Hybrid Bio-Composites Reinforced with Kenaf and Snake Grass Fibers and Neem Gum: Synergistic Effects and Role of Fiber Aspect Ratio

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The influence of neem gum powder (NGP) was evaluated relative to the mechanical, physical, and morphological properties of hybrid epoxy composites reinforced with varying ratios of kenaf and snake grass fibers. Six composite samples (KS1 to KS6) were fabricated with a constant epoxy content of 60 wt%. KS1 to KS5 incorporated 10 wt% NGP, while KS6 served as the control sample without gum. The results revealed a substantial improvement in mechanical performance with the inclusion of gum. The KS4 composite, containing 20% kenaf and 10% snake grass fiber, exhibited the highest tensile strength (59 MPa), flexural strength (82 MPa), inter-laminar shear strength (11.8 MPa), hardness (85.5 Shore D), and impact strength (5.23 J), along with the lowest water absorption (27%). In contrast, KS6 showed significantly lower values in all these properties, confirming the reinforcing effect of NGP. Scanning electron microscopic analysis of fractured surfaces revealed enhanced fiber-matrix adhesion in gum-containing composites, with fewer voids, reduced fiber pull-out, and minimal crack propagation, validating the mechanical test results. These findings demonstrated that the synergistic effect of hybrid fibers and gum significantly improved overall performance, making these composites promising for structural and eco-friendly applications.

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INTRODUCTION

Increasing environmental concerns and the growing demand for sustainable materials have led to a significant shift in research and industrial practices toward the development of bio-based and eco-friendly composite materials (Guna *et al*. 2018). Traditional composites reinforced with synthetic fibers such as glass, carbon, and aramid offer excellent mechanical properties but pose serious environmental challenges because of their non-biodegradability, high energy consumption during manufacturing, and difficulties in disposal (Mani *et al*. 2023). In contrast, natural fiber-reinforced polymer composites (NFRPCs) have emerged as promising alternatives owing to their renewability, biodegradability, low cost, low density, and relatively good mechanical performance (Ramesh 2016; Sumesh *et al.* 2024).

Among the wide variety of available natural fibers, kenaf (*Hibiscus cannabinus*) and snake grass (*Sansevieria cylindrica*) fibers are of particular interest. Kenaf is a bast fiber known for its high tensile strength, high cellulose content, and good fiber-matrix compatibility (Thandavamoorthy *et al*. 2024). It is widely cultivated and processed for composite applications, paper production, and textiles. Snake grass, on the other hand, is a leaf fiber with a unique tubular structure, good mechanical stiffness, and excellent moisture resistance (Sathish *et al.* 2024; Vijay *et al.* 2022). Although not as extensively studied as other common fibers, snake grass offers a high aspect ratio and sufficient interfacial bonding capability, making it suitable for reinforcing polymer matrices (Pachiappan and Santhanam 2023).

Hybridization of fibers—combining two or more types of fibers in a single composite—has proven to be an effective strategy to improve the overall performance by leveraging the unique properties of each fiber type (Vinod *et al.* 2021; Nanthakumar *et al*. 2025). In this study, kenaf and snake grass fibers were used in different weight ratios to reinforce epoxy resin. Epoxy is a thermosetting polymer that is widely used in composite manufacturing due to its superior adhesive properties, low shrinkage, chemical resistance, and excellent mechanical strength (Negi *et al*. 2024). However, like most thermosets, it is inherently brittle and benefits greatly from the reinforcement of both fibers and gum.

In addition to fibers, the introduction of other particulates into fiber-reinforced composites is another effective method to enhance interfacial bonding, improve stress distribution, and reduce moisture uptake (Kumar *et al.* 2022). In recent years, the use of natural gums derived from agricultural and forest residues has garnered attention due to their availability, renewability, and compatibility with natural fibers (Balaji *et al*. 2021). In this regard, Neem Gum Powder (NGP) presents itself as a sustainable option for composite formulation. Neem gum is a water-soluble exudate obtained from the *Azadirachta indica* tree, which contains polysaccharides with excellent adhesive and binding properties (Karuppusamy *et al.* 2025a). Its application is expected to improve fiber-matrix interaction, reduce voids and micro-cracks, and contribute to the mechanical integrity of the composite (Manimaran *et al*. 2018; Mishfa *et al*. 2023).

The core objective of this study was to investigate the combined effect of fiber hybridization and NGP (gum) on the mechanical, physical, and morphological properties of epoxy composites (Rangaraj *et al*. 2022). Six different composite samples were fabricated: five of them (KS1–KS5) contained 10 wt% NGP with varying kenaf and snake grass fiber ratios, while KS6 was kept as a control sample with no gum but a higher total fiber content (Chandramohan *et al*. 2024). The specific combination of kenaf and snake grass was chosen to exploit the strength of kenaf and the structural stiffness and moisture resistance of snake grass, while NGP was expected to act as a performance-enhancing component (Zaman and Khan 2022).

Mechanical characterizations included tensile strength, flexural strength, interlaminar shear strength (ILSS), impact strength, and hardness assessments. These properties are critical for evaluating the load-bearing capacity, resistance to deformation, toughness, and surface durability of the composites. In addition to mechanical testing, water absorption behavior was studied to measure the composite's suitability in humid or aqueous environments (Manickaraj *et al*. 2023; Ramakrishanan *et al.* 2025). Water uptake in natural fiber composites is a critical factor that can lead to swelling, debonding, and deterioration of properties over time (Ramesh *et al*. 2023).

To gain further insight into the failure mechanisms and fiber-matrix interactions, Scanning Electron Microscopy (SEM) was employed to analyze the fractured surfaces of the tested specimens. SEM images can help reveal morphological features such as fiber pull-out, fiber breakage, gum dispersion, resin-rich zones, and voids—factors which directly correlate with the mechanical performance of the composites (Sathishkumar *et al*. 2012). Enhanced interfacial adhesion observed in SEM micrographs provides a qualitative confirmation of the performance improvement due to gum incorporation (Jenish *et al*. 2021). The outcomes of the cited research indicate that the addition of bio-based components such as neem gum can significantly improve the mechanical robustness and environmental stability of natural fiber composites (Sathishkumar *et al*. 2013). This approach aligns with current trends in green materials engineering and supports the development of sustainable, lightweight, and cost-effective composite materials for applications in automotive interiors, furniture, packaging, and low-load structural components (Suriyaprakash *et al*. 2023).

Furthermore, the novelty of incorporating snake grass fibers, which are relatively underexplored, alongside a naturally-derived gum, provides an original contribution to the existing body of knowledge on bio-composites (Lokantara *et al*. 2020). The synergy between the selected fibers and gum, when optimized, not only enhances performance but also promotes the utilization of underused biomass, contributing to value-added product development and waste minimization (Rajamanickam *et al*. 2023). In summary, the current investigation demonstrates a holistic and environmentally conscious pathway for the development of high-performance bio-composites by strategically combining hybrid natural fibers and other green components (Vinodkumara *et al*. 2019). Future work may include durability studies under weathering conditions, fire resistance evaluation, and life cycle assessment to further validate the industrial applicability of these composites.

EXPERIMENTAL

Materials and Methods

Kenaf fiber

Kenaf fibers (K) used in this study were extracted from plants cultivated in the Negamam area of Coimbatore district, Tamil Nadu, India. The raw fibers were manually cleaned to eliminate dust and impurities and then sun-dried to reduce inherent moisture content (Khan *et al*. 2023). To ensure consistency during composite fabrication, the fibers were chopped into uniform lengths of approximately 25 mm (Pandiarajan *et al.* 2025). Figure 1 shows the kenaf fibers.

Snake grass fiber

Snake grass (*Sansevieria cylindrica*) fibers were also obtained from the Negamam region in Coimbatore district. The fibers were extracted through water retting for 12 days, followed by manual mechanical scraping to separate the strands (Ravichandran *et al.* 2025). After thorough washing to remove residual matter, the fibers were dried at ambient temperature and then cut into lengths of 25 mm for reinforcement purposes (Ramesh *et al*. 2018). Figure 2 shows the snake grass fibers.

Fig. 1. Kenaf fiber

Fig. 2. Snake grass fibers

Neem gum powder

Neem gum was sourced from local regions in and around Pollachi, Tamil Nadu. The crude gum was collected and subsequently pulverized using a mechanical grinder. The ground powder was sieved to a small particle size and effective dispersion within the epoxy matrix during mixing (Natarajan *et al*. 2023). Figure 3 shows the neem gum powder.

Fig. 3. Neem gum powder

Epoxy resin

A bisphenol-A-based epoxy resin (LY 556) and its corresponding hardener (HY 951) were procured from Covai Seenu and Seenu Company, Coimbatore. The resin and hardener were mixed in a 10:1 weight ratio, as recommended by the manufacturer (Jenish *et al*. 2022). This epoxy system was selected due to its excellent adhesive strength, dimensional stability, chemical resistance, and compatibility with natural fiber reinforcements (Sahoo *et al*. 2022).

Composite Formulation

Six composite formulations were developed with a constant epoxy resin content of 60 wt%. The remaining 40 wt% consisted of varying proportions of kenaf fiber, snake grass fiber, and NGP (Saravanakumar and Reddy 2022). The formulations are presented in Table 1.

Table 1. Composite Designations

Si No	Fiber Content (%)		Filler Content (%)	Epoxy Resin (%)	Composite Designation
	Kenaf Fiber (K)	Snake Grass Fibers (S)	Neem Gum Powder (NGP)		
1	5	25	10	60	KS1
2	10	20	10	60	KS2
3	15	15	10	60	KS3
4	20	10	10	60	KS4
5	25	5	10	60	KS5
6	20	20	0	60	KS6 (Without Filler)

Composite Fabrication

The composite laminates were fabricated using a combination of the hand lay-up method and compression molding. Initially, the required amount of NGP was thoroughly mixed with the epoxy resin using a mechanical stirrer at 600 rpm for approximately 10 min to ensure uniform dispersion (Iyyadurai *et al*. 2023). Subsequently, the pre-weighed kenaf and snake grass fibers were gradually added to the resin-gum mixture and manually stirred to achieve homogeneous fiber distribution (Thiruvasagam *et al*. 2017). The prepared mixture was then transferred into a rectangular steel mold of dimensions 300 mm × 300 mm × 3 mm, which was pre-coated with a suitable release agent to prevent adhesion. Compression molding was performed by applying uniform pressure using a hydraulic press to compact the laminate and eliminate entrapped air (Prabhu *et al*. 2020). The composites were allowed to cure at room temperature for 24 h under compression, followed by post-curing in a hot air oven at 60 °C for 3 h to enhance the degree of cross-linking and improve mechanical properties. After complete curing, the laminated plates were demolded and cut into standard specimens for mechanical and physical testing using a diamond-tipped saw, adhering to the respective ASTM standards. Figure 4 shows the composite fabricated plate (Dev *et al*. 2025).

Fig. 4. Composite fabricated plate

Mechanical Testing

All mechanical tests were performed at ambient room temperature using specimens prepared according to the respective ASTM standards. Tensile strength was measured following ASTM D638-14 (2022) using a universal testing machine (UTM) at a crosshead speed of 2 mm/min, with dog-bone shaped specimens having a gauge length of 50 mm (Aravindh *et al*. 2022; Maheshwaran *et al*. 2022; Manickam *et al*. 2023; Sathishkumar 2016). Flexural strength was evaluated in accordance with ASTM D790-17 (2017) using the three-point bending method, maintaining a support span of 64 mm and a crosshead speed of 2 mm/min. Interlaminar shear strength (ILSS) was determined by short beam shear testing as per ASTM D2344 2022, with a constant span-to-depth ratio of 5:1. Impact strength was assessed using a Charpy impact tester as per ASTM D256 (2023), employing un notched rectangular specimens. Surface hardness was measured using a Shore D durometer in line with ASTM D2240-15 (2021), with five readings taken from different regions of each specimen to obtain an average value (Balaji *et al*. 2016; Nithyanandhan *et al*. 2024; Ramadoss *et al*. 2024).

Water Absorption Test

Water absorption was tested according to ASTM D570-22 (2022). Specimens were dried in an oven at 50 °C for 24 h, cooled in a desiccator, weighed (W_0), and then immersed in distilled water at room temperature for 72 h. After immersion, the specimens were wiped dry and reweighed (W_1). Water absorption (%) was calculated using Eq. 1 (Vijay and Singaravelu 2016; Dhilipkumar *et al*. 2025)

$$\text{Water Absorption (\%)} = \frac{W1-W0}{W0} x\ 100 \quad (1)$$

Scanning Electron Microscopy

The microstructure of the fractured composite surfaces was analyzed using scanning electron microscopy (SEM) with a JEOL SEM (JEOL GmbH, Gute Änger, Germany) set to an accelerating voltage of 15 kV. The SEM imaging offered comprehensive insights into the distribution of components, the bonding at the interface between the matrix and fibers, as well as the mechanisms of failure observed within the composites (Akil *et al*. 2011). The SEM analysis facilitated an assessment of the morphology, allowing for the identification of voids, cracks, or inadequate filler-matrix interactions that may influence the mechanical performance of the material (Edeerozey *et al*. 2007).

RESULTS AND DISCUSSION

Tensile Strength

Tensile strength is a primary indicator of a composite material's capacity to resist axial stretching forces. The tensile behavior of fiber-reinforced polymer composites is influenced by factors such as fiber-matrix adhesion, fiber volume fraction, aspect ratio, and the uniformity of filler dispersion (Aruchamy *et al*. 2025). In this investigation, a consistent improvement in tensile strength was observed with the incorporation of a hybrid combination of kenaf fiber, snake grass fiber, and NGP. The composite KS4, containing 20% kenaf fiber, 10% snake grass fiber, and 10% NGP, exhibited the highest tensile strength of 59 MPa. This superior performance is attributable to the optimal synergy between the rigid kenaf fibers, which contribute high modulus, and the flexible snake grass fibers, known for their energy-absorbing capabilities. Neem gum powder, with particle sizes below 100 µm, was finely dispersed within the epoxy matrix, enhancing the interface between fibers and matrix by acting as a micro-filler. This led to reduced microvoids and improved stress transfer mechanisms across the matrix and reinforcing phases. The improvement in tensile performance was further validated through SEM analysis of the fracture surfaces. The composite KS4 displayed fewer fiber pull-outs, strong interfacial adhesion, and reduced matrix cracking (Elsaid *et al*. 2011). In contrast, KS6, which lacked NGP, recorded the lowest tensile strength of 39 MPa. SEM images of KS6 showed poor matrix-fiber bonding, prominent voids, and fiber pull-out, indicating ineffective load transfer and weak cohesion. This underscores the importance of the presence of the particles in facilitating mechanical interlocking and chemical bonding at the interface. The progressive enhancement from KS1 to KS4 indicates that the balanced fiber ratios significantly influence the tensile properties. The initial increase in tensile strength from KS1 to KS3 was attributed to the gradual rise in kenaf fiber content, which added stiffness and strength, while the reduction in snake grass fiber content was offset by the toughening effect of the former. At KS4, the composition reached its optimal point with the best fiber and gum synergy. Beyond this, in KS5, where kenaf fiber was increased to 25% and snake grass was reduced to 5%, a slight drop in tensile strength to 53 MPa was observed. This suggests a possible mismatch in the stress-strain behavior of the two fibers, leading to non-uniform stress distribution and increased localized stress concentrations. The incorporation of 10% NGP across KS1 to KS5 consistently contributed to improved mechanical properties by enhancing the matrix continuity, reducing void formation, and increasing the overall stiffness of the matrix. Neem gum's hydrophilic nature possibly improved wetting with natural fibers, thereby improving fiber adhesion and crack bridging capability (Sreenivas *et al*. 2020; Ramakrishnan *et al.* 2025a). In KS6, the absence of gum compromised the microstructural integrity and load-bearing efficiency, which was evident from both mechanical data and SEM imagery. In conclusion, the tensile strength results highlight the significant role of hybrid fiber reinforcement and gum integration in tailoring the tensile behavior of epoxy composites. KS4, with an optimal composition of 20% kenaf, 10% snake grass, and 10% NGP, demonstrated a strong, ductile, and well-integrated microstructure, making it the most suitable formulation for high-performance structural applications involving tensile loading. Figure 5 shows the tensile results of the specimens.

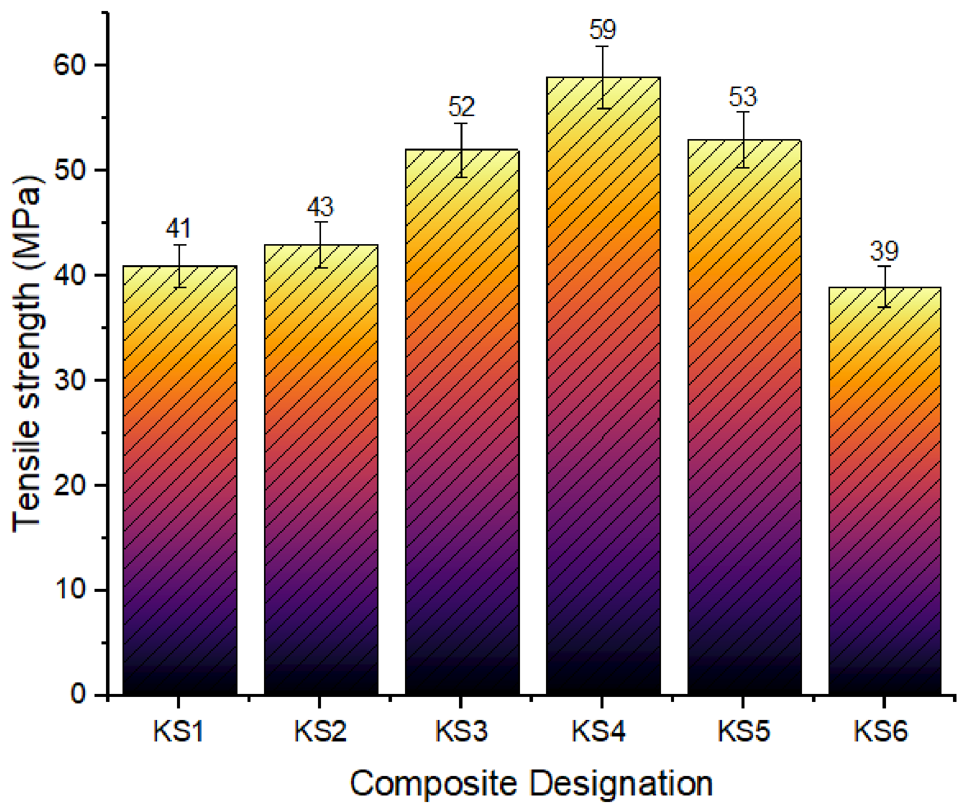

Fig. 5. Tensile strength of composites

Flexural Strength

Flexural strength determines the composite's ability to resist deformation under bending loads. Such resistance is critical for structural applications subjected to transverse stresses (Guo *et al*. 2019). The flexural properties of the developed composites exhibited a trend similar to that of tensile strength, with KS4 showing the highest flexural strength of 82 MPa. This superior bending resistance is a result of the optimal balance between the stiff kenaf fibers and the tough, flexible snake grass fibers. Kenaf's higher cellulose content contributes significantly to load-bearing capacity during bending, while snake grass enhances energy absorption and crack deflection. The matrix-fiber interaction plays a pivotal role in determining flexural behavior (Karuppiah *et al.* 2020). The NGP, acting as a micro-filler, fills voids within the matrix and provides micro-scale reinforcement that enhances stiffness. Its integration improves interfacial bonding by bridging microcracks and distributing stress effectively across the fiber and matrix interface. The presence of neem gum also reduces stress concentrations around fiber ends, delaying crack initiation and propagation under bending loads.

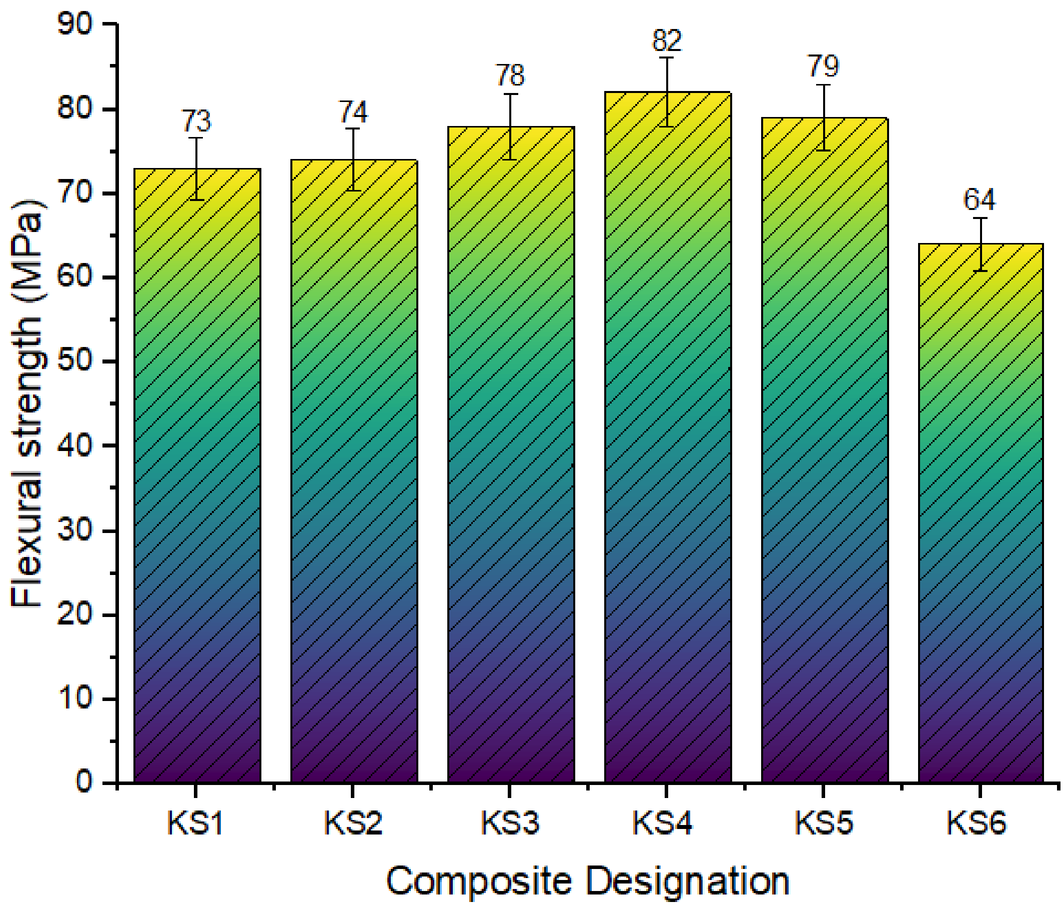

Fig. 6. Flexural strength of composites

SEM micrographs of KS4 confirm minimal fiber pull-out and strong matrix encapsulation around both kenaf and snake grass fibers. This well-bonded interface contributes to effective stress transfer and delayed failure, which is evident in the flexural testing results. The samples KS3 and KS5 also demonstrated relatively high flexural strength values (78 MPa and 79 MPa, respectively), indicating their strong matrix integrity, although slightly lower than KS4 due to imbalances in fiber synergy. The lowest flexural strength was recorded for KS6 (64 MPa), which lacked NGP. SEM images of KS6 revealed prominent voids and fiber debonding, leading to premature failure under bending stress. These observations highlight the significance of the gum phase in reinforcing the composite's bending stiffness and enhancing damage resistance. Overall, the improved flexural strength of hybrid composites with optimized gum and fiber proportions underscores the synergistic effect of hybrid reinforcement in achieving high performance. KS4 once again emerged as the best formulation, suggesting its suitability for applications requiring high flexural rigidity such as automotive panels, flooring, and load-bearing structural components (Hassan *et al*. 2017; Ramakrishnan *et al.* 2025b). Figure 6 shows the flexural strength of the composites.

Interlaminar Shear Strength

Interlaminar shear strength (ILSS) measures the resistance of laminated composites to shearing stresses between layers and is a crucial parameter in evaluating the bonding quality between plies (Malik *et al*. 2021). The highest ILSS value was recorded for KS4 (11.8 MPa), which confirms the strong interfacial bonding and cohesive integrity of the composite. This enhancement in ILSS can be attributed to the optimal hybridization of kenaf and snake grass fibers with NGP, effectively reinforcing the resin-rich interlaminar regions. The addition of 10% NGP across KS1 to KS5 consistently improved ILSS values compared to the control sample KS6 (8.62 MPa), which lacked gum. The gum's fine particle size allowed it to occupy the voids between fibers and resin, creating a denser microstructure that improved the load-bearing capacity in shear. Moreover, the hydrophilic nature of neem gum improves compatibility with natural fibers, enhancing matrix-fiber adhesion and reducing delamination tendencies. SEM analysis of KS4 revealed excellent resin-fiber wetting and fewer resin-starved regions at the interlaminar zones. The well-anchored fibers were surrounded by a dense and continuous matrix with gum particles visibly embedded, which is indicative of improved shear resistance. Conversely, KS6 showed pronounced fiber debonding and microcracks at the interfacial boundaries, which serve as stress concentrators under shear loading.

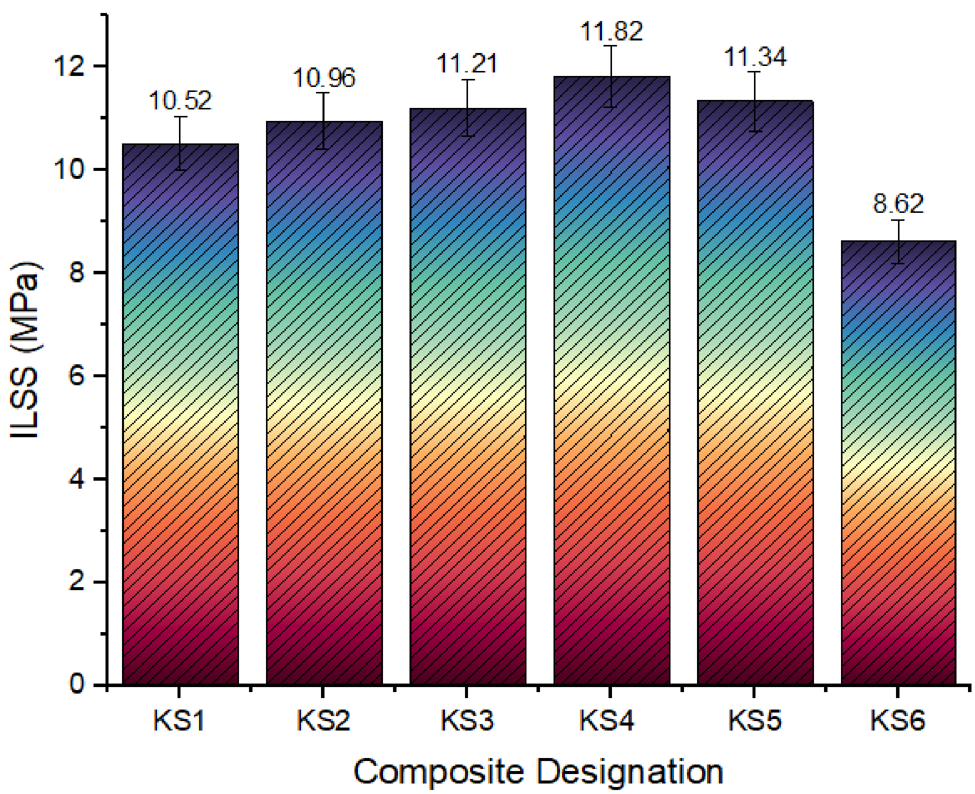

Fig. 7. The ILLS values of specimens

The gradual improvement in ILSS from KS1 to KS4 is consistent with the increasing kenaf fiber content, known for its higher mechanical stiffness and adhesion compatibility. The optimized 20% kenaf to 10% snake grass ratio in KS4 facilitates effective stress distribution between stiff and tough fiber types, thus minimizing interfacial mismatch and internal stress concentrations. These findings suggest that the presence of NGP and the proper balance between different fiber types are essential for enhancing the shear integrity of natural fiber-reinforced epoxy composites. The improved ILSS of KS4 makes it particularly well-suited for applications requiring reliable interlaminar performance, such as marine structures, wind turbine blades, and aircraft interiors (Manickaraj *et al*. 2025b). Figure 7 shows the ILLS of the specimens.

Impact Strength

Impact strength reflects the ability of a material to absorb and dissipate energy under sudden loading. The maximum impact energy was observed in KS4 (5.23 J), demonstrating the superior toughness of this composition (Gurusamy *et al*. 2025). This result suggests that the hybrid combination of kenaf and snake grass fibers, along with the presence of NGP, contributed to enhanced energy absorption and crack arrest mechanisms. The structure-property relationship in KS4 is evident from the morphology of the fracture surface observed under SEM.

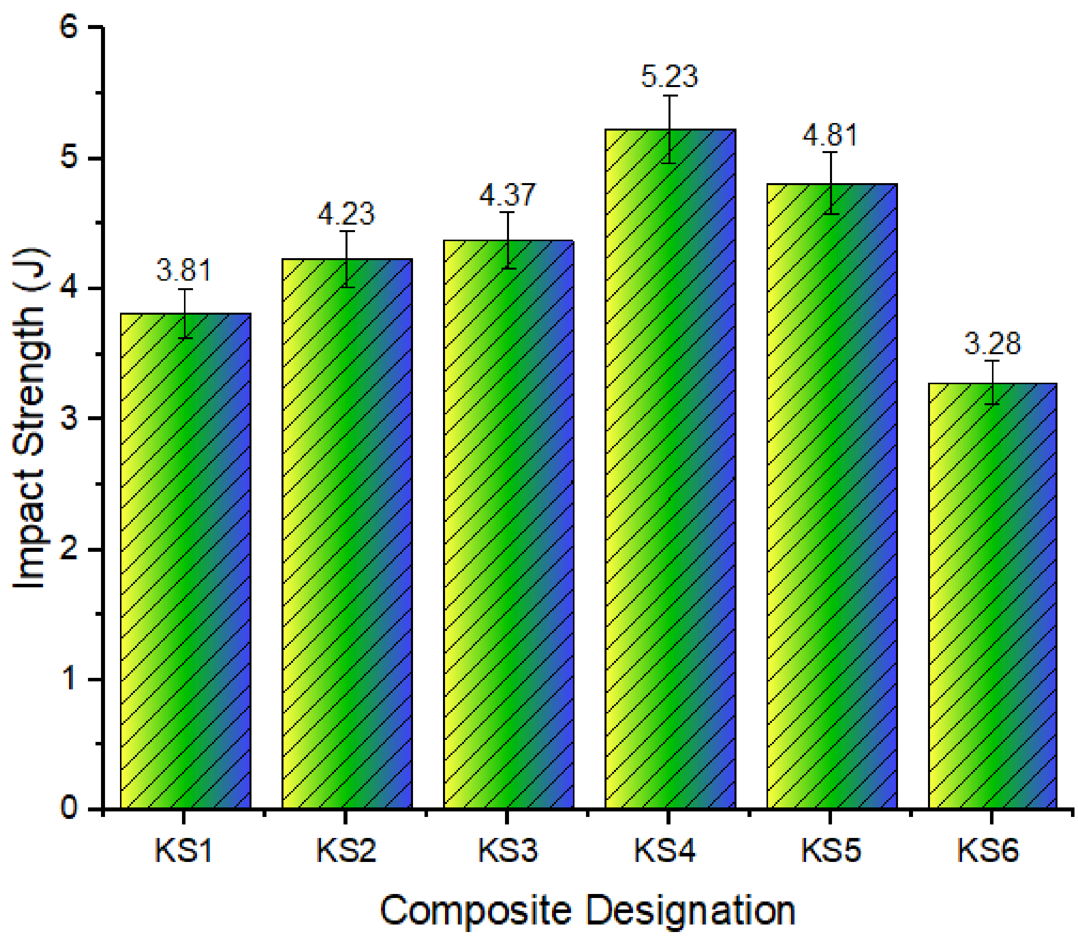

Fig. 8. Impact strength of specimens

The presence of long fiber bridges, extensive matrix deformation, and rough fracture paths indicated a more ductile failure. The intertwined nature of the two fiber types promoted crack deflection and fiber bridging, which enhanced energy dissipation. The NGP further contributed by filling the interstitial spaces, impeding crack propagation, and creating micro-barriers within the matrix. KS6, with an impact strength of only 3.28 J, exhibited a brittle failure with clean fracture surfaces and widespread fiber pull-out under SEM. The absence of gum resulted in poor matrix continuity and a reduced energy-absorbing interface. As the kenaf content increased and snake grass decreased beyond the optimal point (as in KS5), the impact resistance slightly dropped due to reduced flexibility and increased stiffness, causing a decline in the material's ability to undergo plastic deformation. These results emphasize that a well-balanced ratio of stiff and flexible fibers, combined with an appropriate gum particle system, is essential for maximizing toughness in hybrid composites. The significant energy absorption capability of KS4 highlights its potential for applications in protective gear, automotive bumpers, and packaging where impact loading is a concern (Sekar *et al*. 2025). Figure 8 shows the impact strength of the specimens.

Hardness

Hardness reflects the material's resistance to surface indentation and wear. Among the tested composites, KS4 showed the highest Shore D hardness of 85.5, indicating its superior surface integrity and structural compaction.

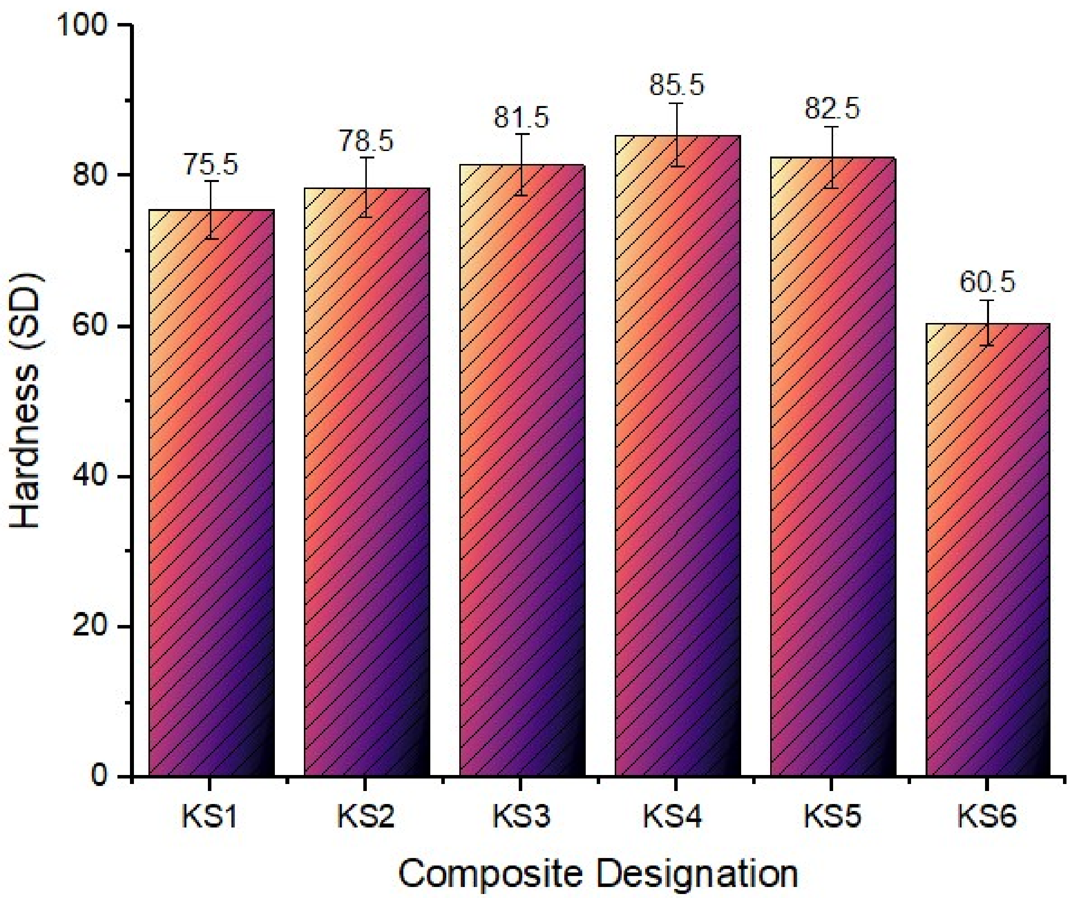

Fig. 9. Hardness of specimens

This enhancement is attributed to the effective dispersion of NGP, which reduces microvoids and increases the matrix density, thereby offering more resistance to localized deformation (Prasad *et al*. 2023; Chithra *et al*. 2024). Kenaf fibers, being stiffer, contributed to higher hardness when present in adequate volume, while snake grass fibers enhanced the matrix bonding through their rough surface topology. SEM images of KS4's surface showed tightly packed fiber-matrix interaction with a smooth and consistent outer layer, reducing surface discontinuities that could lead to premature wear. Sample KS6, which lacked gum, recorded the lowest hardness (60.5 Shore D), indicating a softer and more deformable matrix. SEM revealed numerous voids and fiber pull-outs, supporting the mechanical data. Hardness improved progressively from KS1 to KS4 as the composition approached the optimal fiber-gum balance. However, KS5 showed a slight drop (82.5 Shore D), likely due to an excess of rigid fibers that reduced resin mobility and led to uneven distribution. Higher hardness values are beneficial in applications where abrasion resistance and surface durability are critical, such as in flooring materials, automotive interiors, and electronic casings. The superior hardness of KS4 makes it a reliable candidate for such uses (Muthalagu *et al*. 2021; Karuppusamy *et al*. 2025b). Figure 9 shows the hardness of the specimens.

Water Absorption

Water absorption is a key concern for natural fiber composites, as moisture ingress can lead to swelling, degradation, and loss of mechanical integrity. The study observed a decreasing trend in water absorption with increasing NGP content and optimized fiber ratio (Prasad *et al*. 2023; Manickaraj *et al*. 2024a, 2025a; Thangavel *et al*. 2024).

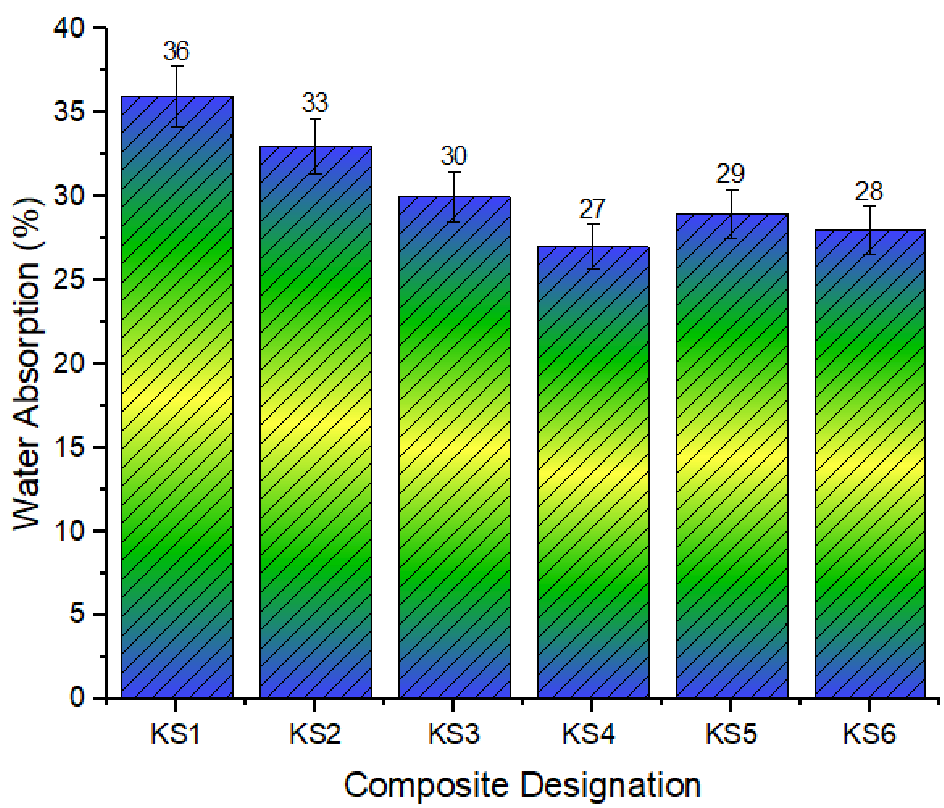

Fig. 10. Water absorption test

Interestingly, KS4 recorded a relatively low water uptake of 27%, compared to KS1 (36%) and KS6 (28%). The improved performance of KS4 can be attributed to the reduced porosity and better gum dispersion, which created a more compact microstructure with minimal water pathways. SEM images showed fewer microcracks and voids, and the fiber surfaces were well encapsulated by the resin. The NGP acted as a hydrophilic-hydrophobic bridge, improving fiber-matrix wetting while simultaneously blocking moisture ingress. KS6, despite having no gum, had lower water absorption than KS1 due to its higher fiber content and better matrix continuity, but it lacked the structural densification provided by gum particles. As snake grass content decreased and kenaf content increased, water absorption reduced up to KS4 and then slightly increased in KS5 due to excessive fiber crowding and interfacial discontinuities. These results highlight the importance of using gums such as NGP in controlling water uptake and enhancing dimensional stability in natural fiber composites. KS4 demonstrated the best moisture resistance, making it viable for humid or marine environments, including decking, outdoor panels, and water-transport components (Krishnadas *et al*. 2024; Manickaraj *et al*. 2024b). Figure 10 shows the results of water absorption tests.

SEM Analysis

The analysis using SEM provided valuable insight into the morphological characteristics of the fractured surfaces and the interfacial behavior between the matrix, fibers, and gum particles. The SEM micrographs of the tensile fracture surface of KS4 revealed a compact and integrated microstructure, with strong fiber-matrix adhesion and minimal fiber pull-out. The NGP appeared well-dispersed, effectively bridging the matrix and fibers, reducing microvoids, and enhancing stress transfer (Gurusamy *et al*. 2024; Ramakrishnan *et al*. 2024). Evidence of crack deflection and fiber bridging confirmed the composite's ability to resist fracture propagation. In contrast, SEM images of KS6 exhibited poor interfacial bonding, numerous microvoids, and signs of fiber debonding and pull-out, indicating insufficient adhesion in the absence of gum. These morphological features explain the lower mechanical performance of KS6. Additionally, KS4 showed matrix shear deformation and rough fracture surfaces, indicative of better energy dissipation during failure.

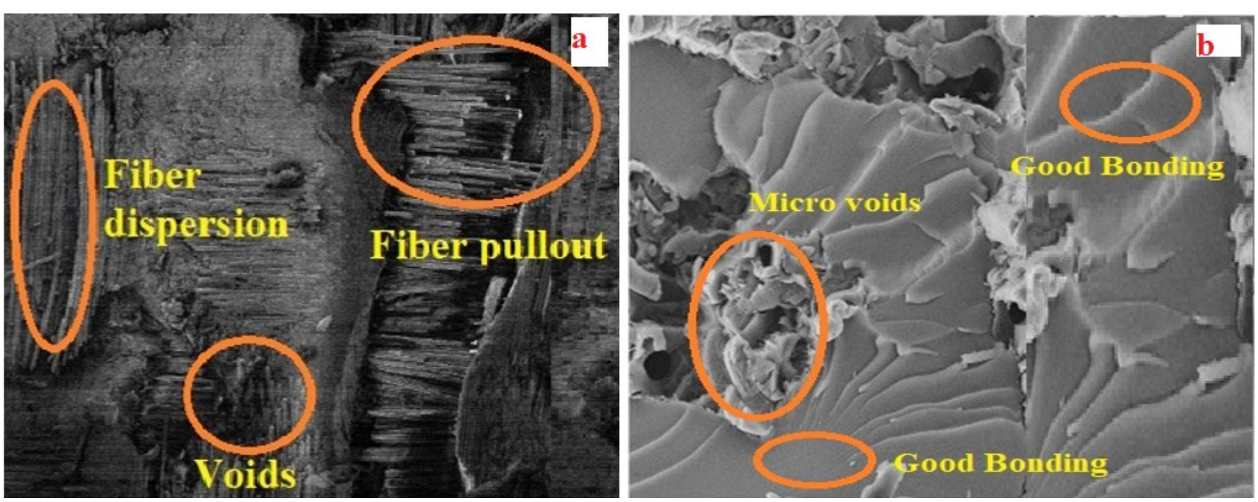

Fig. 11a. KS5 composite specimen; and **11b.** KS4 composite specimen

The combined presence of rigid kenaf fibers, tough snake grass fibers, and finely dispersed NGP resulted in an optimized microstructure that resisted crack propagation and fiber failure (Vinod *et al*. 2022; Palanisamy *et al*. 2023; Raghunathan *et al*. 2024). Therefore, SEM analysis validated the mechanical testing results, reinforcing the effectiveness of fiber hybridization and gum particle integration in enhancing composite integrity and performance. Figures 11a and 11b shows the SEM analysis of the specimens KS5 and KS4, respectively.

In summary, the hybridization of kenaf and snake grass fibers with NGP offers a promising, sustainable route for enhancing the mechanical and physical performance of epoxy composites. These findings open avenues for potential application in automotive interior panels, furniture components, construction panels, and other semi-structural uses where moderate strength and environmental sustainability are required. Future work may involve exploring chemical surface treatments of fibers or hybridization with other natural particles to further tailor the composite's behavior for high-performance engineering applications.

CONCLUSIONS

This study investigated the development and characterization of novel hybrid epoxy composites reinforced with varying proportions of kenaf fiber, snake grass fiber, and neem gum powder (NGP) as a natural component. The mechanical and physical properties, including tensile strength, flexural strength, interlaminar shear strength (ILSS), impact resistance, surface hardness, and water absorption behavior, were evaluated systematically:

1. The results clearly indicate that the incorporation of NGP as a bio-based particulate material significantly enhanced the overall performance of the composite system compared to the control sample without gum (KS6). Among all formulations, the KS4 composite, with 20% kenaf, 10% snake grass, and 10% NGP, exhibited superior mechanical properties—registering the highest tensile strength (59 MPa), flexural strength (82 MPa), ILSS (11.82 MPa), and impact strength (5.23 J). This superior performance is attributed to the synergistic interaction between the two lignocellulosic fibers, leading to better load distribution and crack bridging, while the fine dispersion of neem gum powder helped reduce voids and improve interfacial adhesion with the epoxy matrix.
2. Scanning electron microscope (SEM) analysis further confirmed improved fiber-matrix interaction in KS4, where fewer voids, better particle dispersion, and minimal fiber pull-out were observed. In contrast, the control composite (KS6), which lacked NGP reinforcement, showed inferior bonding and more pronounced debonding regions, leading to lower mechanical performance.
3. Water absorption behavior followed a decreasing trend with the inclusion of gum, indicating reduced hydrophilicity due to the gum's ability to fill microvoids and block moisture pathways. Additionally, hardness values increased with filler loading, reflecting enhanced surface integrity and resistance to localized deformation.
4. The developed composite exhibited good mechanical strength along with low water absorption, ensuring reliable performance under varying environmental conditions. With these advantageous properties, it is well-suited for practical applications such as

automotive interior panels and furniture boards.

5. Future work may explore other natural particles and improved fiber combinations to enhance performance. The effect of different stacking sequences on strength and failure can also be studied. Testing the composites in real industrial conditions will help confirm their practical use.

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Data Availability Statement

Data are 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.

REFERENCES CITED

Akil, Hm., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., and Bakar, A. A. (2011). “Kenaf fiber reinforced composites: A review,” *Materials and Design* 32(8–9), 4107-4121. https://doi.org/10.1016/j.matdes.2011.04.008

Aravindh, M., Sathish, S., Prabhu, L., Raj, R. R., Bharani, M., Patil, P. P., Karthick, A., and Luque, R. (2022). “Effect of various factors on plant fibre-reinforced composites with nanofillers and its industrial applications: A critical review,” *Journal of Nanomaterials* 2022(1), article 4455106. https://doi.org/10.1155/2022/4455106

Aruchamy, K., Karuppusamy, M., Krishnakumar, S., Palanisamy, S., Jayamani, M., Sureshkumar, K., Ali, S. K., and Al-Farraj, S. A. (2025). “Enhancement of mechanical properties of hybrid polymer composites using palmyra palm and coconut sheath fibers: The role of tamarind shell powder,” *BioResources* 20(1), 698-724. https://doi.org/10.15376/biores.20.1.698-724

ASTM D256-23e1 (2023). “Standard test methods for determining the Izod pendulum impact resistance of plastics,” ASTM International, West Conshohocken, PA, USA.

ASTM D570-22 (2022). “Standard test method for water absorption of plastics,” ASTM International, West Conshohocken, PA, USA.

ASTM D638-14 (2022). “Standard test method for tensile properties of plastics,” ASTM International, West Conshohocken, PA, USA.

ASTM D790-17 (2017). “Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials,” ASTM International, West Conshohocken, PA, USA.

ASTM D2344/D2344M-22 (2022). “Standard test method for short-beam strength of polymer matrix composite materials and their laminates,” ASTM International, West Conshohocken, PA, USA.

ASTM D2240-15 (2021). "Standard test method for rubber property—Durometer hardness," ASTM International, West Conshohocken, PA, USA.

Balaji, A. N., Karthikeyan, M. K. V, and Vignesh, V. (2016). "Characterization of new natural cellulosic fiber from kusha grass," *International Journal of Polymer Analysis and Characterization* 21(7), 599-605. https://doi.org/10.1080/1023666X.2016.1192324

Balaji, D., Ramesh, M., Kannan, T., Deepan, S., Bhuvaneswari, V., and Rajeshkumar, L. (2021). "Experimental investigation on mechanical properties of banana/snake grass fiber reinforced hybrid composites," *Materials Today: Proceedings* 42, 350-355. https://doi.org/10.1016/j.matpr.2020.09.548

Chandramohan, P., Kalimuthu, M., Subramanian, K., Nagarajan, R., Muhammed, F. F., Al-Lohedan, H. A., and Krishnan, K. (2024). "Mechanical and thermo-mechanical behaviors of snake grass fiber-reinforced epoxy composite," *BioResources* 19(1), 1119-1135. https://doi.org/10.15376/biores.19.1.1119-1135

Chithra, N. V., Karuppasamy, R., Manickaraj, K., and Ramakrishnan, T. (2024). "Effect of reinforcement addition on mechanical behavior of Al MMC-A critical review," *J. Environ. Nanotechnol*. 13(2), 65-79. https://doi.org/10.13074/jent.2024.06.242632

Dev, B., Rahman, M. A., Rahman, M. Z., Turjo, S. M., Adib, R. J., Jeem, M. H., and Nasim, N. (2025). "Mechanical properties of unidirectional banana/snake plant fiber-reinforced epoxy hybrid composites: experimental and numerical analyses," *Polymer Bulletin* 82, 1-30. https://doi.org/10.1007/s00289-025-05658-x

Dhilipkumar, T., Arunpandian, M., Arumugam, S., Sadeq, A. M., P, K., Oh, T. H., Bahajjaj, A. A. A., Shankar, K. V, and Selvakumar, K. (2025). "Exploring the synergistic effects of graphene on the mechanical and vibrational response of kenaf/pineapple fiber-reinforced hybrid composites," *Polymer Composites* 46(5), 4591-4604. https://doi.org/10.1002/pc.29262

Edeerozey, A. M. M., Akil, H. M., Azhar, A. B., and Ariffin, M. I. Z. (2007). "Chemical modification of kenaf fibers," *Materials Letters* 61(10), 2023-2025. https://doi.org/10.1016/j.matlet.2006.08.006

Elsaid, A., Dawood, M., Seracino, R., and Bobko, C. (2011). "Mechanical properties of kenaf fiber reinforced concrete," *Construction and Building Materials* 25(4), 1991-2001. https://doi.org/10.1016/j.conbuildmat.2010.11.052

Guna, V., Ilangovan, M., Ananthaprasad, M. G., and Reddy, N. (2018). "Hybrid biocomposites," *Polymer Composites* 39, E30-E54. https://doi.org/10.1002/pc.24641

Guo, A., Sun, Z., and Satyavolu, J. (2019). "Impact of chemical treatment on the physiochemical and mechanical properties of kenaf fibers," *Industrial Crops and Products* 141, article 111726. https://doi.org/10.1016/j.indcrop.2019.111726

Gurusamy, M., Soundararajan, S., Karuppusamy, M., and Ramasamy, K. (2024). "Exploring the mechanical impact of fine powder integration from ironwood sawdust and COCO dust particles in epoxy composites," *Matéria (Rio de Janeiro)*, 29, article e20240216. https://doi.org/10.1590/1517-7076-RMAT-2024-0216

Gurusamy, M., Thirumalaisamy, R., Karuppusamy, M., and Sivanantham, G. (2025). "Pistachio shell biochar as a reinforcing filler in short Turkish hemp fiber composites: A path toward sustainable materials," *Journal of Polymer Research*, 32(4), 1-26. https://doi.org/10.1007/s10965-025-04338-8

Hassan, F., Zulkifli, R., Ghazali, M. J., and Azhari, C. H. (2017). "Kenaf fiber composite in automotive industry: An overview," *Int. J. Adv. Sci. Eng. Inf. Technol* 7(1), 315–321.

Iyyadurai, J., Arockiasamy, F. S., Manickam, T., Rajaram, S., Suyambulingam, I., and Siengchin, S. (2023). "Experimental investigation on mechanical, thermal, viscoelastic, water absorption, and biodegradability behavior of *Sansevieria ehrenbergii* fiber reinforced novel polymeric composite with the addition of coconut shell ash powder," *Journal of Inorganic and Organometallic Polymers and Materials* 33(3), 796-809. https://doi.org/10.1007/s10904-023-02537-8

Jenish, I., Felix Sahayaraj, A., Appadurai, M., Fantin Irudaya Raj, E., Suresh, P., Raja, T., Salmen, S. H., Alfarraj, S., and Manikandan, V. (2021). "Fabrication and experimental analysis of treated snake grass fiber reinforced with polyester composite," *Advances in Materials Science and Engineering* 2021(1), article 6078155. https://doi.org/10.1155/2021/6078155

Jenish, I., Sahayaraj, A. F., Suresh, V., Mani Raj, J., Appadurai, M., Irudaya Raj, E. F., Nasif, O., Alfarraj, S., and Kumaravel, A. K. (2022). "Analysis of the hybrid of mudar/snake grass fiber-reinforced epoxy with nano-silica filler composite for structural application," *Advances in Materials Science and Engineering* 2022, 1-10. https://doi.org/10.1155/2022/7805146

Karuppusamy, M., Thirumalaisamy, R., Palanisamy, S., Nagamalai, S., Massoud, E. E. S., and Ayrilmis, N. (2025a). "A review of machine learning applications in polymer composites: advancements, challenges, and future prospects," *Journal of Materials Chemistry A* 13, 16290-16308. https://doi.org/10.1039/D5TA00982K

Karuppusamy, M., Kalidas, S., Palanisamy, S., Nataraj, K., Nandagopal, R. K., Natarajan, R., Samraj, A., Ayrilmis, N., Sahu, S. K., Giri, J., and Kanan, M. (2025b). "Real-time monitoring in polymer composites: Internet of things integration for enhanced performance and sustainability--A review," *BioResources* 20(3), 8093-8118. https://doi.org/10.15376/biores.20.3.Karuppusamy

Karuppiah, G., Kuttalam, K.C., Palaniappan, M., Santulli, C., and Palanisamy, S. (2020. "Multiobjective optimization of fabrication parameters of jute fiber/polyester composites with egg shell powder and nanoclay filler," *Molecules* 25(23), article 5579. https://doi.org/10.3390/molecules25235579

Khan, A., Sapuan, S. M., Siddiqui, V. U., Zainudin, E. S., Zuhri, M. Y. M., and Harussani, M. M. (2023). "A review of recent developments in kenaf fiber/polylactic acid composites research," *International Journal of Biological Macromolecules* 253, article 127119. https://doi.org/10.1016/j.ijbiomac.2023.127119

Krishnadas, G., Karuppasamy, R., Selvam, S., and Manickaraj, K. (2024). "Evolving sandwich composites through structural modifications with polyurethane foam and glass fiber," *Materia-Rio De Janeiro* 29(4), article e20240507. https://doi.org/10.1590/1517-7076-rmat-2024-0507

Kumar, R. P., Muthukrishnan, M., and Sahayaraj, A. F. (2022). "Experimental investigation on jute/snake grass/kenaf fiber reinforced novel hybrid composites with annona reticulata seed filler addition," *Materials Research Express* 9(9), article 95304. https://doi.org/10.1088/2053-1591/ac92ca

Lokantara, I. P., Suardana, N. P. G., Surata, I. W., and Winaya, I. N. S. (2020). "A review on natural fibers: Extraction process and properties of grass fibers," *International Journal of Mechanical Engineering and Technology (IJMET)* 1(11), 84–91.

Maheshwaran, R., Dhanasekaran, C., Sivaganesan, S., and Pugazhenthi, R. (2022). "Investigation of mechanical behavior of biodegradable natural composite PLA reinforced with snake grass fiber and sisal fiber," in: *Recent Advances in Materials and Modern Manufacturing: Select Proceedings of ICAMMM 2021* 165-173.

https://doi.org/ 10.1007/978-981-19-0244-4_17

Malik, K., Ahmad, F., and Gunister, E. (2021). "A review on the kenaf fiber reinforced thermoset composites," *Applied Composite Materials* 28(2), 491-528. https://doi.org/10.1007/S10443-021-09871-5

Mani, V., Krishnaswamy, K., Arockiasamy, F. S., and Manickam, T. S. (2023). "Mechanical and dielectric properties of *Cissus quadrangularis* fiber-reinforced epoxy/TiB2 hybrid composites," *International Polymer Processing* 38(4), 435-446. https://doi.org/10.1515/ipp-2022-4321

Manickam, T., Iyyadurai, J., Jaganathan, M., Babuchellam, A., Mayakrishnan, M., and Arockiasamy, F. S. (2023). "Effect of stacking sequence on mechanical, water absorption, and biodegradable properties of novel hybrid composites for structural applications," *International Polymer Processing* 38(1), 88-96. https://doi.org/10.1515/ipp-2022-4274

Manickaraj, K., Ramamoorthi, R., Sathish, S., and Johnson Santhosh, A. (2023). "A comparative study on the mechanical properties of African teff and snake grass fiber-reinforced hybrid composites: effect of bio castor seed shell/glass/SiC fillers," *International Polymer Processing* 38(5), 551-563. https://doi.org/10.1515/ipp-2023-4343

Manickaraj, K., Aravind, S., Ramakrishnan, T., Sudha, N., Ramamoorthi, R., and Nithyanandhan, T. (2024a). "Advancing polymer composites through computational learning and artificial intelligence integration," in: *2024 International Conference on Emerging Research in Computational Science (ICERCS)* 1–5. https://doi.org/10.1109/ICERCS63125.2024.10895062

Manickaraj, K., Ramamoorthi, R., Karuppasamy, R., Sakthivel, K. R., and Vijayaprakash, B. (2024b). "A review of natural biofiber-reinforced polymer matrix composites," in: *Manufacturing, Design and Operational Practices for Resource and Environmental Sustainability* Ch-11, 135-141. https://doi.org/10.1002/9781394198221.ch11

Manickaraj, K., Karthik, A., Palanisamy, S., Jayamani, M., Ali, S. K., Sankar, S. L., and Al-Farraj, S. A. (2025a). "Improving mechanical performance of hybrid polymer composites: Incorporating banana stem leaf and jute fibers with tamarind shell powder," *BioResources* 20(1), 1998-2025. https://doi.org/10.15376/biores.20.1.1998-2025

Manickaraj, K., Thirumalaisamy, R., Palanisamy, S., Ayrilmis, N., Massoud, E. E. S., Palaniappan, M., and Sankar, S. L. (2025b). "Value-added utilization of agricultural wastes in biocomposite production: Characteristics and applications," *Annals of the New York Academy of Sciences* 1-20. https://doi.org/10.1111/nyas.15368

Manimaran, P., Senthamaraikannan, P., Murugananthan, K., and Sanjay, M. R. (2018). "Physicochemical properties of new cellulosic fibers from Azadirachta indica plant," *Journal of Natural Fibers* 15(1), 29-38. https://doi.org/10.1080/15440478.2017.1302388

Mishfa, K. F., Alim, M. A., Repon, M. R., Habibullah, M. D., Tonmoy, M. A. H., Jurkonienė, S., and Shukhratov, S. (2023). "Preparation and characterization of snake plant fiber reinforced composite: A sustainable utilization of biowaste," *SPE Polymers* 5(1), 35-44. https://doi.org/10.1002/pls2.10108

Muthalagu, R., Srinivasan, V., Sathees Kumar, S., and Krishna, V. M. (2021). "Extraction and effects of mechanical characterization and thermal attributes of jute, *Prosopis juliflora* bark and kenaf fibers reinforced bio composites used for engineering applications," *Fibers and Polymers* 22(7), 2018-2026.

https://doi.org/10.1007/s12221-021-1092-9
Nanthakumar, J., Palanisamy, Y., Palanisamy, S., Karuppusamy, M., Raja, R., Abbas, M., Alagarsamy, A., and Rahman, M. Z. (2025). "Eco-friendly synthesis of ZnO nanoparticles using *Delonix elata* extract with enhanced antibacterial activity," *RSC Advances* 15(46), 39305-39313. https://doi.org/10.1039/D5RA05208D
Natarajan, P., Rajasekaran, P., Mohanraj, M., and Devi, S. (2023). "Mechanical and tribological properties of snake grass fibers reinforced epoxy composites: Effect of Java plum seed filler weight fraction," *International Polymer Processing* 38(5), 582-592. https://doi.org/10.1515/ipp-2023-4376
Negi, P., Bhatt, P., Sharma, H., and Brar, G. S. (2024). "Physio-mechanical and thermal behavior of kenaf (*Hibiscus cannabinus* L.) fiber-reinforced epoxy composites: effect of eco-friendly treatment," *Biomass Conversion and Biorefinery* 15, 1-10. https://doi.org/10.1007/s13399-024-06112-0
Nithyanandhan, T., Manickaraj, K., Sathish, K., Ramachandran, N., and Sachuthananthan, B. (2024). "Effects of palm stalk ash on mechanical properties of Al6061 reinforced with graphite by using stir casting process," in: *2024 10th International Conference on Advanced Computing and Communication Systems (ICACCS)* 2357-2364. https://doi.org/10.1109/ICACCS60874.2024.10717271
Pachiappan, A., and Santhanam, S. K. V. (2023). "Mechanical behavior of snake grass fiber with neem gum filler hybrid composite," *Polímeros* 33, article e20230033. https://doi.org/10.1590/0104-1428.20220116
Palanisamy, S., Kalimuthu, M., Santulli, C., Palaniappan, M., Nagarajan, R., and Fragassa, C. (2023). "Tailoring epoxy composites with *Acacia caesia* bark fibers: Evaluating the effects of fiber amount and length on material characteristics," *Fibers* 11(7), 63. https://doi.org/10.3390/fib11070063
Pandiarajan, P., Baskaran, P. G., Palanisamy, S., Karuppusamy, M., Marimuthu, K., Rajan, A., Almansour, M. I., Ma, Q., and Al-Farraj, S. A. (2025). "Enhancing polyester composites with nano *Aristida hystrix* fibers: Mechanical and microstructural insights," *BioResources* 20(4), 9257-9281. https://doi.org/10.15376/biores.20.4.9257-9281
Prabhu, L., Krishnaraj, V., Sathish, S., Gokulkumar, S., Sanjay, M. R., and Siengchin, S. (2020). "Mechanical and acoustic properties of alkali-treated *Sansevieria ehrenbergii*/*Camellia sinensis* fiber–reinforced hybrid epoxy composites: Incorporation of glass fiber hybridization," *Applied Composite Materials* 27, 915-933.
Prasad, L., Kapri, P., Patel, R. V., Yadav, A., and Winczek, J. (2023). "Physical and mechanical behavior of ramie and glass fiber reinforced epoxy resin-based hybrid composites," *Journal of Natural Fibers* 20(2), 1-13. https://doi.org/10.1080/15440478.2023.2234080
Raghunathan, V., Kumar, V. V., Rajan, B. S., Ayyappan, V., Rangappa, S. M., and Siengchin, S. (2024). "Synergy effect of synthetic-mineral fibers in automobile brake friction composites," in: *Synthetic and Mineral Fibers, Their Composites and Applications* Ch-28, 745-763. https://doi.org/10.1016/B978-0-443-13623-8.00028-9
Rajamanickam, S. kumar, Ponnusamy, N., Mohanraj, M., and Julias Arulraj, A. (2023). "Experimental investigation on mechanical and tribological characteristics of snake grass/sisal fiber reinforced hybrid composites," *International Polymer Processing* 38(3), 331-342. https://doi.org/10.1515/ipp-2022-4301
Ramadoss, P. K., Mayakrishnan, M., and Arockiasamy, F. S. (2024). "Discarded custard

apple seed powder waste-based polymer composites: an experimental study on mechanical, acoustic, thermal and moisture properties," *Iranian Polymer Journal* 33(4), 461-479. https://doi.org/10.1007/s13726-023-01266-6
Ramakrishnan, T., Manickaraj, K., Prithiv, S. P., Aditya, S. L., Rajanarayanan, N., and Gopalsamy, S. (2024). "Advancements in aluminum metal matrix composites: Reinforcement, manufacturing, and applications," in: *AIP Conference Proceedings* 3221, article 020030. https://doi.org/10.1063/5.0235881
Ramakrishnan, S. K., Arivendan, A., and Vijayananth, K. (2025a). "*Abelmoschus mallow* and *Bambusa vulgaris* Fiber, *Ipomoea batatas* vegetable waste filler: Cellulose extraction and compatibility with PLA bio composites," *International Journal of Biological Macromolecules* 306, article 141353. https://doi.org/10.1016/j.ijbiomac.2025.141353
Ramakrishnan, S. K., Arivendan, A., and Vijayananth, K. (2025b). "Cellulose extraction from red sage fiber, Prosopis Juliflora fiber, vegetable waste filler: Applications in PLA based bio composites," *International Journal of Biological Macromolecules*, 285, article 138102. https://doi.org/10.1016/j.ijbiomac.2024.138102
Ramesh, M. (2016). "Kenaf (*Hibiscus cannabinus* L.) fibre based bio-materials: A review on processing and properties," *Progress in Materials Science* 78, 1-92. https://doi.org/10.1016/j.pmatsci.2015.11.001
Ramesh, M., Selvan, M. T., and Sahayaraj, A. F. (2023). "Grass fiber-based epoxy composites: Thermal and mechanical properties," in: *Epoxy-Based Biocomposites* Ch-5, 101-120. https://doi.org/10.1201/9781003271017
Ramesh, P., Durga Prasad, B., and Narayana, K. L. (2018). "Characterization of kenaf fiber and its composites: A review," *Journal of Reinforced Plastics and Composites* 37(11), 731-737. https://doi.org/10.1177/0731684418760206
Rangaraj, R., Sathish, S., Mansadevi, T. L. D., Supriya, R., Surakasi, R., Aravindh, M., Karthick, A., Mohanavel, V., Ravichandran, M., and Muhibbullah, M. (2022). "Investigation of weight fraction and alkaline treatment on *Catechu linnaeus*/*Hibiscus cannabinus*/*Sansevieria ehrenbergii* plant fibers-reinforced epoxy hybrid composites," *Advances in Materials Science and Engineering* 2022(1), article 4940531. https://doi.org/10.1155/2022/4940531
Ravichandran, G., Ramasamy, K., Manickaraj, K., Kalidas, S., Jayamani, M., Mausam, K., Palanisamy, S., Ma, Q., and Al-Farraj, S. A. (2025). "Effect of sal wood and babool sawdust fillers on the mechanical properties of snake grass fiber-reinforced polyester composites," *BioResources* 20(4), 8674-8694. https://doi.org/10.15376/biores.20.4.8674-8694
Sahoo, M. R., Gopinathan, R., Kumar, K. V. P., Rani, J. J. A., Pradhan, R., and Parida, L. (2022). "Study on the influence of stacking pattern on mechanical behaviour of banana/snake grass fibers hybrid epoxy composite," *Materials Today: Proceedings* 69, 1164-1168. https://doi.org/ 10.1016/j.matpr.2022.08.185
Saravanakumar, A., and Reddy, S. A. (2022). "Optimization of process parameter in drilling of snake grass fiber reinforced composites," *Materials Today: Proceedings* 62, 5460-5466. https://doi.org/10.1016/j.matpr.2022.04.144
Sathish, K., Manickaraj, K., Krishna, S. A., Basha, K. M., and Pravin, R. (2024). "Integrating sustainable materials in exoskeleton development: A review," in: *AIP Conference Proceedings* 3221, article 020021. https://doi.org/10.1063/5.0235913
Sathishkumar, T. P. (2016). "Dynamic mechanical analysis of snake grass fiber-reinforced polyester composites," *Proceedings of the Institution of Mechanical Engineers, Part*

L: Journal of Materials: Design and Applications 230(1), 160-174. https://doi.org/10.1177/1464420714552541

Sathishkumar, T. P., Navaneethakrishnan, P., and Shankar, S. (2012). "Tensile and flexural properties of snake grass natural fiber reinforced isophthallic polyester composites," *Composites Science and Technology* 72(10), 1183-1190. https://doi.org/10.1016/j.compscitech.2012.04.001

Sathishkumar, T. P., Navaneethakrishnan, P., Shankar, S., and Kumar, J. (2013). "Mechanical properties of randomly oriented snake grass fiber with banana and coir fiber-reinforced hybrid composites," *Journal of Composite Materials* 47(18), 2181–2191. https://doi.org/10.1177/0021998312454903

Sekar, D., Udhayakumar, K. R. B., Dyson, C., Karuppusamy, M., Natarajan, S., and Annamalai, K. (2025). "The influence of supplementary cementitious materials on concrete properties," *Matéria (Rio de Janeiro)* 30, article e20240873. https://doi.org/10.1590/1517-7076-RMAT-2024-0873

Sreenivas, H. T., Krishnamurthy, N., and Arpitha, G. R. (2020). "A comprehensive review on light weight kenaf fiber for automobiles," *International Journal of Lightweight Materials and Manufacture* 3(4), 328-337. https://doi.org/10.1016/j.ijlmm.2020.05.003

Suriyaprakash, M., Ranganathan, R., Sree Balaji, V. S., and Nallusamy, M. (2023). "Effect of alkali treatment on mechanical properties and microstructural analysis of *Luffa cylindrica* and snake grass fiber-reinforced epoxy composites," *Surface Review and Letters* 30(03), article 2350012. https://doi.org/10.1142/S0218625X23500129

Sumesh, K. R., Ajithram, A., Anjumol, K. S., and Sai Krishnan, G. (2024). "Influence of natural fiber addition and fiber length in determining the wear resistance of epoxy-based composites," *Polymer Composites* 45(4), 3029-3042. https://doi.org/10.1002/pc.27968

Thandavamoorthy, R., Mohanavel, V., Sivapragasam, A., Vekariya, V., Paul, D., Velmurugan, P., Al Obaid, S., Alharbi, S. A., and Basavegowda, N. (2024). "Environmental sustainability and waste conversion of Prosopis juliflora fibre-reinforced ZnO nanofiller particulates PLA composite-mechanical and thermal analysis," *Heliyon* 10(19), article e38327. https://doi.org/10.1016/j.heliyon.2024.e38327

Thangavel, N., Shanmugavel, N. K., Karuppusamy, M., and Thirumalaisamy, R. (2024). "Friction and wear behavior of premixed reinforcement hybrid composite materials," *Matéria (Rio de Janeiro)* 29(4), article e20240552. https://doi.org/10.1590/1517-7076-RMAT-2024-0552

Thiruvasagam, C., Prabagaran, S., and Suresh, P. (2017). "Study of the mechanical performance and analysis of hybrid natural snake grass-jute-glass fiber strengthened polyester composite," *International Journal of Engineering and Technology* 7, 78-83.

Vijay, R., and Singaravelu, D. L. (2016). "Experimental investigation on the mechanical properties of *Cyperus pangorei* fibers and jute fiber-based natural fiber composites," *International Journal of Polymer Analysis and Characterization* 21(7), 617-627. https://doi.org/10.1080/1023666X.2016.1192354

Vijay, R., James Dhilip, J. D., Gowtham, S., Harikrishnan, S., Chandru, B., Amarnath, M., and Khan, A. (2022). "Characterization of natural cellulose fiber from the barks of *Vachellia farnesiana*," *Journal of Natural Fibers* 19(4), 1343-1352. https://doi.org/10.1080/15440478.2020.1764457

Vinod, A., Tengsuthiwat, J., Gowda, Y., Vijay, R., Sanjay, M. R., Siengchin, S., and

Dhakal, H. N. (2022). "Jute/hemp bio-epoxy hybrid bio-composites: Influence of stacking sequence on adhesion of fiber-matrix," *International Journal of Adhesion and Adhesives* 113, article 103050. https://doi.org/10.1016/j.ijadhadh.2021.103050

Vinod, A., Gowda, T. G. Y., Vijay, R., Sanjay, M. R., Gupta, M. K., Jamil, M., Kushvaha, V., and Siengchin, S. (2021). "Novel Muntingia Calabura bark fiber reinforced green-epoxy composite: A sustainable and green material for cleaner production," *Journal of Cleaner Production* 294, article 126337. https://doi.org/10.1016/j.jclepro.2021.126337

Vinodkumar, T., Chandrasekaran, M., Vivek, P., Arunkumar, S., and Padmanabhan, S. (2019). "Evaluating the mechanical properties of snake grass fibre and sisal fibre hybrid composites by injection moulding method," *International Journal of Vehicle Structures and Systems* 11(3), 236-240. https://doi.org/10.4273/ijvss.11.3.01

Zaman, H. U., and Khan, R. A. (2022). "Effect of fiber surface modifications on the properties of snake grass fiber reinforced polypropylene bio-composites," *Journal of Adhesion Science and Technology* 36(13), 1439-1457. https://doi.org/10.1080/01694243.2021.1970397

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