Eco-Friendly Hybrid Epoxy Composites Reinforced with Snake Grass Fiber and Dual Agro-Waste Fillers for Enhanced Mechanical and Acoustic Performance

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This study examined the mechanical, acoustic, and microstructural performance of epoxy composites reinforced with Snake Grass Fiber (SGF) and hybrid agro-waste fillers—Tamarind Seed Powder (TSP) and Wood Apple Shell Powder (WASP). Composites were fabricated by compression molding with a constant SGF content of 30 wt% and varying hybrid filler contents (5 to 15 wt%). Mechanical properties including tensile, flexural, compressive, impact strength, hardness, and water absorption were evaluated alongside sound absorption behavior. The incorporation of hybrid fillers significantly improved mechanical strength, surface hardness, and dimensional stability while reducing moisture uptake compared to SGF-only composites. The optimized hybrid composition exhibited superior properties, achieving tensile, flexural, compressive, and impact strengths of 58 MPa, 87 MPa, 70 MPa, and 8.98 J, respectively, with a hardness of 84 Shore D and reduced water absorption of 23%. Acoustic analysis revealed enhanced sound absorption, with a maximum absorption coefficient of 0.24 at an optimal filler-to-fiber ratio, attributed to synergy between fibrous reinforcement and porous fillers. SEM analysis confirmed uniform filler dispersion, improved interfacial bonding, and reduced voids, supporting the observed mechanical and acoustic enhancements. SGF-based hybrid agro-waste composites offer improved structural and sound-absorbing performance, making them suitable for sustainable automotive, construction, and acoustic insulation applications.

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INTRODUCTION

In recent decades, rapid industrialization, urban expansion, and the extensive exploitation of non-renewable resources have significantly intensified global environmental challenges such as climate change, ecological degradation, pollution, and biodiversity loss (Das *et al.* 2025). These concerns, coupled with increasing regulatory pressure and societal awareness regarding the environmental impact of conventional synthetic materials, have driven substantial research interest toward the development of sustainable, renewable, and environmentally benign material alternatives (Kumar *et al.* 2022). Within this context, plant-based natural fiber–reinforced polymer composites have emerged as promising candidates to replace or partially substitute synthetic fiber composites, owing to their biodegradability, renewability, low density, reduced carbon footprint, and favorable life-cycle characteristics (Sri *et al.* 2023).

Natural fiber composites derived from lignocellulosic resources offer multiple sustainability advantages, including lower embodied energy, reduced greenhouse gas emissions, and end-of-life disposal options such as recycling or biodegradation. These attributes strongly support circular economy principles and green manufacturing practices, making such materials attractive for applications across automotive, construction, packaging, furniture, marine, and consumer goods industries (Pachiappan and Santhanam 2023). Additionally, the utilization of agricultural residues and plant-based fibers contributes to effective waste management while creating economic value from low-cost, abundantly available biomass resources (Kibria *et al.* 2025).

Among various polymer matrices, epoxy resin is widely employed due to its excellent mechanical strength, dimensional stability, corrosion resistance, adhesion characteristics, and thermal performance, thus enabling its extensive use in aerospace, automotive, marine, construction, and packaging sectors (Chandramohan *et al.* 2024). However, despite these advantages, epoxy resins suffer from inherent brittleness, non-biodegradability, and relatively high cost, which limit their sustainability and impact resistance. To overcome these limitations, reinforcement with natural fibers and bio-fillers has been increasingly explored as an effective strategy to enhance mechanical performance while improving environmental compatibility (Rajamanickam *et al.* 2023; Ramakrishnan *et al.* 2025a).

In this regard, lignocellulosic plant fibers represent a viable and sustainable reinforcement option. Snake Grass Fiber (SGF), a lesser-known but mechanically promising natural fiber derived from tropical plant species, has recently attracted attention for composite applications (Manickaraj *et al.* 2024b). SGF possesses favorable characteristics such as high tensile strength, low density, renewable availability, and a suitable aspect ratio, offering an underutilized alternative to conventional natural fibers such as jute, flax, kenaf, and hemp. Its relatively high cellulose content contributes to improved stiffness and load-bearing capability, while hemicellulose and lignin enhance bonding potential and thermal stability, making SGF particularly suitable for reinforcing thermosetting matrices such as epoxy (Vinod *et al.* 2022; Parthasarathy *et al.* 2024).

Alongside natural fiber reinforcement, the incorporation of agro-waste–derived fillers provides an additional pathway to enhance composite performance and sustainability. Agro-waste materials such as tamarind shell powder (TSP) and wood apple shell powder (WASP), generated as by-products of fruit processing industries, are often discarded or underutilized, leading to disposal and environmental challenges (SD 2021). These hard, lignocellulosic shells are rich in cellulose and lignin, making them suitable as particulate fillers capable of improving stiffness, hardness, wear resistance, and dimensional stability of polymer composites. Moreover, their utilization reduces material cost, energy consumption, and dependence on synthetic fillers, thereby improving the overall ecological profile of the composite system (Jenish *et al.* 2025; Sali *et al.* 2025).

While numerous studies have reported the benefits of single natural fiber reinforcement or individual agro-waste fillers, limited attention has been paid to the synergistic effects arising from the incorporation of dual agro-waste fillers within a natural fiber–reinforced epoxy matrix (Das *et al.* 2025a). In particular, SGF-reinforced epoxy composites incorporating hybrid combinations of WASP and TSP at varying weight fractions remain insufficiently explored. The influence of such hybrid filler systems on interfacial adhesion, filler dispersion, stress transfer mechanisms, and overall mechanical synergy is not yet well understood, creating a notable research gap in this domain (Gökdai and Borazan 2016).

Furthermore, detailed insights into microstructural features such as fiber–matrix–filler interactions, void formation, filler agglomeration, fiber pull-out, and failure mechanisms are limited, necessitating systematic microstructural investigations using advanced characterization techniques such as scanning electron microscopy (SEM) (Vijay *et al.* 2022; Gurusamy *et al.* 2024). Addressing these gaps is essential for optimizing composite formulations and improving performance reliability for practical applications. Therefore, the primary objective of this study was to systematically investigate the mechanical behavior of epoxy composites reinforced with a constant weight fraction of SGF and varying contents (5%, 10%, and 15%) of TSP and WASP, both individually and in hybrid combinations. The study evaluated key mechanical properties, including tensile strength, flexural strength, impact toughness, and surface hardness, while correlating these results with microstructural observations obtained through SEM analysis to elucidate failure mechanisms and interfacial characteristics (Ramadoss *et al.* 2024). The research further aimed to identify an optimal hybrid filler composition that maximizes mechanical performance, environmental sustainability, and economic feasibility.

The significance of this work extends beyond material development, as it promotes agricultural-waste valorization and supports rural socio-economic development by creating potential income opportunities for communities involved in biomass collection and processing (Sathish *et al.* 2024). Moreover, the developed bio-composites exhibit strong potential for use in non-load-bearing and semi-structural applications such as automotive interior components, door panels, ceiling tiles, insulation boards, building partitions, furniture, packaging, and consumer products, where lightweight design, mechanical robustness, cost efficiency, and environmental compliance are critical (Sathishkumar *et al.* 2022). By aligning with global sustainability frameworks, including the United Nations Sustainable Development Goals related to responsible consumption, climate action, and sustainable industrialization, this research contributes to advancing eco-friendly composite materials capable of integrating seamlessly into modern manufacturing and circular material life-cycle systems (Karuppusamy *et al.* 2025).

This study introduces a dual agro-waste filler strategy employing tamarind seed powder (TSP) and wood apple shell powder (WASP) in snake grass fiber (SGF)–reinforced epoxy composites. Unlike prior studies that primarily focus on single bio-fillers or fiber-dominant systems, the present work systematically demonstrates synergistic reinforcement through controlled hybrid filler ratios. The novelty lies in achieving simultaneous improvement in tensile, compressive, flexural, impact, moisture-resistance, and acoustic performance using low-cost lignocellulosic wastes.

EXPERIMENTAL

Materials

The materials selected for the present study were chosen based on their availability, reinforcing potential, and compatibility with epoxy matrix systems. All materials were carefully sourced from reliable vendors to ensure consistency and quality in the experimental work (Repon *et al*. 2024).

Epoxy resin

The matrix material used for the fabrication of the composites was a room temperature curable epoxy system comprising LY556 grade epoxy resin and HY951 hardener, procured from Covai Seenu Company, Coimbatore, India. The LY556 resin is a liquid, unmodified bisphenol-A-based epoxy resin, renowned for its excellent mechanical strength, low shrinkage, superior chemical resistance, and good thermal stability. The corresponding amine hardener, HY951, is designed for curing the epoxy at room temperature, yielding a highly crosslinked thermoset structure suitable for structural applications (Mohammed *et al*. 2023).

Snake grass fiber

Snake grass fiber, a lignocellulosic natural fiber, was selected as the primary reinforcement in this study owing to its notable tensile strength, stiffness, and abundance, making it an eco-friendly and sustainable alternative to synthetic reinforcements. The raw fibers were sourced from the Anamalai region, Pollachi, Tamil Nadu, India, a region known for its rich variety of natural fiber-yielding plants. Figures 1a and 1b shows the snake grass plant and its fiber (Gurusamy *et al*. 2024).

Fig. 1a. Snake grass plant, **1b.** Snake grass fiber

Tamarind seed powder (TSP)

TSP was utilized as a lignocellulosic filler, sourced from the local area of Pollachi, Tamil Nadu, India. The tamarind fruit seeds were collected, cleaned to remove residual pulp, and sun-dried for 3 days to reduce moisture content. Subsequently, the shells were mechanically crushed using a grinder and sieved using a standard ASTM sieve to obtain ensuring uniform dispersion and consistent filler-matrix interaction (Arpitha *et al*. 2017). The fine particle size was selected to maximize the surface area, enhance filler distribution within the resin, and improve mechanical properties by reducing stress concentrations. Figures 2a and 2b show the tamarind seeds and their powder.

Fig. 2a. Tamarind seeds; **2b.**Tamarind seed powder

Wood apple shell powder (WASP)

Similarly, WASP was acquired from Amman Impex, Pollachi, Tamil Nadu, India.

(a) (b)

Fig. 3a. Wood Apple ; **3b.** Wood Apple shell powder

The shell powder, rich in lignin and cellulose, was stored in airtight containers to prevent moisture absorption before incorporation into the composite (Ramesh *et al*. 2022b). Figures 3a and 3b show the wood apple fruits and its shell powder.

Methods

Alkali treatment of SGF

To enhance the compatibility and interfacial adhesion between the naturally hydrophilic SGF and the hydrophobic epoxy resin, the cleaned fibers underwent alkali treatment. This surface modification involved immersing the fibers in a 5% sodium hydroxide (NaOH) solution for 4 h at room temperature. The alkali treatment effectively removed non-cellulosic constituents such as hemicellulose, lignin, pectin, and other amorphous components, thereby increasing the surface roughness and promoting better mechanical interlocking with the epoxy matrix (Chowdhury *et al*. 2025). Following the treatment, the fibers were thoroughly rinsed multiple times with distilled water to remove any residual NaOH and ensure a neutral pH, preventing any possible degradation or fiber weakening. Subsequently, the alkali-treated fibers were oven-dried at 60 °C for 24 h to remove residual moisture, ensuring they were ready for composite fabrication.

Composite fabrication

The composite laminates were fabricated using the compression molding technique, which ensures better consolidation, reduced void content, and superior mechanical properties compared to traditional methods (Ramakrishnan *et al.* 2024). A cleaned and PVA-coated steel mold of 300 mm × 300 mm × 3 mm was used. The epoxy resin (LY556) and hardener (HY951) were mixed in a 100:10 ratio by weight. Pre-weighed dried SGF fiber, TSP, and WASP were gradually incorporated into the resin-hardener mixture under constant stirring to ensure uniform dispersion. The mixture was then poured into the mold cavity and compressed at 5 to 7 MPa for 24 h at room temperature. Post-curing was carried out at 60 °C for 2 h to complete the curing process and enhance the laminate properties. The cured panels were demolded and cut into standard ASTM test specimens (Shafqat *et al*. 2023). The composite formulations are presented in Table 1.

Table 1. Composite Formulations

No.	Filler Content (%)		Fiber Content (%)	Epoxy Resin (%)	Composite Designation
	TSP	WASP	SGF		
1	2.5	12.5	25	60	S1
2	5	10	25	60	S2
3	7.5	7.5	25	60	S3
4	10	5	25	60	S4
5	12.5	2.5	25	60	S5

Composite preparation

Snake Grass Fiber was cleaned with distilled water, sun-dried for 48 h, and alkali-treated in a 5% NaOH solution for 4 h to improve fiber-matrix adhesion (Mohan Kumar *et al*. 2023). The treated fibers were rinsed to neutral pH, oven-dried at 60 °C for 24 h, and cut to lengths of 25 to 30 mm. The samples of TSP and WASP, both procured from Amman Impex, Pollachi, were sun-dried, ground, and sieved before use as fillers in the composites.

The epoxy composites were fabricated using the matrix material composed of a room temperature curable epoxy system containing LY556 grade epoxy resin and HY951 hardener.

Mechanical Testing

A comprehensive series of mechanical tests were conducted to evaluate the performance of the fabricated epoxy composites reinforced with SGF and varying proportions of TSP and WASP. All tests were carried out following the standard procedures outlined by ASTM, ensuring the reliability and reproducibility of the results (Manickaraj *et al.* 2024a).

Tensile testing

The tensile properties of the composites, including tensile strength, tensile modulus, and percentage elongation at break, were assessed in accordance with ASTM D638-14 2022 using a Universal Testing Machine (UTM), Model: Tinius Olsen H50KS equipped with a 50 kN load cell. The dog-bone-shaped specimens conformed to the Type I dimensions specified by the standard, with a gauge length of 50 mm, width of 13 mm, and thickness of 3 mm. Testing was conducted at a crosshead speed of 2 mm/min, and the force versus elongation data were recorded until failure. To ensure data accuracy and to account for any variability in material properties, five specimens for each composite formulation were tested, and the average values with standard deviation were reported (Islam *et al*. 2025).

Flexural test

Flexural strength and flexural modulus were determined using the three-point bending method in accordance with ASTM D790-17 2017 (Herlina Sari *et al*. 2024). Testing was performed on the same UTM using a three-point bending fixture, where specimens of 127 mm length, 12.7 mm width, and 3 mm thickness were loaded over a span length of 48 mm, maintaining a span-to-depth ratio of 16:1. An average of five specimens per group was tested to obtain statistically significant results.

Impact test

Impact energy absorption capacity of the composites was assessed by conducting Charpy impact tests according to ASTM D6110-18 2018. Unnotched specimens with dimensions of 125 mm × 12.7 mm × 3 mm were subjected to impact loading using a Tinius Olsen IT504 Charpy Impact Tester with an impact hammer energy capacity of 15 J. The absorbed energy at fracture was measured directly, and five samples were tested for each formulation, ensuring consistency in observations (Thandavamoorthy *et al*. 2024).

Compressive strength test

To assess the load-bearing capacity of the composites under compressive forces, compressive strength tests were performed according to ASTM D695-15 2015. Specimens of dimensions 12.7 mm × 12.7 mm × 25.4 mm were prepared and tested using the same UTM equipped with compression platens (Rajeshkumar *et al*. 2021). The loading rate was maintained at 1.3 mm/min, and the maximum compressive strength was determined based on the maximum load sustained by the specimen before visible crushing or deformation. As with other tests, five specimens per formulation were tested, and the average values were recorded with corresponding standard deviations (Sharma *et al*. 2022).

Hardness test

Surface hardness of the composite samples was measured using a Shore D Durometer, adhering to the testing protocol described in ASTM D2240-15 2021. Each specimen was placed on a flat, rigid surface, and the durometer indenter was applied perpendicularly under consistent pressure (Vignesh *et al*. 2021).

Scanning electron microscopic analysis

To gain insights into the fracture behavior, interfacial adhesion, and filler dispersion within the composite matrix, scanning electron microscopic (SEM) analysis was performed on the fractured surfaces of selected tensile and impact test specimens (Aredla *et al*. 2024). Fractured composite surfaces were carefully sectioned, cleaned with acetone to remove any surface contaminants, and subsequently sputter-coated with a thin layer of gold using a Quorum Q150R Plus Sputter Coater, ensuring conductivity for high-resolution imaging. The coated specimens were then examined under a JEOL JSM-6390LV SEM (The JEOL Ltd., Akishima, Tokyo, Japan), operated at an accelerating voltage of 15 kV. This morphological analysis provided crucial evidence to support the mechanical performance data, allowing correlation between the observed failure modes and the reinforcement mechanisms attributed to SGF, TSP, and WASP in the composite system (Sathishkumar 2014).

Water absorption test

Water absorption behavior of the composites was evaluated following the ASTM D570-22 2022 standard. Specimens measuring 50 mm × 50 mm × 3 mm were oven-dried at 50°C for 24 h, weighed, and then immersed in distilled water at room temperature for 72 h. After immersion, samples were surface-dried and reweighed (Khalil *et al*. 2006). The percentage of water absorption was calculated using,

$$Water\ Absorption\ (\%) = \frac{Wf - Wi}{Wi}\ x\ 100 \tag{1}$$

where Wi and Wf represent the initial dry weight and the final wet weight in grams, respectively.

Sound absorption test

The sound absorption behaviour of the hybrid composites was evaluated as per ASTM C423-17 (2017) using the Impedance Tube Method. The specimens (3 mm thickness) were tested in a Bruel & Kjaer Type 4206 system over a 250 to 4000 Hz frequency range. The sound absorption coefficient (SAC) was determined by measuring the ratio of incident to reflected sound pressure levels (Yang and Li 2012). Tests were performed at room temperature, each repeated three times for consistency, and the average SAC values were used to assess the composites' acoustic damping efficiency and optimal fiber–filler ratio (Pandiarajan *et al*. 2025).

RESULTS AND DISCUSSION

Tensile Strength

The tensile behavior of Snake Grass Fiber (SGF)–reinforced epoxy composites containing Tamarind Seed Powder (TSP), Wood Apple Shell Powder (WASP), and their hybrid combinations reflects the combined influence of filler chemistry, particle morphology, dispersion quality, and interfacial interactions. The control composite (S1), reinforced solely with SGF, exhibited a tensile strength of 40 MPa, representing the inherent load-bearing capacity of lignocellulosic fiber–epoxy systems. This value is comparable to previously reported tensile strengths of natural fiber–reinforced thermosetting composites, where failure is predominantly governed by matrix cracking, fiber pull-out, and limited stress transfer due to the hydrophilic nature of plant fibers (Lette *et al.* 2018). The marginal improvement in tensile strength observed for S2 (42 MPa) with 5 wt% TSP addition indicates that low-volume particulate fillers primarily act as matrix stiffeners rather than major load-bearing elements. The rigid lignocellulosic particles restrict polymer chain mobility and delay matrix yielding under tensile loading, resulting in modest enhancement. Similar trends have been reported in agro-waste–filled epoxy systems, where tensile improvement remains limited at low filler loadings unless strong interfacial adhesion is achieved (Manickaraj *et al.* 2025a; Ramakrishnan *et al.* 2025b). A more pronounced increase in tensile strength was achieved in S3 (51 MPa) with the incorporation of 5 wt% WASP, highlighting the superior reinforcing efficiency of WASP compared to TSP. This enhancement is attributed to WASP's higher lignin content, greater intrinsic stiffness, and rougher surface morphology, which promotes improved mechanical interlocking and stronger filler–matrix adhesion. Lignin-rich fillers have been shown to enhance stress transfer efficiency and suppress crack initiation by improving compatibility with thermosetting matrices (Sombatsompop and Wimolmala 2006). Consequently, WASP particles contribute more effectively to load sharing and crack-bridging mechanisms, delaying tensile failure.

The hybrid filler composite S4 exhibited the highest tensile strength (58 MPa), demonstrating a clear synergistic reinforcement effect arising from the combined use of TSP and WASP. Hybridization of fillers with different particle sizes, shapes, and chemical characteristics improves dispersion and minimizes agglomeration, leading to a dense and well-packed microstructure with fewer stress concentration sites. This promotes efficient stress redistribution and forces propagating cracks to follow more tortuous paths, thereby increasing fracture resistance (Kaewpruk *et al.* 2021). Additionally, the hybrid system enhances the interfacial transition zone through multiple reinforcement mechanisms—matrix stiffening from TSP and mechanical interlocking from WASP—resulting in improved load transfer from the epoxy matrix to SGF. However, a reduction in tensile strength was observed for S5 (52 MPa) at higher hybrid filler loading (7.5 wt% TSP + 7.5 wt% WASP), indicating the existence of an optimal filler threshold. Excessive filler content increases particle agglomeration, reduces resin wetting, and promotes filler–filler interactions, which disrupt matrix continuity and introduce stress concentration zones. Similar tensile strength deterioration at high filler contents has been widely reported in agro-waste–filled polymer composites (Bhowmik *et al.* 2017). Overall, the tensile results confirm that optimized hybrid filler incorporation significantly enhances the tensile performance of SGF-reinforced epoxy composites through improved interfacial bonding, efficient stress transfer, and crack deflection mechanisms. Figure 4 illustrates the comparative tensile behavior of the developed composites.

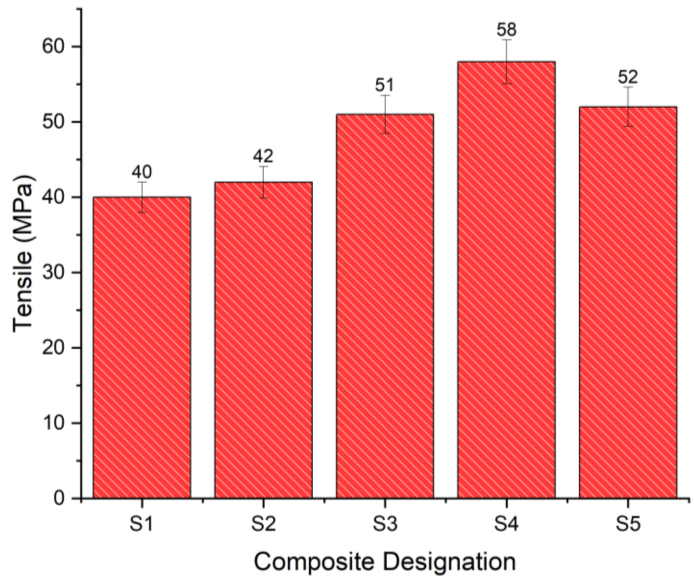

Fig. 4. Tensile strength

Flexural Strength

The flexural strength behavior of the SGF-reinforced epoxy composites (S1 to S5) demonstrates a progressive improvement with the incorporation of natural fillers and their hybrid combinations, underscoring the strong influence of filler type, dispersion, and loading level on bending performance. The control composite, S1, containing 30 wt% SGF without fillers, exhibited a baseline flexural strength of 76 MPa. This response reflects the inherent bending resistance of lignocellulosic fiber–epoxy systems, governed by fiber stiffness, matrix rigidity, and the efficiency of stress transfer under three-point bending conditions (Hossain *et al.* 2014). The introduction of 5 wt% Tamarind Seed Powder (TSP) in S2 resulted in a moderate increase in flexural strength to 79 MPa. This improvement can be attributed to the rigid particulate nature of TSP, which acts as localized stress-transfer sites within the epoxy matrix. Under flexural loading, these particles restrict matrix deformation and enhance resistance to compressive and tensile stresses on opposite sides of the neutral axis. Similar enhancements in flexural performance at low filler contents have been reported for agro-waste-filled epoxy composites, where fillers improve stiffness by limiting polymer chain mobility (Raghunathan *et al.* 2022; Periasamy *et al.* 2024). A further increase in flexural strength was observed in S3 (83 MPa) with the incorporation of 5 wt% Wood Apple Shell Powder (WASP). The superior performance of WASP-filled composites is attributed to the higher lignin and cellulose content of WASP, which provides greater intrinsic stiffness and load-bearing capability. In addition, the rougher surface morphology of WASP particles enhances mechanical interlocking and filler–matrix interfacial bonding, thereby improving stress transfer efficiency and reducing microcrack initiation during bending. The hybrid composite S4, containing equal proportions of TSP and WASP (5 wt% each), exhibited the highest flexural strength of 87 MPa, indicating a pronounced synergistic reinforcement effect. The combination of fillers with differing particle sizes and surface characteristics promotes uniform dispersion and minimizes stress concentration sites. This hybrid configuration enhances interfacial adhesion and creates a denser microstructure, forcing cracks to follow more tortuous paths and increasing resistance to flexural failure. The presence of multiple reinforcement mechanisms—matrix stiffening from TSP and mechanical interlocking from WASP—contributed significantly to the improved bending performance. However, a slight reduction in flexural strength was observed for S5 (84 MPa) at higher hybrid filler loading (7.5 wt% TSP + 7.5 wt% WASP). This decline is attributed to filler agglomeration, insufficient resin wetting, and increased filler–filler interactions, which introduce stress concentration zones and weaken the composite under bending loads (Aruchamy *et al.* 2025). Overall, the flexural results confirm that moderate hybrid filler incorporation effectively enhanced the bending performance of SGF-reinforced epoxy composites, while excessive filler content compromised interfacial integrity (Alrasheedi *et al.* 2025). Figure 5 illustrates the comparative flexural strength behavior of all composite formulations.

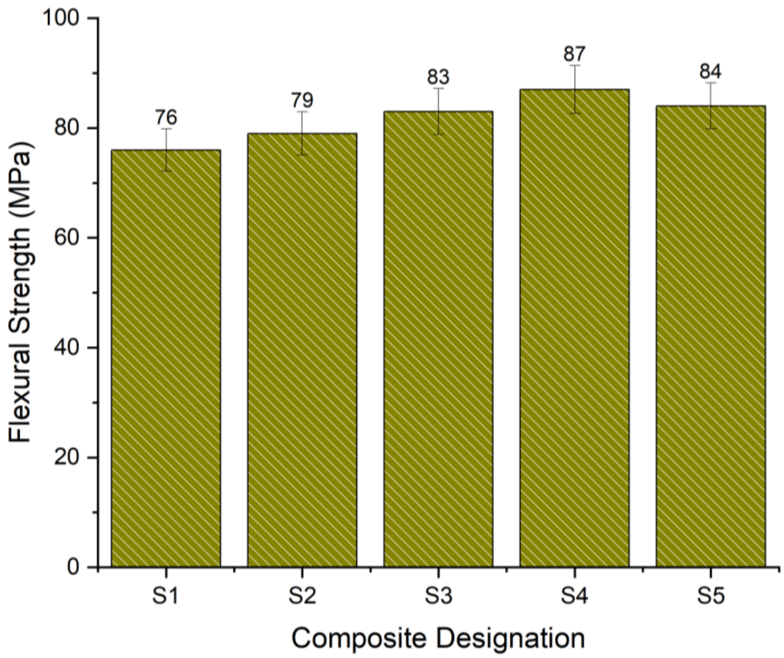

Fig. 5. Flexural strength

Compressive Strength

The compressive strength behavior of the SGF-reinforced epoxy composites (S1 to S5) demonstrates a pronounced dependence on filler type, loading level, and hybridization strategy, highlighting the critical role of particulate reinforcement in enhancing resistance to compressive deformation. The control composite, S1, containing 30 wt% Snake Grass Fiber (SGF) without fillers, exhibited a compressive strength of 48 MPa. This baseline response reflects the inherent compressive load-bearing capability of lignocellulosic fiber–epoxy systems, where failure is typically governed by matrix yielding, fiber microbuckling, and localized interfacial debonding under axial compressive stress (Vijay and Singaravelu 2016). The introduction of 5 wt% Tamarind Seed Powder (TSP) in S2 resulted in a modest increase in compressive strength to 51 MPa. This improvement is primarily attributed to the rigid nature of TSP particles, which act as micro-scale load-bearing inclusions within the epoxy matrix. Under compressive loading, these particles restrict matrix deformation and delay the onset of localized shear bands, thereby improving the overall compressive response. Additionally, the presence of well-dispersed TSP particles enhances stress distribution throughout the matrix, reducing stress concentrations around the fibers (Lotfy *et al.* 2025). However, at this low filler loading, the dominant failure mechanisms remain fiber buckling and matrix yielding, resulting in only a moderate strength enhancement. A more substantial improvement was observed in S3, which incorporated 5 wt% Wood Apple Shell Powder (WASP), achieving a compressive strength of 61.2 MPa. The superior performance of WASP-filled composites can be attributed to the higher lignin content and intrinsic stiffness of WASP, which provide greater resistance to matrix deformation and suppress fiber microbuckling under compressive loads. Furthermore, the rough surface texture and chemical compatibility of WASP enhanced filler–matrix interfacial adhesion, facilitating more effective stress transfer and improved load sharing between the matrix, fibers, and fillers. As a result, compressive failure was delayed, and the composite exhibited improved structural stability under sustained loading (Chithra *et al.* 2024). The hybrid composite S4, containing equal proportions of TSP and WASP (5 wt% each), exhibited the highest compressive strength of 70 MPa, clearly demonstrating a synergistic reinforcement effect.

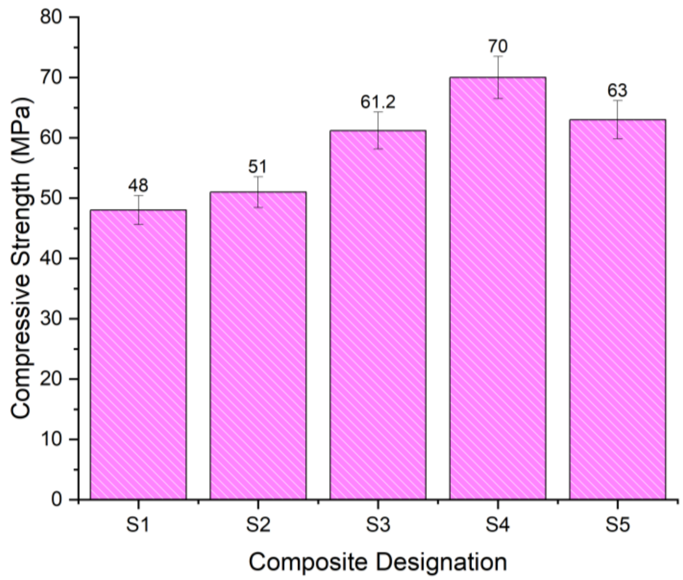

Fig. 6. Compressive strength

The combination of fillers with different particle sizes, morphologies, and chemical compositions promotes better packing density and reduces void content within the matrix. This hybrid filler network enhances matrix confinement and restricts fiber instability, thereby significantly improving resistance to compressive loads. Additionally, the hybrid fillers create multiple stress transfer pathways and improve interfacial integrity, allowing the composite to sustain higher compressive stresses before failure (Yuan *et al.* 2013). However, further increasing the hybrid filler content in S5 (7.5 wt% TSP + 7.5 wt% WASP) led to a reduction in compressive strength to 63 MPa. This decline is attributed to filler agglomeration, insufficient resin wetting, and increased filler–filler interactions, which disrupt matrix continuity and introduce stress concentration zones. Excessive filler loading also reduces the effective matrix volume available to bind fibers and fillers, thereby weakening the composite under compressive stress. Overall, the compressive strength results confirm that moderate hybrid filler incorporation significantly enhances the compressive load-bearing capability of SGF-reinforced epoxy composites (Das *et al.* 2021). In contrast, excessive filler content compromises interfacial bonding and structural integrity. Figure 6 illustrates the comparative compressive strength behavior of all composite formulations.

Impact Strength

The impact strength behavior of the SGF-reinforced epoxy composites (S1 to S5) clearly demonstrated the positive influence of Tamarind Seed Powder (TSP), Wood Apple Shell Powder (WASP), and their hybrid combinations on the energy absorption capability of the material under sudden loading conditions. Impact strength is a critical indicator of a composite's resistance to crack initiation and propagation during high strain-rate events, and it is strongly governed by matrix toughness, fiber–matrix adhesion, and the presence of effective energy-dissipating mechanisms. The control composite, S1, reinforced solely with Snake Grass Fiber (SGF), exhibited an impact strength of 7.56 J. This baseline performance reflects the inherent toughness contribution of SGF, which contains a hierarchical lignocellulosic structure capable of absorbing impact energy through fiber pull-out, fiber fracture, and matrix cracking mechanisms. Natural fibers such as SGF enhance impact resistance by promoting progressive failure rather than catastrophic fracture, as reported in earlier studies on plant fiber–reinforced epoxy systems (Savitha *et al.* 2019; Raghunathan *et al.* 2024). However, the absence of fillers limits additional crack-deflection and energy-dissipation pathways, resulting in moderate impact performance. The addition of 5 wt% TSP in S2 led to a marginal improvement in impact strength to 7.98 J. At this loading, TSP particles primarily function as rigid inclusions that restrict localized matrix deformation during impact. These particles act as crack arrestors, interrupting crack propagation and increasing the energy required for fracture initiation. Nevertheless, because TSP particles are relatively stiff and less effective in plastic deformation, the improvement remains limited, indicating that impact resistance at low filler content is still dominated by the fiber–matrix interaction. A further increase in impact strength was observed in S3 (8.12 J) with the incorporation of 5 wt% WASP. The superior performance of WASP-filled composites can be attributed to the higher lignin content and inherent toughness of WASP particles, which enhance matrix ductility and improve interfacial bonding. Enhanced adhesion between WASP and the epoxy matrix promotes efficient stress transfer and suppresses brittle fracture behavior, allowing greater energy dissipation through microcrack formation, crack pinning, and localized plastic deformation (Vivek and Kanthavel 2019). These mechanisms collectively reduce crack growth velocity under impact loading. The hybrid filler composite S4 exhibited the highest impact strength of 8.98 J, confirming a strong synergistic effect between TSP and WASP. The coexistence of fillers with different morphologies and mechanical characteristics is expected to result in a balanced combination of stiffness and toughness. Under impact loading, the hybrid filler network promotes multiple crack deflection, crack branching, and filler debonding mechanisms, which significantly increase the fracture surface area and energy absorption capacity. Moreover, the hybrid fillers improve stress redistribution within the matrix and enhance fiber–matrix interfacial integrity, delaying catastrophic failure and maximizing impact resistance. In contrast, S5, containing a higher hybrid filler content (7.5 wt% TSP + 7.5 wt% WASP), showed a slight reduction in impact strength to 8.51 J. This decline is attributed to filler agglomeration and increased filler–filler interactions, which reduce matrix continuity and create stress concentration zones. These localized defects facilitate premature crack initiation, thereby limiting the composite's ability to dissipate impact energy effectively. Similar reductions at high filler loadings have been reported in agro-waste-filled polymer composites due to compromised interfacial bonding and reduced matrix ductility (Ahmad *et al.* 2015). Overall, the impact strength results clearly demonstrate that moderate hybrid filler incorporation significantly enhances the toughness and impact resistance of SGF-reinforced epoxy composites through improved interfacial bonding, crack deflection, and energy dissipation mechanisms (Mahmud *et al.* 2025). Figure 7 illustrates the comparative impact performance of all composite formulations.

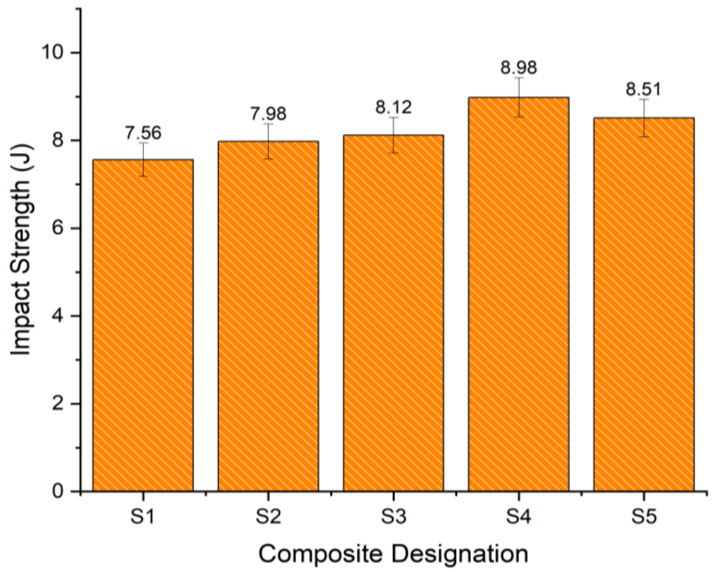

Fig. 7. Impact strength

Hardness

The Shore D hardness results of the SGF-reinforced epoxy composites (S1 to S5) clearly demonstrate the beneficial role of Tamarind Seed Powder (TSP), Wood Apple Shell Powder (WASP), and their hybrid combinations in enhancing surface resistance to indentation and localized deformation. Hardness is a critical property for applications involving abrasion, contact loading, and surface durability, and it is strongly influenced by matrix stiffness, filler rigidity, interfacial bonding, and microstructural compactness. The control composite, S1, reinforced only with Snake Grass Fiber (SGF), exhibited a hardness value of 72 SD. This baseline hardness is primarily governed by the intrinsic stiffness of SGF and its load-bearing contribution within the epoxy matrix. The presence of SGF restricts matrix deformation under indentation by providing internal reinforcement, which aligns with previous reports on natural fiber–reinforced epoxy systems (Maguteeswaran *et al.* 2024). However, the absence of particulate fillers limits further densification of the surface layer, resulting in moderate hardness. The incorporation of 5 wt% TSP in S2 increased the hardness to 76 SD, indicating improved resistance to localized plastic deformation. TSP particles, being rigid lignocellulosic fillers, acted as hard inclusions embedded within the epoxy matrix. Under indentation, these particles are expected to resist penetration and effectively constrain matrix flow, thereby increasing surface stiffness. Additionally, the improved filler–matrix adhesion enables efficient stress transfer at the interface, reducing micro-yielding in the surrounding matrix and contributing to enhanced hardness. A further improvement in hardness was observed in S3 (79 SD) with the addition of 5 wt% WASP.

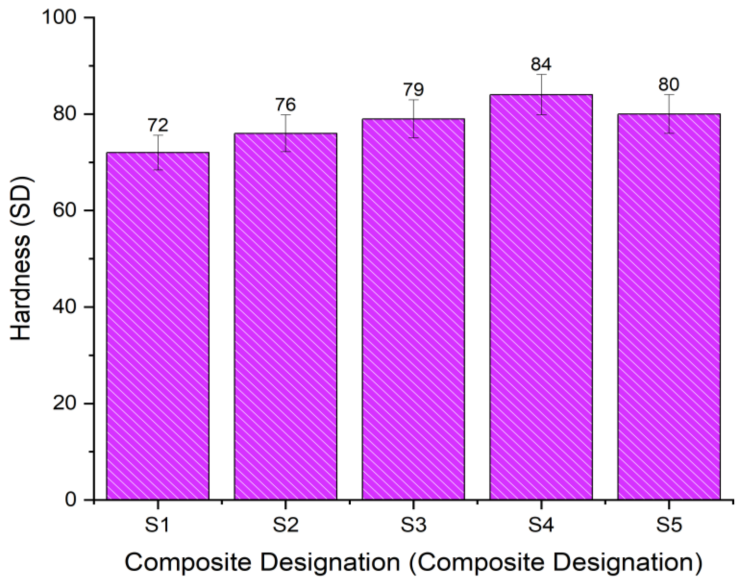

Fig. 8. Hardness

The superior performance of WASP-filled composites can be attributed to the higher lignin content and dense cellular structure of WASP particles, which impart greater intrinsic hardness than TSP. The rough surface morphology of WASP promotes strong mechanical interlocking with the epoxy matrix, leading to a more compact surface structure. This improved interfacial bonding minimizes microvoids and inhibits localized deformation during indentation, resulting in higher Shore D values. The hybrid filler composite, S4, exhibited the maximum hardness value of 84 SD, clearly demonstrating a synergistic reinforcement effect. The combined presence of TSP and WASP enhanced filler packing efficiency and promoted uniform dispersion, leading to a dense and well-integrated microstructure. The hybrid fillers restricted polymer chain mobility more effectively than single fillers and provided multiple load-bearing pathways under indentation. Moreover, the improved interfacial transition zone reduced stress concentration and prevented localized matrix failure, thereby maximizing surface hardness. In contrast, S5, containing a higher hybrid filler content (7.5 wt% TSP + 7.5 wt% WASP), showed a slight reduction in hardness to 80 SD. This decline is attributed to filler agglomeration and incomplete resin wetting at higher filler loadings. Agglomerated particles can create microstructural imperfections and stress concentration sites that locally reduce resistance to indentation. Excessive filler content may also disrupt matrix continuity, slightly compromising surface integrity despite the presence of hard particles. Overall, the Shore D hardness results confirm that moderate incorporation of hybrid agricultural-waste fillers significantly enhanced the surface hardness of SGF-reinforced epoxy composites through improved matrix stiffening, efficient stress transfer, and microstructural densification. However, exceeding the optimal filler threshold can lead to agglomeration-induced defects that marginally reduce hardness (Ravichandran *et al.* 2025). These findings are consistent with previous observations on particulate-filled polymer composites (Gurusamy *et al.* 2025). Figure 8 illustrates the comparative hardness performance of all composite formulations.

Water Absorption

The water absorption behavior of the SGF-reinforced epoxy composites (S1 to S5) clearly demonstrates the influence of Tamarind Seed Powder (TSP), Wood Apple Shell Powder (WASP), and their hybrid combinations in mitigating moisture uptake (Raja and Devarajan 2025). Moisture absorption is a critical parameter for natural-fiber-reinforced composites, as hydrophilic fiber constituents, void content, and filler–matrix interfacial quality significantly affect dimensional stability, mechanical integrity, and long-term durability. The control composite, S1, without any fillers, exhibited the highest water absorption of 32%. This relatively elevated uptake is primarily due to the hydrophilic nature of SGF, which contains cellulose and hemicellulose groups capable of binding water molecules through hydrogen bonding. Additionally, the absence of particulate fillers allows for increased free volume and microvoids in the matrix, which act as diffusion pathways for water ingress. Such behavior aligns with previous studies reporting high moisture susceptibility in unfilled natural fiber composites (Sekar *et al.* 2025). In S1, the epoxy matrix alone was unable to fully encapsulate the fibers, leading to microcapillaries that facilitate water penetration. Incorporation of 5 wt% TSP in S2 reduced water absorption to 29%. TSP contains a higher lignin content than SGF, which imparts hydrophobic characteristics to the composite and restricts polymer chain mobility, effectively limiting water diffusion. The rigid TSP particles create tortuous pathways for water molecules, slowing the ingress rate. Moreover, improved interfacial adhesion between TSP and the epoxy matrix reduces microvoid formation, thereby limiting the available sites for moisture accumulation. These observations corroborate findings in other studies where lignin-rich agro-waste fillers enhanced moisture resistance in polymer composites (Manickaraj *et al.* 2025a; Ramakrishnan *et al.* 2025b). Sample S3, containing 5 wt% WASP, further reduced water absorption to 26%. WASP is known for its dense, lignin-rich structure and inherent hydrophobicity, which impedes water penetration. The rough surface morphology and good chemical compatibility of WASP with the epoxy matrix enhanced interfacial bonding, filling microvoids and creating a more impermeable composite network. This improved interfacial integrity not only reduced moisture uptake but it also contributed to better mechanical performance under humid conditions (Sombatsompop and Wimolmala 2006). The hybrid filler composite, S4, with 5% TSP + 5% WASP, showed the lowest water absorption of 23%, indicating a synergistic effect. The combination of fillers resulted in a denser microstructure with enhanced packing density and optimized filler dispersion, effectively balancing the hydrophilic tendencies of SGF with the hydrophobic nature of the agro-waste fillers. Multiple interfacial bonding mechanisms—mechanical interlocking from WASP and matrix stiffening from TSP—create a barrier against water ingress, improving dimensional stability and durability in moisture-rich environments (Kaewpruk *et al.* 2021; Bhowmik *et al.* 2017). Sample S5, with higher hybrid filler loading (7.5% TSP + 7.5% WASP), showed a slight increase in water absorption to 25%. This minor rise is attributed to filler agglomeration and inadequate resin wetting at higher filler contents, which introduce microvoids and imperfect interfaces that facilitate water diffusion. This trend highlights the existence of an optimal filler threshold, beyond which additional particulate content may negatively affect moisture resistance (Das *et al*. 2021). In conclusion, the water absorption analysis demonstrates that moderate incorporation of hybrid agro-waste fillers significantly enhances the moisture resistance of SGF-reinforced epoxy composites by reducing voids, improving filler–matrix adhesion, and introducing hydrophobic pathways. These improvements are crucial for maintaining composite performance and dimensional stability in humid and outdoor applications. Figure 9 presents the water absorption results.

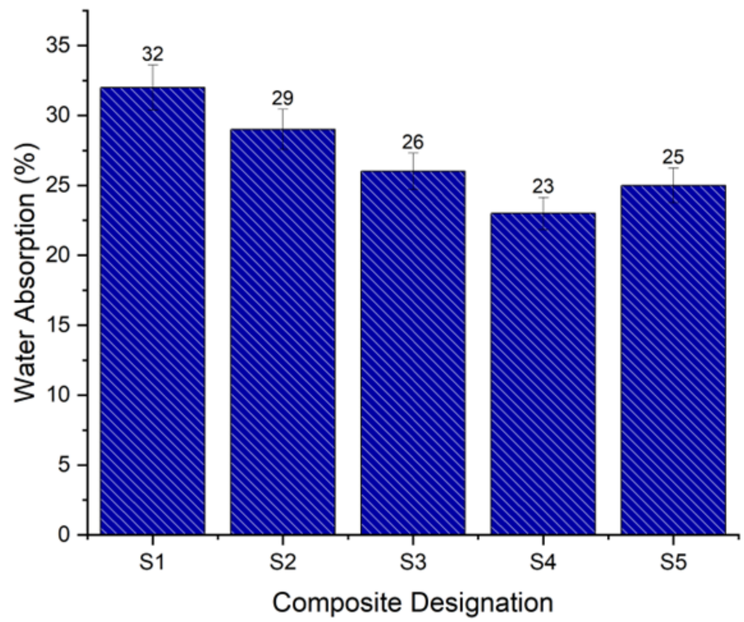

Fig. 9. Water absorption

Sound Absorption Coefficient Analysis

The sound absorption coefficient (SAC) of the SGF-reinforced epoxy composites filled with Tamarind Seed Powder (TSP) and Wood Apple Shell Powder (WASP) reflects the interplay between fiber content, filler type, microstructural porosity, and interfacial interactions. The SAC values of the composites ranged from 0.16 (S1) to 0.24 (S4), highlighting the critical influence of the fiber–filler ratio and hybrid filler incorporation on acoustic performance. The control composite S1, containing only SGF, exhibited the lowest SAC (0.16). The relatively dense structure of this composite, combined with limited air cavities, restricted its ability to dissipate incident sound energy, as the intact epoxy matrix and fibrous network allow minimal internal friction and viscous damping (Nanthakumar *et al.* 2025; Ravichandran *et al.* 2025). Addition of 5% TSP in S2 resulted in a marginal increase in SAC to 0.18. Here, the particulate TSP promoted slight micro-void formation and increases interfacial friction between fillers, fibers, and matrix, contributing to moderate acoustic energy dissipation. A more notable improvement was observed in S3 (5% WASP), with SAC rising to 0.21. WASP, with its rough surface morphology and higher lignin content, enhanced mechanical interlocking with the epoxy matrix and induced more localized damping effects. The increased interfacial friction, coupled with the presence of fine microvoids, facilitated multiple scattering and viscous dissipation of sound waves within the composite, consistent with prior observations that lignin-rich bio-fillers improve acoustic damping in polymer matrices (Huang *et al.* 2025). The hybrid filler composite S4, containing 5% TSP + 5% WASP, exhibited the highest SAC of 0.24. This optimal performance arose from the synergistic interaction of the two fillers: TSP contributed matrix stiffening and controlled microstructural rigidity, while WASP promoted mechanical interlocking and enhanced void distribution. Together, they created a heterogeneous network with sufficient porosity to trap and scatter sound waves efficiently, while maintaining mechanical stability to sustain vibrational damping. The hybrid composition produced multiple crack and micro-void pathways that increase energy dissipation, confirming that controlled filler dispersion and optimized fiber–filler ratios are critical for maximizing acoustic performance (Manickaraj *et al.* 2025b; Aly *et al.* 2021).

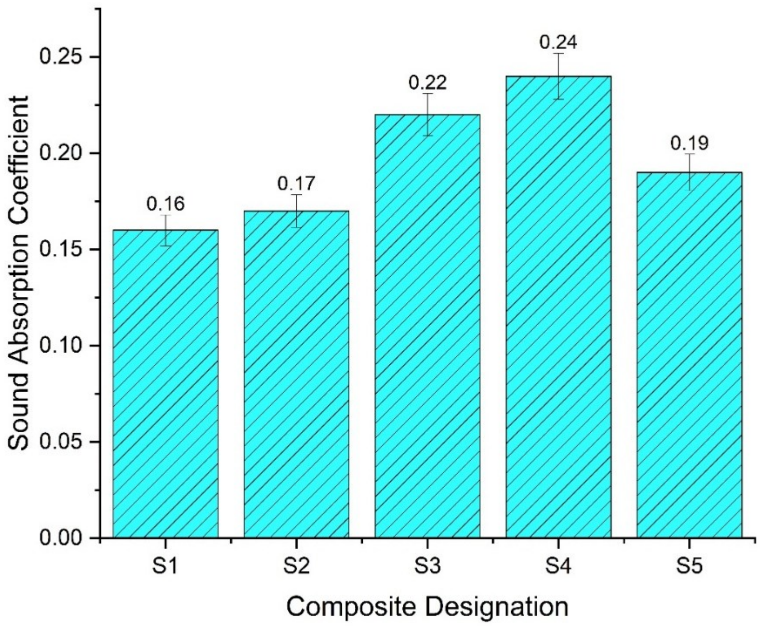

Fig. 10. Sound absorption analysis

In S5, with higher filler loading (7.5% TSP + 7.5% WASP), the SAC decreased to 0.19. The slight reduction is attributed to particle agglomeration and matrix densification at elevated filler contents, which reduce effective porosity and limits the number of micro-voids available for sound wave scattering. Excessive fillers may also reduce flexibility in the matrix, hindering vibration absorption and internal friction, which are essential for efficient sound damping. Similar trends have been reported in hybrid natural-fiber composites, where SAC peaks at moderate filler content and decreases at higher loadings due to densification and reduced internal damping (Huang *et al.* 2025). Overall, the SAC analysis demonstrated that moderate hybrid filler incorporation in SGF-reinforced epoxy composites enhanced acoustic energy dissipation by promoting controlled porosity, increased interfacial friction, and tortuous microstructural pathways. The correlation between mechanical reinforcement and acoustic damping suggests that composites optimized for tensile and flexural properties can also exhibit superior sound absorption, making these eco-friendly hybrid materials promising for applications in automotive interiors, building panels, and acoustic insulation systems. Figure 10 presents the detailed SAC results.

Scanning Electron Microscopy Analysis

Scanning Electron Microscopy was employed to investigate the fracture surfaces of the fractured specimens after mechanical testing, providing insights into the interfacial bonding, fiber-matrix adhesion, filler dispersion, and failure mechanisms of the composites (Sukhija *et al*. 2024; Thangavel *et al*. 2024). The SEM micrographs of the control composite (S1) revealed relatively smooth fracture surfaces with visible fiber pull-out and matrix cracking. The pull-out of SGF indicated moderate fiber-matrix adhesion, which could be attributed to the hydrophilic nature of the fibers and partial wetting by the epoxy matrix. Some voids and microcracks were observed around the fiber-matrix interface, which may act as stress concentrators and contribute to lower mechanical performance. In sample S2 (with 5% TSP), SEM images showed improved fiber wetting and better matrix encapsulation around the fibers compared to S1. The TSP particles appeared well distributed within the matrix, enhancing the compactness of the composite microstructure (Vinod *et al*. 2021). The presence of TSP reduced microvoids and contributed to a more tortuous crack path, thereby improving load transfer and mechanical properties. Sample S3 (with 5% WASP) displayed similar improvements in filler dispersion, with the WASP particles uniformly embedded within the matrix (Sumesh *et al*. 2024). The SEM micrographs revealed strong interfacial adhesion between WASP particles and epoxy, indicated by the absence of gaps or debonding. The matrix around the WASP particles showed plastic deformation features, suggesting effective stress transfer from the matrix to the fillers. The hybrid filler composites, S4 and S5, exhibited the most compact and homogeneous microstructure. SEM analysis of S4 showed a well-integrated network of SGF, TSP, and WASP with minimal void content. The fillers appeared to act synergistically to reinforce the matrix, with crack deflection and fiber bridging mechanisms clearly visible (Verma *et al*. 2024). This microstructural integrity correlated well with the enhanced mechanical properties observed. In S5, despite the overall good filler dispersion, occasional agglomerations of fillers were observed, which might explain the slight reduction in some mechanical properties due to localized stress concentrations. Overall, the SEM analysis confirms that alkali treatment of SGF improved fiber surface roughness and adhesion, while the inclusion of TSP and WASP fillers enhanced the matrix compactness and reduced void content (Balakrishnan *et al*. 2022; Ramesh *et al*. 2022a). The hybrid filler system contributed to better load transfer and crack resistance, leading to superior composite performance. Figure 11 shows the sample of the S4.

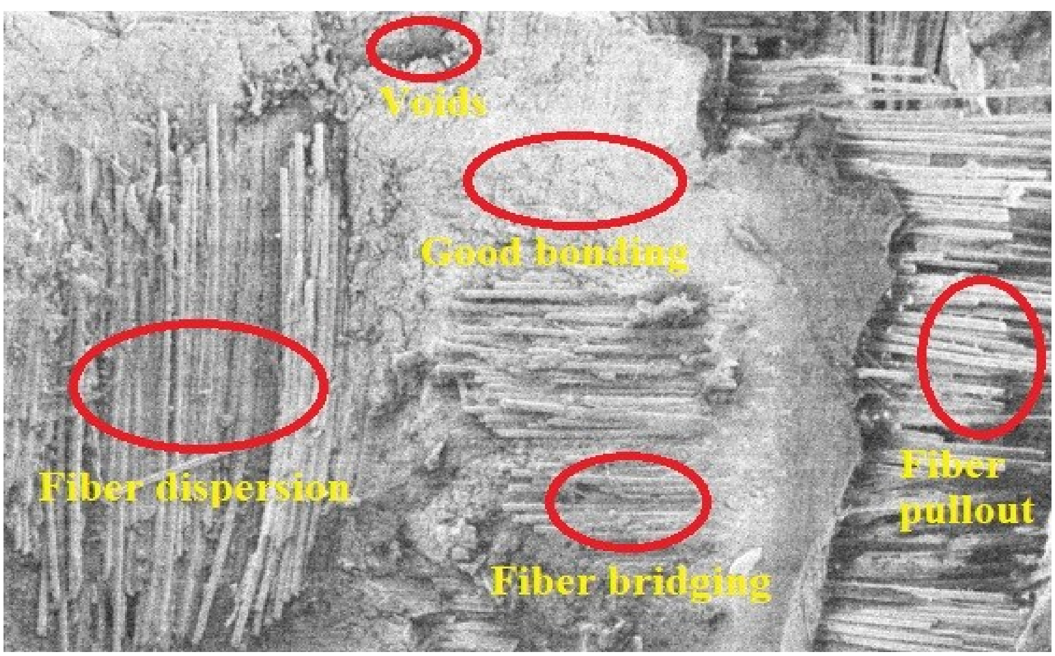

Fig. 11. Morphological and microstructural analysis

CONCLUSIONS

This study investigated the mechanical, acoustic, and microstructural performance of epoxy composites reinforced with Snake Grass Fiber (SGF) and hybrid agro-waste fillers—Tamarind Seed Powder (TSP) and Wood Apple Shell Powder (WASP). The results demonstrated that the incorporation of hybrid fillers significantly enhanced the overall performance of SGF-reinforced epoxy composites compared to SGF-only systems.

The optimized hybrid composite exhibited notable improvements in tensile, flexural, compressive, and impact strengths, along with increased Shore D hardness, which were primarily attributed to improved fiber–matrix adhesion, uniform filler dispersion, and synergistic reinforcement effects. Water absorption was substantially reduced in hybrid composites due to enhanced interfacial bonding and the presence of lignin-rich fillers, resulting in improved dimensional stability. Acoustic evaluation revealed superior sound absorption behavior in the hybrid system, driven by increased microvoids and interfacial friction that promoted effective sound energy dissipation. SEM analysis corroborated these findings by confirming reduced void content, improved filler distribution, and effective crack deflection mechanisms.

The hybrid composite outperformed single-filler and high-loading systems, with enhanced performance arising from synergistic interactions between TSP and WASP. Their complementary morphology, composition, and interfacial behavior provide balanced stiffness, toughness, moisture resistance, and acoustic damping, highlighting the multifunctional advantage of this eco-friendly composite.

The study was limited to short-term experimental evaluation under controlled conditions; long-term durability, thermal behavior, fatigue performance, and environmental aging were not investigated and should be addressed in future work.

Overall, the developed SGF-based hybrid agro-waste epoxy composites showed strong potential for use in lightweight, non-load-bearing, and semi-structural applications such as automotive interior components, building panels, insulation boards, and acoustic materials, offering a sustainable and cost-effective alternative to conventional synthetic composites.

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Data Availability Statement

Data is available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Disclosure of AI Tool Usage

ChatGPT (OpenAI) was used to assist with drafting text, and QuillBot was used for paraphrasing and language editing. All AI-assisted content was reviewed and edited by the authors. No AI tools were used to create images or figures.

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