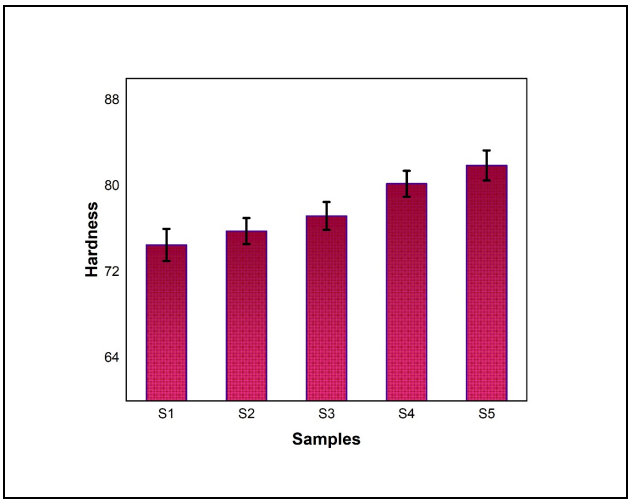


Fig. 6: Hardness of the specimen without (S1) and with (S2-S5) ZrO_2 nanoparticles

3.3 Hardness Test

Fig. 6 represents the relationship between the filler concentration and the hardness of peepal fiber- epoxy composites reinforced with ZrO_2. specimens that were not filled with ZrO_2 had a lower hardness than epoxy composites that were filled with 7 wt% of ZrO_2. In composite materials, filler helps increase the specimen's hardness by increasing its cross-linking density (Xu *et al.* 2024). The increase in hardness is caused by the strong bonding that occurs among the filler materials, fibers, and matrix. Because peepal fiber contains hard phases of cellulose and lignin, it is also noticeable that the hardness increases in all samples. However, cellulose is a very organized molecule that contains microfibril chains of 15–45 crystalline units. A strong connection to fiber is helped along by the lignin found in peepal fiber. Peepal lignin is structurally identical to grass lignin. At 1260 cm^{-1}, it exhibits vibration absorption peaks characteristic of the benzene ring skeleton. The covalent and crossed-linked structures of peepal fiber are supported by these two components. As a result, it becomes harder. The bond with peepal fiber and the structure of the fibers make the composite harder. The material's hardness is determined by its resistance to plastic deformation in response to an indentation.

An unreinforced matrix has limited resistance to plastic deformation and is characteristically soft. The significant mobility of molecular chains in an orderly polymer matrix accounts for this phenomenon. The mobility of epoxy molecular chains is considerably reduced upon the incorporation of hard phases, such as peepal fiber and ZrO2, into the matrix. The augmentation of hardness is attributed to the incorporation of multiple reinforcing phases that reduce segmental mobility. Hardness is not directly proportional to the quantity of reinforcements incorporated into the epoxy matrix; instead, it is significantly affected by factors such as reinforcement distribution and matrix bonding. The mobility of epoxy molecular chains remains unaffected in instances of insufficient dispersion or inadequate bonding. Both reinforcements adhered effectively to the epoxy, and the dispersion was uniform, as evidenced by the enhanced hardness value. Conversely, ZrO2's hardness (9 on the Moh's scale) and its dimensions and morphology render it an optimal constituent for matrix mixing due to its hexagonal close-packed structure. The superior hardness and finer dispersion of the ZrO2 filler are seen in its significant enhancement of hardness of S1. The hardness of the 7 wt% ZrO2-filled samples was elevated, consistent with observations found in prior studies (Alhotan *et al*. 2021). Compared to 7 wt% ZrO_2 filled composites, the hardness values of 0 wt%, 1 wt%, 3 wt%, and 5 wt%, witnessed 9.03%, 7.4%, 5.73% and 2.07% increase. The specimen containing 7% wt ZrO_2 exhibited the composite's peak hardness when assessed by Shore D measurement. The addition of filler contributes to the increased hardness due to the typical compaction, contact, and interconnection of the thermoset matrix phase, solid fiber phase, and filler phase. Likewise, hybrid polyester composites with jack tree and jute fibers with eggshell filler showed balanced mechanical properties and sustainability. Jack tree fiber enhanced impact resistance, while eggshell improved hardness. The molecular interaction and structural integrity were confirmed by FTIR and SEM (Islam *et al.* 2024).

3.4 Fourier Transforms Infrared Red Analysis (FTIR)

Fig. 7 shows the FTIR spectra of the composites S1, S3 and S5. The broad absorption band at 3352.7 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of hydroxyl groups in the natural fiber and their potential for hydrogen bonding with the epoxy matrix. Peaks at 2934.5 cm^{-1} and 2874.2 cm^{-1} are associated with aliphatic C–H stretching, confirming the presence of cellulose and

epoxy hydrocarbon chains. A moderate peak at 2368.3 cm^{-1} may be linked to CO_2 overtones or residual functional groups. The region from 1748.1 to 1315.3 cm^{-1} shows multiple peaks due to C=O stretching (1748.1, 1699.7 cm^{-1}), aromatic C=C vibrations (1533.1 cm^{-1}), and CH_2 bending (1401.1, 1315.3 cm^{-1}). Distinct bands at 1255.4 cm^{-1}, 1104.4 cm^{-1}, and 1044.5 cm^{-1} confirm the presence of C–O–C ether linkages in the epoxy network. Peaks observed in the fingerprint region below 1000 cm^{-1}, such as 924.1 cm^{-1}, 902.3 cm^{-1}, and 574.3 cm^{-1}, correspond to out-of-plane C–H bending and Zr–O vibrations. Changes in intensity and shifts in these peaks between spectra (a), (b), and (c) indicate successful incorporation of ZrO_2 particles and enhanced interfacial interactions in the modified composites. The study confirmed good crystallinity and bonding (Hariharan *et al.* 2023).

3.5 SEM Analysis for Tensile Specimen

Fig. 8 presents scanning electron images of fractured composite specimens, evaluated to understand the failure mechanisms and fiber–matrix interactions at the microstructural level. Prior to imaging, all samples were sputter-coated with a thin layer of gold to eliminate electron charging during SEM examination and enhance conductivity. Fig. 8(a) shows the fractured surface of the S1 specimen without the addition of ZrO_2 fillers. This surface is characterized by evident fiber pull-out, interfacial debonding, and broken fibers indicating weak fiber–matrix bonding. These features suggest insufficient load transfer from the matrix to the fibers, resulting in reduced tensile performance. The morphology predominantly demonstrates brittle characteristics, corroborated by the clean fiber fractures and delamination zones visible on the surface. In contrast, Fig. 8(b) depicts a specimen with ZrO_2 filler, revealing significantly improved fiber embedding and reduced fiber detachment. The fractured surface displays a more cohesive morphology, suggesting enhanced fiber–matrix interfacial bonding. The presence of ZrO_2 appears to contribute to better stress distribution and mechanical interlocking, which mitigates premature fiber pull-out. Fig. 8(c) illustrates another ZrO_2-reinforced specimen, where fibers are entirely coated and integrated with the epoxy matrix, with minimal voids or cracks. This encapsulation confirms strong interfacial bonding and supports improved load-bearing capacity. The morphology is consistent with a controlled brittle fracture, indicating that the composite resisted crack propagation until peak load failure. Similar behavior has been reported by Suresh *et al.* (2024) for SiC-reinforced epoxy systems. Overall, the presence of ZrO_2 fillers has facilitated stronger interfacial bonding, reduced fiber-matrix separation, and enhanced the mechanical integrity of the composite. The synergy between the epoxy and peepal fibers, particularly with 7 wt.% ZrO_2, significantly contributes to improved fracture resistance and structural performance.

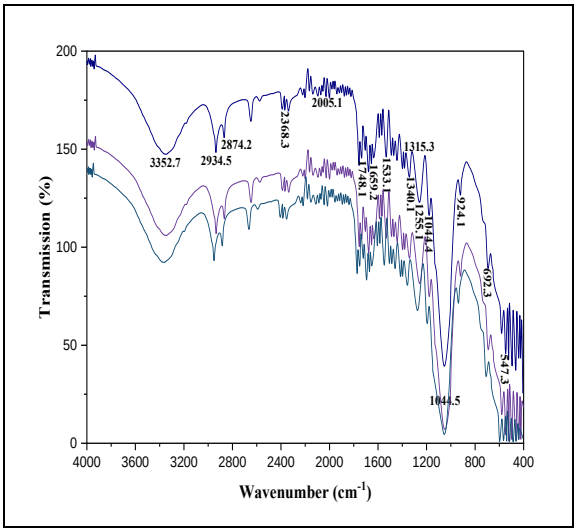


Fig. 7: Infrared spectrum of S1, S3 and S5 composite specimens

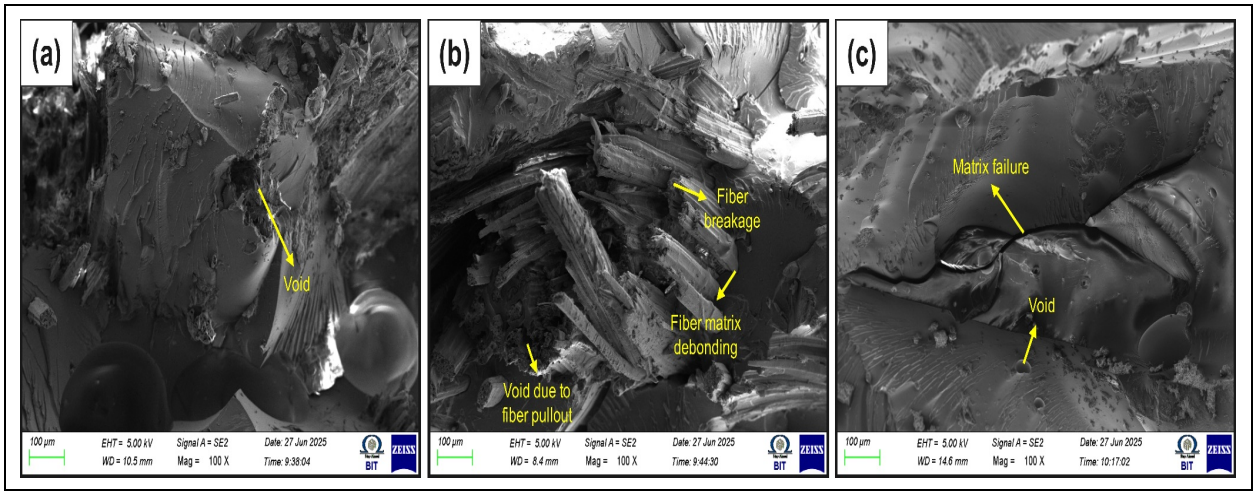


Fig. 8: SEM images of (a) S1 (b) S2 and (c) S5 composite specimens

4. CONCLUSIONS

Peepal fiber epoxy composites were fabricated using the compression molding technique with varying concentrations of ZrO_2 nanofiller, and the results highlight the superior performance of composites containing 7 wt% filler. The strong adhesion between fiber and matrix significantly enhanced tensile, impact, and hardness properties, with 1 wt% and 3 wt% filler composites showing brittle fracture behavior. Infra-red analysis confirmed improved cellulose characteristics in alkali-treated fibers, while SEM revealed failure modes such as fiber delamination, matrix debonding, and fracture. Among all samples, the S5 composite (7 wt% ZrO_2) exhibited the best performance, achieving tensile strength of 24.21 MPa, hardness of 81.9, and impact strength of 182 J/m^2. Compared to lower filler contents, the 7 wt% ZrO_2 composites demonstrated tensile strength improvements of up to 28.95%, hardness enhancements of up to 9.03%, and impact strength gains of 67.03%. These improvements were attributed to the uniform distribution of ZrO_2 particles and strong fiber–matrix bonding. Furthermore, composites reinforced with ZrO_2 and peepal fibers showed improved machinability, reduced weight, higher strength, and excellent absorption capacity, making them cost-effective for practical applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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