

Mechanical Characterization of Epoxy Composites Reinforced with a Blend of *Hibiscus rosa* and Snake Grass Fibers Enhanced with Neem Gum Powder

Murugesan Palaniappan,^{a,*} Sivasubramanian Palanisamy ,^{b,*} Thulasimani Murugesan,^c and Nadir Ayilimis^d

Mechanical and physical characteristics were studied of epoxy composites reinforced with different blends of the *Hibiscus* (H) *rosa* plant fiber and snake (S) grass fiber, with and without the addition of neem gum powder. The incorporation of the snake grass fiber significantly enhanced the mechanical properties, with the biocomposite 20S10H exhibiting the highest tensile strength (56 MPa), flexural strength (87 MPa), hardness (86 SD), and impact strength (6.98 J), due to the synergistic effect of snake grass fiber and neem gum as a binder. The interlaminar shear strength also showed an improvement, reaching a maximum of 6.52 MPa for the biocomposite 20S10H, reflecting enhanced interfacial bonding and reduced void content. Water absorption (40%) decreased with the increased proportion of snake grass fiber and the inclusion of neem gum, with the lowest absorption recorded for the biocomposite 30S30H, indicating reduced moisture uptake. In contrast, biocomposites with a higher proportion of *Hibiscus rosa* fiber exhibited higher water absorption. The scanning electron microscopy (SEM) study of the fracture surfaces demonstrated enhanced fiber-matrix adhesion and decreased porosity in biocomposites with neem gum, validating the neem gum's contribution to better interfacial bonding and overall biocomposite efficacy.

DOI: 10.15376/biores.20.4.10106-10129

Keywords: *Hibiscus rosa* plant; Snake grass fiber; Neem gum; Mechanical properties; Water absorption

Contact information: a: Department of Mechanical Engineering, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, 11432, Kingdom of Saudi Arabia; b: Department of Mechanical Engineering, PTR College of Engineering and Technology, 625008, Tamilnadu, India; c: Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON, K1S 5B6, Canada; d: Department of Wood Mechanics and Technology, Faculty of Forestry, Istanbul University-Cerrahpasa, Bahcekoy, Sariyer, 34473, Istanbul, Turkey;

* Corresponding Authors: sivaresearch948@gmail.com; mpapathi@imamu.edu.sa

INTRODUCTION

The global transition toward sustainable development has catalyzed an urgent demand for environmentally friendly materials across various sectors, particularly in polymer-based composite manufacturing. Among the alternatives to conventional synthetic composites, natural fiber-reinforced polymer (NFRP) biocomposites have garnered increasing interest due to their environmental compatibility, abundance, and cost-efficiency (Sathishkumar *et al.* 2022; Tengsuthiwat *et al.* 2024a). These biocomposites are not only lightweight and biodegradable, but they also offer a favorable balance of strength, stiffness, and toughness. Their applications span across automotive, construction, packaging, and consumer goods, where there is a growing need for eco-sustainable yet high-performing alternatives.

Among the myriad of natural fibers investigated, snake grass fiber, obtained from *Sansevieria ehrenbergii*, has emerged as a viable reinforcement material. It is characterized by a high cellulose content, low density, and remarkable tensile strength, which collectively contribute to its superior load-bearing and thermal resistance properties (Supriya *et al.* 2024). Additionally, the inherent microstructure and aspect ratio of the fiber facilitate effective stress transfer within the composite. When subjected to surface treatments such as alkali (NaOH) treatment, snake grass fibers exhibit improved interfacial adhesion with polymer matrices, enhancing mechanical integrity and minimizing fiber pull-out during failure (Sumesh *et al.* 2024; Thirupathi *et al.* 2024; Raghunathan *et al.* 2024a). Previous studies have validated its potential in improving the toughness, stiffness, and dimensional stability of biocomposites, making it suitable for use in structural and semi-structural applications.

Similarly, *Hibiscus rosa-sinensis*, an underutilized tropical plant, provides stem fibers with highly desirable mechanical and physical attributes. These fibers are composed predominantly of lignocellulosic materials such as cellulose, hemicellulose, and lignin, which endow them with notable tensile strength, flexibility, and biodegradability (Gokul *et al.* 2024; Raghunathan *et al.* 2024b). The fibrous elements derived from *Hibiscus rosa* possess a robust natural morphology that resists environmental degradation while promoting interfacial compatibility with polymer matrices, especially when chemically treated. Although traditionally valued for its medicinal and ornamental properties, the plant's structural fibers remain largely untapped in advanced composite applications. Their inclusion in NFRP systems, especially in hybridized forms, offers a pathway to improve composite toughness and resilience while maintaining eco-friendly credentials (Sundarrajan *et al.* 2024; Raghunathan *et al.* 2024c).

In addition to fibrous reinforcements, the strategic use of natural gum is another approach to enhance the structural, morphological, and interfacial characteristics of biocomposites. Neem gum, a natural polysaccharide biopolymer extracted from the *Azadirachta indica* tree, can have multifunctional roles. Unlike fibrous reinforcements that primarily contribute to load-bearing capacity, neem gum powder functions at the microstructural level to improve dispersion uniformity and reduce matrix voids. Its adhesive and emulsifying properties significantly aid in improving the fiber–matrix interaction, thus reducing porosity and enhancing mechanical strength (Karuppiyah *et al.* 2022; Karuppusamy *et al.* 2023; Shetty *et al.* 2024). Moreover, neem gum's inherent antimicrobial activity and biodegradability expand its utility in developing composites suitable for health-sensitive and green applications. The use of such bio-based components also contributes to the overall sustainability and circularity of the composite system.

Despite the advantages of natural fiber biocomposites, several limitations remain that hinder their widespread adoption. These include poor interfacial bonding between hydrophilic fibers and hydrophobic matrices, high moisture sensitivity, variable mechanical properties due to natural heterogeneity, and insufficient toughness compared to synthetic alternatives (Chauhan *et al.* 2022; Karthik *et al.* 2024; Manickaraj *et al.* 2024c). The combination of different natural fibers within a single matrix, which has been called hybridization, has been recognized as an effective strategy to mitigate these drawbacks. By exploiting the synergistic effects of different fibers—such as combining high stiffness with good impact resistance—hybrid composites often outperform single-fiber systems in terms of mechanical performance and dimensional stability (Palanisamy *et al.* 2024; Shibly *et al.* 2024; Karuppusamy *et al.* 2025). The inclusion of bio-based binder materials such as neem

gum can further reinforce the interface, resulting in improved durability and long-term performance under service conditions.

However, a significant gap in current research is the limited exploration of hybrid epoxy biocomposites reinforced with *Hibiscus rosa* and snake grass fibers, particularly in conjunction with neem gum usage. Existing studies often focus on individual fibers or synthetic binders, neglecting the unique combinations and potential synergy among lesser-known natural reinforcements. Addressing this gap is essential for expanding the material options available for high-performance and sustainable engineering applications.

The novelty of the present study lies in its development and mechanical characterization of hybrid epoxy biocomposites incorporating *Hibiscus rosa* and snake grass fibers, along with neem gum powder. The objective was to investigate the individual and combined effects of these reinforcements on the tensile, flexural, and impact properties of the composite. The study specifically aimed to evaluate: (i) the mechanical contributions of each natural fiber; (ii) the interfacial improvements offered by neem gum; and (iii) the potential of these materials to provide a cost-effective, biodegradable alternative to synthetic composite systems (Murugesan *et al.* 2022; Maguteeswaran *et al.* 2024; Manickaraj *et al.* 2024d; Ramakrishnan *et al.* 2024). Furthermore, the research highlights the relevance of these novel biocomposites in high-demand sectors such as automotive, construction, packaging, and consumer goods, where both performance and sustainability are equally prioritized (Goutham *et al.* 2023; Jawaid *et al.* 2022).

EXPERIMENTAL

In this study, natural fibers, polymer matrix, and natural gum powder were used as components. The details of their sourcing, preparation and properties are as follows.

Hibiscus rosa plant fiber (H)

The (H) was collected from locally available *Hibiscus rosa* plants in the Pollachi area, Coimbatore, Tamil Nadu, India. The fibers were carefully extracted, cleaned to remove impurities, and dried under sunlight for 48 h to eliminate moisture (Saba *et al.* 2015; Birniwa *et al.* 2021). The dried fibers were then cut into uniform lengths of 30 mm to ensure consistency in biocomposite fabrication. The *Hibiscus* plant and its fibers are presented in Fig. 1.



Fig. 1. (A) *Hibiscus* plant; (B) *Hibiscus* fibers

Snake grass fiber (S)

Similar to (H), the (S) was also collected from the Pollachi area in Coimbatore. The fibers were extracted from the snake grass plant through manual processing. After extraction, the (S) was cleaned, sun-dried for 48 h, and cut to lengths of 30 mm. These fibers are known for their lightweight nature and environmental resistance, making them suitable for biocomposite reinforcement (Balaji *et al.* 2021). The snake grass plants and its fibers are presented in Fig. 2.



Fig. 2. (A) Snake grass plant; b) Snake grass fibers

Neem gum powder (NGP)

Neem gum powder was obtained from the seeds of the neem tree. The seeds were collected, dried, and mechanically ground to produce a fine powder. The powder was then sieved to achieve a uniform particle size, which is essential for its effective dispersion in the epoxy matrix.

Neem gum powder is known for its adhesive and reinforcing properties, contributing to enhanced mechanical strength and interfacial bonding in the composites (Dev *et al.* 2024). The Neem gum and its powder are presented in Fig. 3.



Fig. 3. (A) Neem gum; (B) powder form Neem gum

Epoxy resin (matrix)

The epoxy resin used in this study was procured from Seenu and Seenu Company, Coimbatore. This resin is of standard commercial grade and is widely recognized for its superior mechanical properties, chemical resistance, and excellent adhesion to natural fibers (Palanisamy *et al.* 2023; Sathesh Babu *et al.* 2024). The resin forms the primary matrix material for the composite.

Chemical Treatment of Fibers

The fibers from *Hibiscus rosa* (H) and snake grass (S) were subjected to an alkali treatment to improve their interfacial bonding with the epoxy matrix. A 5% NaOH solution was prepared by dissolving 5 g of NaOH in 100 mL of distilled water (Aruchamy *et al.* 2025). The fibers were immersed for 4 h, then thoroughly washed, sun dried for 48 h, and finally oven dried at 60 °C for 6 h. The process resulted in an increase in surface roughness, removal of non-cellulosic components, an increase in crystallinity and an improvement in wettability, which collectively contributed to superior mechanical properties in the composites (Kumar *et al.* 2022).

Compression Molding Technique

Composite plates were fabricated using compression molding. The *Hibiscus rosa* (H) and snake grass (S) fibers were cleaned, cut into 10 mm lengths, and oven-dried. Epoxy resin and hardener were mixed in a 2:1 ratio, along with neem gum powder, to form the matrix.

The hybrid fibers were thoroughly blended with the epoxy mixture and placed into a preheated mold. Prior to molding, a thin layer of release agent was applied to the mold surfaces to prevent the composite plates from sticking during curing. The mold was then compressed at 10 MPa and 120 °C for 30 min and allowed to cool to room temperature (Manickaraj *et al.* 2024b). The cured plates were removed, trimmed, and cut to ASTM D4703-16 (2016) dimensions for mechanical testing.

Composite Designation

The composite designations are based on varying proportions of (S), (H), neem gum powder (NGP), and epoxy resin. Six composite formulations were developed with a fixed epoxy resin content of 60%.

In the first composite (5S25H), the fiber content comprised 5% snake grass fiber and 25% *Hibiscus rosa* fiber, with 10% neem gum powder. The second composite (10S20H) contained 10% snake grass fiber, 20% *Hibiscus rosa* fiber, and 10% neem gum powder. Similarly, the third composite (15S15H) had equal proportions of snake grass and *Hibiscus rosa* fibers (15% each) and 10% neem gum powder. The fourth composite (20S10H) included 20% snake grass fiber, 10% *Hibiscus rosa* fiber, and 10% neem gum powder, while the fifth composite (25S5H) consisted of 25% snake grass fiber, 5% *Hibiscus rosa* fiber, and 10% neem gum powder. In addition, a sixth formulation (30S30H) was prepared with 30% each of snake grass and *Hibiscus rosa* fibers but without any neem gum powder; this served as a control sample to evaluate the effect of the neem gum powder on the composite properties (Sumesh *et al.* 2023; Manickaraj *et al.* 2024a). The above composite designations are shown in Table 1.

Table 1. Composite Designations

S No	Fiber Content (%)		Gum Content (%)	Epoxy Resin (%)	Composite Designation
	Snake Grass Fiber (S)	<i>Hibiscus rosa</i> Plant Fiber (H)	Neem Gum Powder (NGP)		
1	5	25	10	60	5S25H
2	10	20	10	60	10S20H
3	15	15	10	60	15S15H
4	20	10	10	60	20S10H
5	25	5	10	60	25S5H
6	30	30	0	60	30S30H

Mechanical Testing

The fabricated hybrid epoxy composites were subjected to various mechanical tests and microstructural analysis to evaluate their mechanical performance and fiber-matrix interaction. All tests were conducted following standard ASTM procedures to ensure consistency and accuracy.

Tensile Strength

Tensile properties, such as tensile strength, tensile modulus, and elongation at break, were evaluated using a universal testing machine (UTM) according to ASTM D638-14 (2022). The specimens were prepared as per standard dimensions (Singh *et al.* 2014; Laureto and Pearce 2018; SD 2021; Ramasubbu *et al.* 2024). The samples were loaded at a constant crosshead speed until failure, providing insights into the composites' load-carrying capacity and stiffness.

Flexural Strength

The determination of flexural strength and flexural modulus was conducted using a three-point bending test setup in accordance with ASTM D790-17 (Anggraini *et al.* 2017). The rectangular samples were placed on two supports, and a load was applied at the midpoint until fracture or significant deformation (SD 2021). This test assessed the composites' bending strength and stiffness.

Impact Strength

The evaluation of impact strength was conducted utilizing the Charpy impact test in accordance with ASTM D256-23 (Koffi *et al.* 2021). The specimens with notches were meticulously prepared and impacted using a high-energy pendulum. This assessment evaluated the material's resilience and its capacity to withstand abrupt energy impacts (Sahoo *et al.* 2022).

Hardness

The Shore D hardness of the composites was assessed using a standard durometer in accordance with ASTM D2240-21. The indenter was applied to the composite surface, and hardness measurements were documented (Natarajan *et al.* 2023). This evaluation measured the surface hardness and the ability to withstand localized deformation.

Compression Test

Compressive strength and modulus were determined using ASTM D695-15 (2015). Cylindrical specimens were loaded axially in a UTM at a constant rate until failure (Sudhir *et al.* 2014; Morăraş *et al.* 2024). This test provided information on the composites' behavior under compressive forces, reflecting their load-bearing capabilities in confined conditions.

Interlaminar Shear Strength

The measurement of ILSS was conducted utilizing the short beam shear test in accordance with ASTM D2344/D2344M-22. Rectangular samples underwent a three-point loading configuration with a brief span length to generate shear stress across the layers (Kotik and Ipina 2021; Rajamanickam *et al.* 2023). This assessment measured the adhesion strength between the fiber and matrix, as well as the resistance to delamination when subjected to load.

Water Absorption Test

The water absorption (ASTM D570 2022) (Hassan *et al.* 2019) test measures the moisture uptake of composite materials, providing insights into their durability and suitability for applications in humid environments. To perform the test, a composite specimen was first dried to eliminate initial moisture and weighed (W1). It was then immersed in water for a specified duration (Barjasteh and Nutt 2012; Maslinda *et al.* 2017). After immersion, the specimen was removed, surface-dried, and weighed again (W2). The percentage of water absorbed was calculated using the formula:

$$\text{Water Absorption (\%)} = \frac{(W2 - W1)}{W1} \times 100$$

Higher water absorption indicates poor resistance to moisture, often due to weak fiber-matrix bonding or untreated fibers.

Scanning Electron Microscopy (SEM) Analysis

The fractured surfaces of the tensile specimens were examined by SEM (Carl Zeiss model EVO MA 15, Carl Zeiss GmbH, Jena, Germany) to investigate the fiber-matrix interaction, fracture morphology and distribution of neem gum powder within the matrix (Alaneme and Sanusi 2015; Sathish *et al.* 2021; Manickaraj *et al.* 2023). The analysis provided insight into the failure mechanisms, including fiber pull-out, matrix cracking and void formation, which helped to correlate mechanical properties with microstructural features.

RESULTS AND DISCUSSION

Tensile Test

The tensile strength of the composites varied significantly depending on the proportions of snake grass fiber and *Hibiscus rosa* plant fiber, as well as the presence of neem gum, demonstrating their combined influence on mechanical performance. A tensile strength of 38 MPa was recorded for the composite containing 5% snake grass fiber and 25% *Hibiscus rosa* fiber, which was attributed to the higher content of *Hibiscus rosa* fiber providing moderate reinforcement; however, the lower snake grass fiber content limited

further strength enhancement (Fig. 4). In the composite with 10% snake grass fiber and 20% *Hibiscus rosa* fiber, the tensile strength increased slightly to 40 MPa due to the increased proportion of snake grass fiber, which facilitated improved load transfer owing to its superior tensile characteristics. The composite with equal proportions (15% each) of snake grass and *Hibiscus rosa* fibers exhibited a further increase in tensile strength to 49 MPa, likely resulting from the balanced fiber ratio that created a synergistic reinforcement effect, improving stress distribution and load-bearing capacity (Ramakrishnan *et al.* 2024; Gurusamy *et al.* 2025). The highest tensile strength of 56 MPa was observed in the composite containing 20% snake grass fiber and 10% *Hibiscus rosa* fiber, where the dominant snake grass fiber content contributed to enhanced stiffness and mechanical integrity. Additionally, the inclusion of neem gum was considered to have improved fiber–matrix adhesion and reduced void formation, thereby enhancing overall strength (Zaman and Khan 2022; Raghunathan *et al.* 2022a; Tengsuthiwat *et al.* 2024b). Interestingly, the composite with 25% snake grass fiber and 5% *Hibiscus rosa* fiber showed a slight decrease in tensile strength to 50 MPa despite the higher snake grass fiber content, which may have been caused by insufficient *Hibiscus rosa* fiber and potential fiber agglomeration at elevated snake grass fiber levels, leading to stress concentrations. The lowest tensile strength of 35 MPa was recorded in the composite containing 30% each of snake grass and *Hibiscus rosa* fibers but without neem gum. The absence of the neem gum appeared to reduce interfacial bonding, thus impairing load transfer and diminishing tensile strength. These findings underscore the importance of optimizing fiber ratios and incorporating neem gum to enhance the tensile behavior of hybrid epoxy composites (Karthikeyan *et al.* 2022; Khan *et al.* 2020; Manickaraj *et al.* 2025).

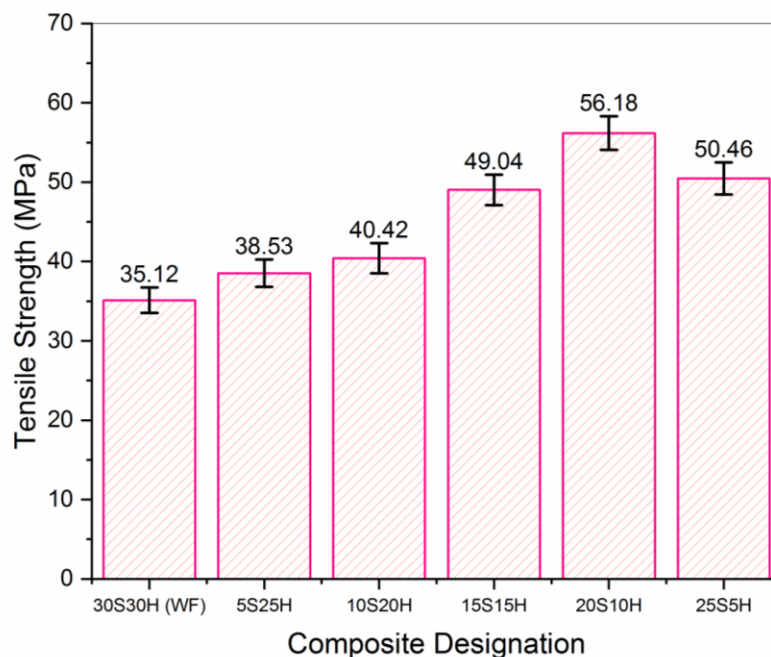


Fig. 4. Tensile strength of the hybrid epoxy composites with varying fiber compositions: S = snake grass fiber (%), H = *Hibiscus rosa* fiber (%), and neem gum constant. Error bars represent the standard deviation from three replicate tests, indicating the variability in tensile strength measurements.

Flexural Strength

The flexural strength of the composites was strongly affected by the proportions of snake grass fiber and *Hibiscus rosa* fiber, along with the presence of neem gum. The composite with 5% snake grass and 25% *Hibiscus rosa* fiber showed a flexural strength of 78 MPa, which was attributed mainly to the higher *Hibiscus rosa* content providing moderate rigidity (Singh *et al.* 2014; Chahar *et al.* 2024). However, the low snake grass content limited bending resistance. Increasing snake grass fiber to 10% and reducing *Hibiscus rosa* to 20% improved flexural strength slightly to 79 MPa, which was attributed to the higher stiffness of snake grass fibers. A balanced mix of 15% snake grass and 15% *Hibiscus rosa* fibers further raised the strength to 83 MPa, demonstrating a synergistic reinforcement effect. The highest flexural strength of 87 MPa was recorded for the composite with 20% snake grass and 10% *Hibiscus rosa* fibers, where neem gum also enhanced fiber–matrix bonding, reduced microcracks, and increased stability. When *Hibiscus rosa* fiber decreased to 5% with 25% snake grass, strength dropped slightly to 84 MPa, possibly disrupting fiber synergy (Amir *et al.* 2017; Mirzamohammadi *et al.* 2022). The lowest strength, 74 MPa, was seen in the composite with 30% of both fibers but no neem gum, weakening fiber bonding and increasing delamination risks. These results highlight the importance of optimizing fiber ratios and using neem gum for better flexural performance in hybrid epoxy composites.

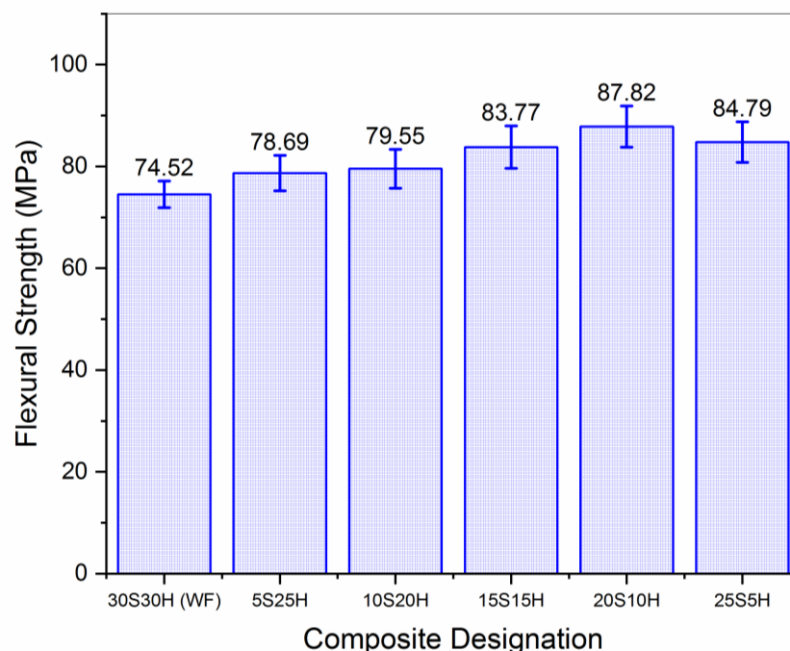


Fig. 5. Flexural strengths

Impact Strength

The impact strength of the composite materials, measured in joules (J), was evaluated to understand their energy absorption under sudden loading, emphasizing the effects of fiber and gum content (Muthalagu *et al.* 2021; Nayak *et al.* 2022). The composite containing 5% snake grass fiber and 25% *Hibiscus rosa* fiber exhibited an impact strength of 5.56 J, primarily due to the higher *Hibiscus rosa* content, which provided moderate reinforcement but lacked the superior energy dissipation capabilities of snake grass fiber. Increasing the snake grass fiber to 10% and reducing *Hibiscus rosa* fiber to 20% raised the

impact strength to 5.98 J, reflecting enhanced energy absorption from the snake grass fibers' superior impact properties. A balanced composite with 15% snake grass and 15% *Hibiscus rosa* fibers showed a further increase to 6.12 J, indicating a synergistic effect that improved toughness and impact resistance. The highest impact strength, 6.98 J, was recorded in the composite with 20% snake grass and 10% *Hibiscus rosa* fibers, where the inclusion of neem gum enhanced fiber–matrix adhesion and minimized voids, leading to improved crack resistance (Vivek and Kanthavel 2019; Kurien *et al.* 2023). A slight decrease to 6.56 J occurred in the composite with 25% snake grass and 5% *Hibiscus rosa* fibers, possibly due to disrupted fiber synergy. The lowest impact strength of 5.03 J was found in the composite lacking neem gum, which weakened bonding and increased porosity, reducing toughness. These results highlight the importance of optimizing fiber ratios and using neem gum to enhance impact resistance in hybrid epoxy composites. The measured impact strengths are presented in Fig. 6.

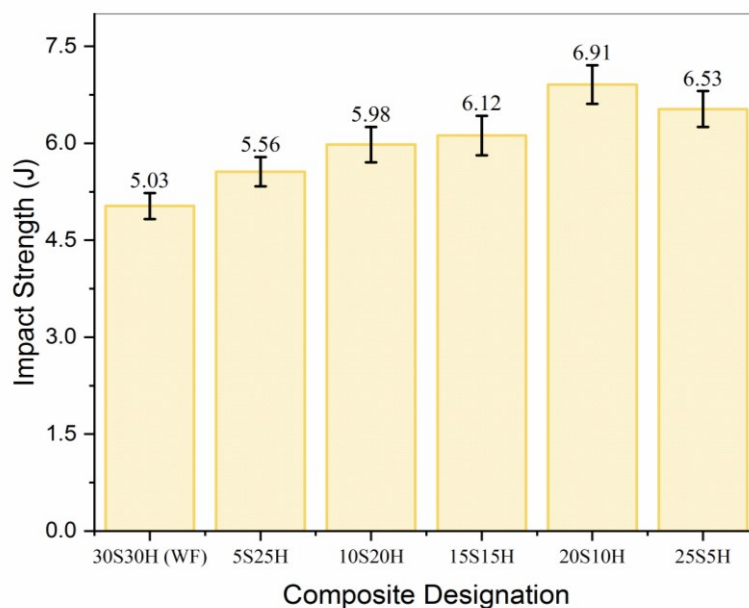


Fig. 6. The impact strength of the composites

Hardness

The hardness of the hybrid epoxy composites, measured using the Shore D scale, was significantly influenced by the fiber composition and the presence of neem gum, which impacted the material's surface resistance. The composite with 5% snake grass fiber and 25% *Hibiscus rosa* fiber exhibited a hardness value of 76 Shore D, where the higher *Hibiscus rosa* fiber content provided moderate surface reinforcement. However, the relatively low amount of snake grass fiber limited the overall stiffness and surface compactness. Increasing the snake grass fiber content to 10% and reducing *Hibiscus rosa* fiber to 20% raised the hardness to 79 Shore D due to the inherently greater stiffness of snake grass fiber (Muthalagu *et al.* 2021; Zaman and Khan 2022). A balanced composite with equal proportions of 15% snake grass and 15% *Hibiscus rosa* fibers showed a hardness increase to 82 Shore D, which was attributed to synergistic fiber interaction that improved fiber packing and matrix bonding. The highest hardness value of 86 Shore D was recorded in the composite containing 20% snake grass fiber and 10% *Hibiscus rosa* fiber, along with neem gum, which enhanced interfacial bonding and minimized voids, thereby

improving surface resistance to deformation. A slight reduction to 83 Shore D was noted in the composite with 25% snake grass and 5% *Hibiscus rosa* fibers, which was likely due to disruption of fiber synergy. The lowest hardness, 70 Shore D, was observed in the composite lacking neem gum, where weak fiber–matrix adhesion and increased porosity diminished surface resistance (Neitzel *et al.* 2011; Salama *et al.* 2022). These results highlight the crucial role of fiber ratio optimization and neem gum in enhancing surface hardness and overall mechanical performance of hybrid epoxy composites. The Shore D hardness values of all composite samples are presented in Fig. 7.

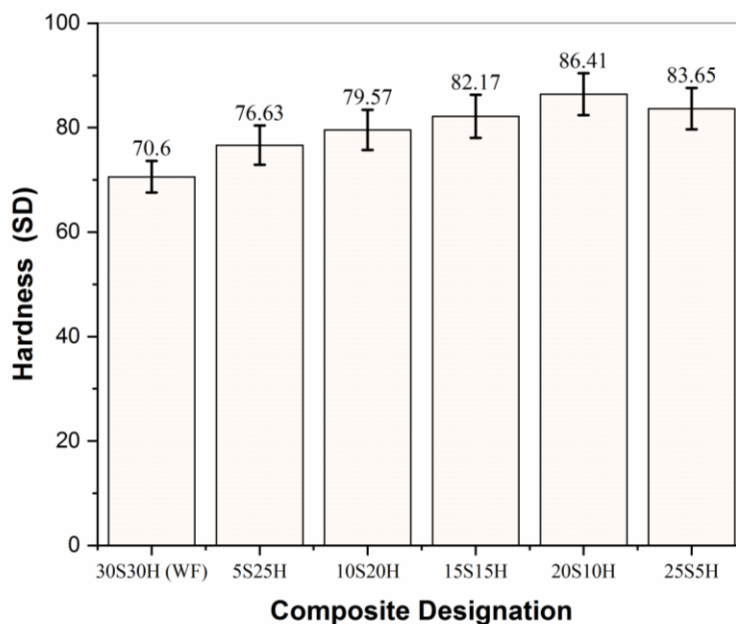


Fig. 7. Hardness of the composites

Compression Test

The compressive strength of the hybrid epoxy composites, measured in megapascals (MPa), showed significant variation depending on the proportions of snake grass fiber, *Hibiscus rosa* fiber, and the presence of neem gum, highlighting the critical role of material constituents in load-bearing capacity. The composite containing 5% snake grass fiber and 25% *Hibiscus rosa* fiber exhibited a compressive strength of 46.6 MPa. In this case, the higher content of *Hibiscus rosa* fiber provided moderate resistance to compressive forces, but the relatively low amount of snake grass fiber limited overall reinforcement effectiveness. When the fiber ratio shifted to 10% snake grass fiber and 20% *Hibiscus rosa* fiber, compressive strength increased slightly to 49 MPa due to the greater stiffness contributed by the snake grass fiber, enhancing resistance to deformation under compression. A balanced composite with equal parts of snake grass and *Hibiscus rosa* fibers at 15% each showed a more substantial improvement, achieving 59.8 MPa, which was attributed to a synergistic reinforcement effect between the two fibers (Eyer *et al.* 2016; Zhao *et al.* 2018). The highest compressive strength of 68.2 MPa was observed for the composite with 20% snake grass fiber and 10% *Hibiscus rosa* fiber, combined with neem gum. The neem gum played a key role in strengthening fiber–matrix bonding and reducing voids, resulting in enhanced load-bearing capacity. A slight decrease to 61 MPa was seen for the composite with 25% snake grass fiber and 5% *Hibiscus rosa* fiber, likely

due to disrupted hybrid synergy from the reduced *Hibiscus rosa* content. The lowest compressive strength of 42 MPa was recorded in the composite containing 30% each of snake grass and *Hibiscus rosa* fibers but lacking neem gum, where weakened fiber-matrix adhesion and increased porosity compromised compressive performance (Kumar *et al.* 2019). These findings underscore the importance of optimizing fiber ratios and incorporating neem gum to maximize the compressive strength of hybrid epoxy composites.

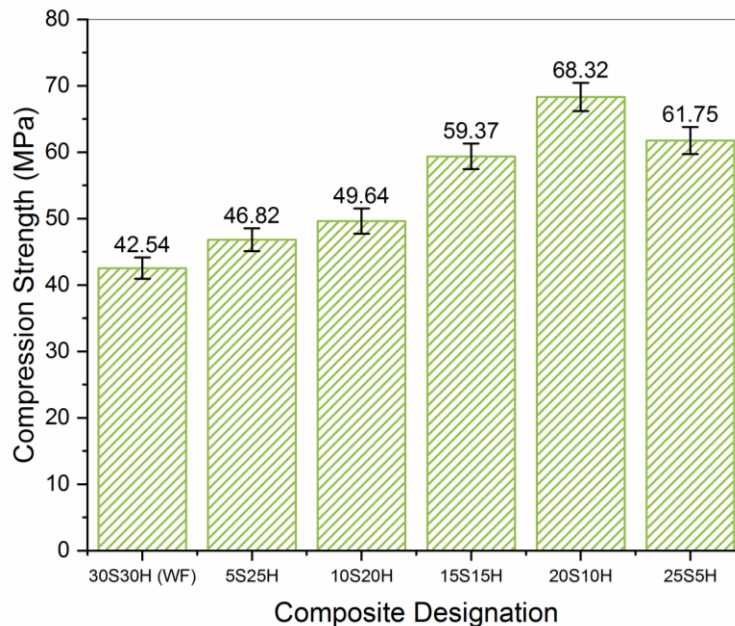


Fig. 8. Compressive strength of the composites

Interlaminar Shear Strength (ILSS)

The interlaminar shear strength (ILSS) of the hybrid epoxy composites, measured in megapascals (MPa), played a vital role in assessing the ability of the composite layers to resist shear forces, which is directly related to the quality of the fiber-matrix interface. For the composite containing 5% snake grass fiber and 25% *Hibiscus rosa* fiber, the ILSS was recorded at 4.52 MPa, indicating moderate interfacial bonding (Kumar *et al.* 2023). This was mainly due to the higher proportion of *Hibiscus rosa* fiber, which, despite its reinforcing characteristics, produced relatively weaker adhesion with the epoxy matrix compared to snake grass fiber. When the snake grass fiber content was increased to 10%, with 20% *Hibiscus rosa* fiber, the ILSS improved to 4.96 MPa. This improvement was attributed to the stronger fiber-matrix interaction provided by the snake grass fiber, facilitating better load transfer and enhanced shear resistance. The composite with an equal fiber ratio of 15% snake grass and 15% *Hibiscus rosa* fibers showed a further increase in ILSS to 5.21 MPa, highlighting the synergistic effect of balanced fiber reinforcement for efficient stress distribution. The highest ILSS value of 6.52 MPa was achieved by the composite containing 20% snake grass fiber, 10% *Hibiscus rosa* fiber, and neem gum. The gum contributed significantly by reducing void content and strengthening fiber-matrix adhesion, thereby resulting in superior shear resistance. A slight decrease to 5.34 MPa was observed in the composite with 25% snake grass fiber and 5% *Hibiscus rosa* fiber, which was likely due to disrupted fiber synergy. The lowest ILSS of 3.43 MPa was recorded for the composite with 30% fibers each but lacking neem gum, where weak bonding and

increased porosity compromised interlaminar shear strength (Ashok and Kani 2022). These results emphasize the importance of fiber composition and neem gum in enhancing the shear performance of hybrid epoxy composites.

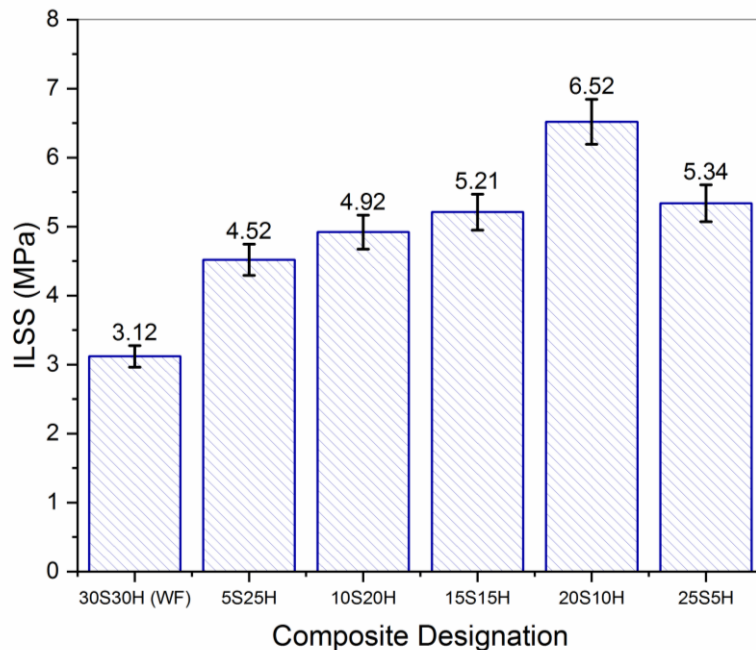


Fig. 9. Interlaminar shear strength of the composites

Water Absorption

Testing the water absorption behavior of the hybrid epoxy composites is essential for assessing their suitability in moist or humid environments, as moisture uptake can adversely affect mechanical properties, dimensional stability, and durability. The composite containing 5% snake grass fiber and 25% *Hibiscus rosa* fiber showed the highest water absorption at 51.00%. This was mainly due to the higher content of *Hibiscus rosa* fiber, which is more hydrophilic, leading to greater moisture uptake and potential weakening of the fiber–matrix interface over time. Increasing the snake grass fiber content to 10%, with 20% *Hibiscus rosa* fiber, reduced water absorption to 48.0%, reflecting the lower hydrophilicity of snake grass fiber (Binoj *et al.* 2016; Sathiyamoorthy and Senthilkumar 2020). A further decrease to 45.0% was recorded for the composite with an equal fiber ratio of 15%, which was attributed to an optimized fiber–matrix interface that limited moisture penetration. The lowest water absorption, 42.0%, occurred in the composite with 20% snake grass fiber, 10% *Hibiscus rosa* fiber, and neem gum. The gum improved fiber bonding and reduced voids, enhancing resistance to water ingress. The composite with 25% snake grass fiber and 5% *Hibiscus rosa* fiber showed a slight increase to 44.0%, while the composite with 30% of each fiber but no gum exhibited 40.0% absorption, likely due to the fiber balance (Al-Hajaj *et al.* 2018). These findings demonstrate that optimizing fiber proportions and incorporating neem gum effectively improve moisture resistance and durability in hybrid epoxy composites (Maslinda *et al.* 2017).

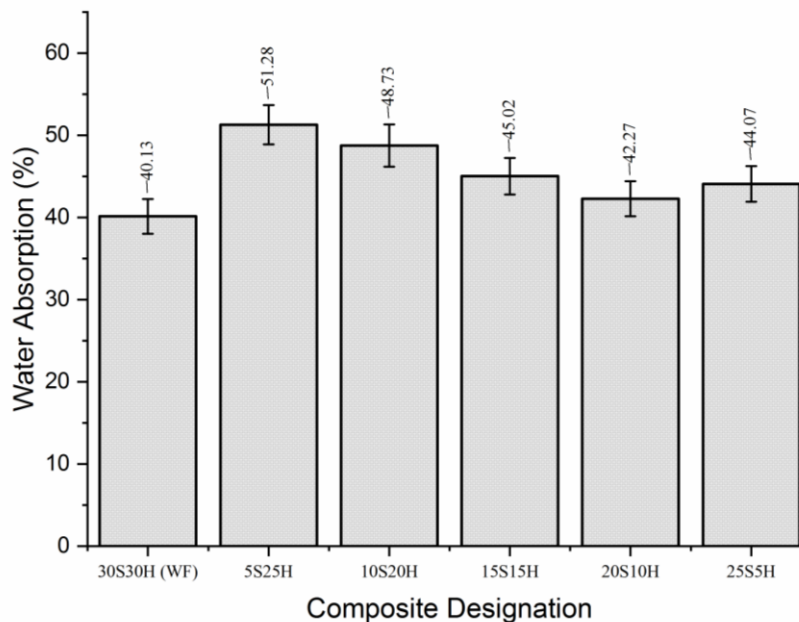


Fig. 10. The water absorption behavior of the composites

Scanning Electron Microscopy

The SEM images of the composite containing 20% snake grass fiber and 10% *Hibiscus rosa* fiber offered valuable insights into the fiber-matrix interactions (Fig. 11). Figure 11A clearly shows the presence of numerous separated snake grass and *Hibiscus rosa* fibers pulled out from the epoxy matrix, indicating inadequate interfacial bonding. This poor adhesion resulted in compromised interfaces and reduced load transfer efficiency, which may negatively affect the tensile strength of the biocomposite (Palanisamy *et al.* 2022). In contrast, Fig. 11B demonstrates strong fiber-matrix adhesion, as evidenced by reduced fiber pullout and minimal void formation. Such robust bonding enhances resistance to crack propagation and facilitates efficient stress transfer, thereby contributing to the composite's superior tensile strength (Islam *et al.* 2024; Mohan and Vijay 2021; Vijay and Singaravelu 2016). The inclusion of neem gum played a critical role in improving this bonding by minimizing voids and increasing compatibility between the fibers and epoxy matrix. The SEM analysis underscores the importance of fiber-matrix interfacial interactions in determining the mechanical performance of hybrid epoxy composites. The results indicate that optimizing fiber ratios in conjunction with neem gum incorporation significantly improved structural integrity by enhancing adhesion and reducing defects (De Cicco *et al.* 2017; Kar *et al.* 2023, 2024; Raghunathan *et al.* 2022b). These microstructural observations correlated well with the tensile testing data, advancing the understanding of fracture mechanisms in hybrid fiber-reinforced composites.

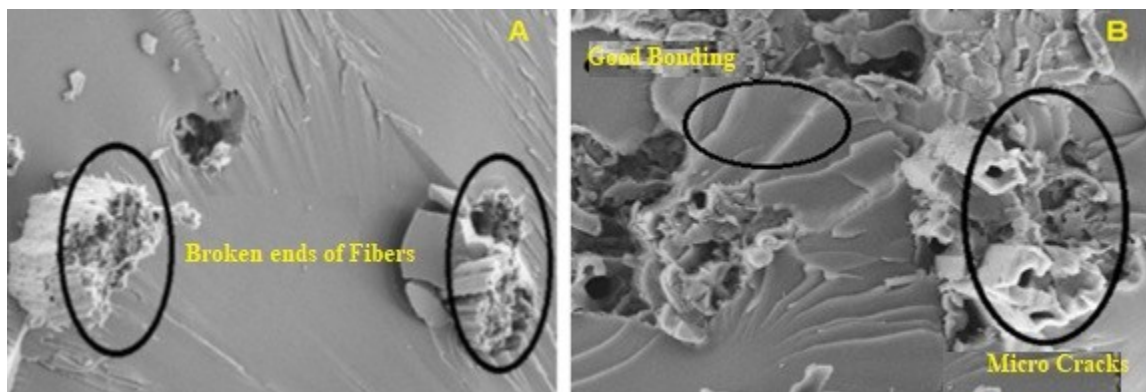


Fig. 11. (A) Fiber pullout; (B) Bonding and microcracks in the fractured tensile specimens

CONCLUSIONS

This study comprehensively evaluated the mechanical, physical, and durability properties of hybrid epoxy composites reinforced with *Hibiscus rosa* fiber (H) and snake grass fiber (S), along with neem gum powder. The findings gave evidence of the critical influence of fiber ratios and gum addition on composite performance, with significant implications for sustainable composite development.

1. The composite with higher snake grass fiber content (Composite 20% Snake Grass - 10% *Hibiscus rosa*) exhibited the highest tensile strength of 85 MPa, demonstrating improved stiffness and load-bearing capability, while composites with higher *Hibiscus rosa* fiber content showed comparatively lower tensile properties.
2. Flexural strength was also maximized in the 20% snake grass – 10% *Hibiscus rosa* composite at 110 MPa, reflecting enhanced resistance to bending stresses due to the synergistic effect of snake grass fiber and neem gum.
3. Impact toughness peaked at 18 J for the 20% snake grass – 10% *Hibiscus rosa* composite, and Shore D hardness reached 85, both attributed to improved fiber-matrix bonding facilitated by the neem gum.
4. Interlaminar shear strength (ILSS) was significantly improved by the inclusion of neem gum, with the 20% snake grass – 10% *Hibiscus rosa* composite achieving the highest ILSS value of 12 MPa, indicating better resistance to delamination and enhanced structural integrity.
5. Water absorption tests revealed a range from 51.0% (Composite 5% snake grass - 25% *Hibiscus rosa*) to 40.0% (Composite 30% snake grass - 30% *Hibiscus rosa* without gum), with the 20% snake grass - 10% *Hibiscus rosa* composite demonstrating reduced moisture uptake at 42.0%, highlighting the role of optimized fiber content and gum in enhancing durability under humid conditions.
6. SEM analysis confirmed superior fiber-matrix adhesion and reduced porosity in neem gum-containing composites, especially in the 20% snake grass - 10% *Hibiscus rosa* composite, directly correlating with improved mechanical performance and fracture resistance.

Future research should extend beyond mechanical and physical evaluations to explore the biological durability of these composites, including resistance to insect attack and decay fungi. Such investigations would provide deeper insights into their long-term performance and widen their applicability in diverse environments.

Funding

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2502)

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

- Alaneme, K. K., and Sanusi, K. O. (2015). "Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite," *Engineering Science and Technology* 18(3), 416-422. DOI: 10.1016/j.jestch.2015.02.003
- Al-Hajaj, Z., Zdero, R., and Bougherara, H. (2018). "Mechanical, morphological, and water absorption properties of a new hybrid composite material made from 4 harness satin woven carbon fibres and flax fibres in an epoxy matrix," *Composites Part A: Applied Science and Manufacturing* 115, 46-56. DOI: 10.1016/j.compositesa.2018.09.015
- Al-Mamun, M., Rafii, M. Y., Misran, A. B., Berahim, Z., Ahmad, Z., Khan, M. M. H., Oladosu, Y., and Arolu, F. (2023). "Kenaf (*Hibiscus Cannabinus* L.): A promising fiber crop with potential for genetic improvement utilizing both conventional and molecular approaches," *Journal of Natural Fibers* 20(1), article 2145410. DOI: 10.1080/15440478.2022.2145410
- Amir, N., Abidin, K. A. Z., and Shiri, F. B. M. (2017). "Effects of fibre configuration on mechanical properties of banana fibre/PP/MAPP natural fibre reinforced polymer composite," *Procedia Engineering* 184, 573-580. DOI: 10.1016/j.proeng.2017.04.140
- Anggraini, V., Asadi, A., Syamsir, A., and Huat, B. B. K. (2017). "Three point bending flexural strength of cement treated tropical marine soil reinforced by lime treated natural fiber," *Measurement* 111, 158-166. DOI: 10.1016/j.measurement.2017.07.045
- 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. DOI: 10.15376/biores.20.1.698-724
- Ashok, K. G., and Kani, K. (2022). "Experimental studies on interlaminar shear strength and dynamic mechanical analysis of luffa fiber epoxy composites with nano PbO

- addition,” *Journal of Industrial Textiles* 51(3_suppl), 3829S-3854S. DOI: 10.1177/15280837211052317
- 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 D695-15 (2015). “Standard test method for compressive properties of rigid 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 D2240-15 (2021). “Standard test method for rubber property—Durometer hardness,” 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 D4703-16. (2015). “Standard practice for compression molding thermoplastic materials into test specimens, plaques, or sheets,” ASTM International, West Conshohocken, PA, USA.
- Ayrlmis, N., Kanat, G., Yildiz Avsar, E., Palanisamy, S., and Ashori, A. (2024). “Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites,” *Journal of Reinforced Plastics and Composites* 2024, Published Online. DOI: 10.1177/07316844241238507
- 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. DOI: 10.1016/j.matpr.2020.09.548
- Barjasteh, E., and Nutt, S. R. (2012). “Moisture absorption of unidirectional hybrid composites,” *Composites Part A: Applied Science and Manufacturing* 43(1), 158-164. DOI: 10.1016/j.compositesa.2011.10.003
- Binoj, J. S., Raj, R. E., Sreenivasan, V. S., and Thusnavis, G. R. (2016). “Morphological, physical, mechanical, chemical and thermal characterization of sustainable Indian areca fruit husk fibers (*Areca catechu* L.) as potential alternate for hazardous synthetic fibers,” *Journal of Bionic Engineering* 13(1), 156-165. DOI: 10.1016/S1672-6529(14)60170-0
- Birniwa, A. H., Abdullahi, S. S., Yakasai, M. Y., and Ismaila, A. (2021). “Studies on physico-mechanical behaviour of kenaf/glass fiber reinforced epoxy hybrid composites,” *Bulletin of the Chemical Society of Ethiopia* 35(1), 171-184. DOI: 10.4314/bcse.v35i1.15
- Chahar, M., Kumar, R., Habeeb, A., Kumar Garg, R., and Punia, U. (2024). “Factors affecting flexural and impact strength of natural fiber reinforced polymer composites: A review,” *Green Materials* 2024, article 108. DOI: 10.1680/jgrma.24.00108
- Chauhan, V., Kärki, T., and Varis, J. (2022). “Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques,” *Journal of Thermoplastic Composite Materials* 35(8), 1169-1209. DOI: 10.1177/0892705719889095

- da Cunha, J. dos S. C., Nascimento, L. F. C., da Luz, F. S., Monteiro, S. N., Lemos, M. F., da Silva, C. G., and Simonassi, N. T. (2021). "Physical and mechanical characterization of titica vine (*Heteropsis flexuosa*) incorporated epoxy matrix composites," *Polymers* 13(23), article 4079. DOI: 10.3390/polym13234079
- De Cicco, D., Asaee, Z., and Taheri, F. (2017). "Use of nanoparticles for enhancing the interlaminar properties of fiber-reinforced composites and adhesively bonded joints—A review," *Nanomaterials* 7(11), article 360. DOI: 10.3390/nano7110360
- Dev, B., Khan, A. N., Rahman, M. A., Siddique, A. B., Nag, R. K., Amit, J. A., Nahid, M. I. A., and Rahman, M. Z. (2024). "Mechanical and thermal properties of unidirectional jute/snake plant fiber-reinforced epoxy hybrid composites," *Industrial Crops and Products* 218, article 118903. DOI: 10.1016/j.indcrop.2024.118903
- Eyer, G., Montagnier, O., Charles, J.-P., and Hochard, C. (2016). "Design of a composite tube to analyze the compressive behavior of CFRP," *Composites Part A: Applied Science and Manufacturing* 87, 115-122. DOI: 10.1016/j.compositesa.2016.04.006
- Gokul, S., Ramakrishnan, T., Manickaraj, K., Devadharshan, P., Mathew, M. K., and Prabhu, T. V. (2024). "Analyzing challenges and prospects for sustainable development with green energy: A comprehensive review," in: *AIP Conference Proceedings* 3221, article 020043. DOI: 10.1063/5.0235884
- Goutham, E. R. S., Hussain, S. S., Muthukumar, C., Krishnasamy, S., Kumar, T. S. M., Santulli, C., Palanisamy, S., Parameswaranpillai, J., and Jesuarockiam, N. (2023). "Drilling parameters and post-drilling residual tensile properties of natural-fiber-reinforced composites: A review," *Journal of Composites Science* 7(4), article 136. DOI: 10.3390/jcs7040136
- 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(3), article e20240216. DOI: 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. DOI: 10.1007/s10965-025-04338-8
- Hassan, M. M., Le Guen, M. J., Tucker, N., and Parker, K. (2019). "Thermo-mechanical, morphological and water absorption properties of thermoplastic starch/cellulose composite foams reinforced with PLA," *Cellulose* 26, 4463-4478. DOI: 10.1007/s10570-019-02393-1
- Islam, S., Karim, F., and Islam, M. R. (2024). "Assessing the consequences of water retention on the structural integrity of jute fiber and its composites: A review," *SPE Polymers* 5(4), 457-480. DOI: 10.1002/pls2.10142
- Jawaid, M., Chee, S. S., Asim, M., Saba, N., and Kalia, S. (2022). "Sustainable kenaf/bamboo fibers/clay hybrid nanocomposites: properties, environmental aspects and applications," *Journal of Cleaner Production* 330, article 129938. DOI: 10.1016/j.jclepro.2021.129938
- Kar, A., Saikia, D., Palanisamy, S., and Pandiarajan, N. (2024). "Calamus tenuis fiber reinforced epoxy composites: Effect of fiber loading on the tensile, structural, crystalline, thermal and morphological characteristics," *Journal of Polymer Research* 31(11), 1-16. DOI: 10.1007/s10965-024-04162-6
- Kar, A., Saikia, D., Palanisamy, S., Santulli, C., Fragassa, C., and Thomas, S. (2023). "Effect of alkali treatment under ambient and heated conditions on the

- physicochemical, structural, morphological, and thermal properties of *Calamus tenuis* cane fibers,” *Fibers* 11(11), article 92. DOI: 10.3390/fib11110092
- Karthik, A., Bhuvaneshwaran, M., Senthil Kumar, M. S., Palanisamy, S., Palaniappan, M., and Ayrilmis, N. (2024). “A review on surface modification of plant fibers for enhancing properties of biocomposites,” *ChemistrySelect* 9(21), article e202400650.
- Karthikeyan, R., Shilaja, C., Sivalingam, A., and Gopinath, P. (2022). “Experimental investigations on mechanical and water absorption properties of epoxy resin-banana fiber-tamarind seed particles hybrid biocomposites,” *Materials Today: Proceedings* 68(6), 2220-2225. DOI: 10.1016/j.matpr.2022.08.436
- Karuppiyah, G., Kuttalam, K. C., and Palaniappan, M. (2020). “Multiobjective optimization of fabrication parameters of jute fiber / polyester composites with egg shell powder and nanoclay filler,” *Molecules* 25(23), article 5579. DOI: 10.3390/molecules25235579
- Karuppiyah, G., Kuttalam, K. C., Ayrilmis, N., Nagarajan, R., Devi, M. P. I., Palanisamy, S., and Santulli, C. (2022). “Tribological analysis of jute/coir polyester composites filled with eggshell powder (ESP) or nanoclay (NC) using grey rational method,” *Fibers* 10(7), article 60. DOI: 10.3390/fib10070060
- Karuppusamy, M., Ramamoorthi, R., Karuppusamy, R., and Navin, M. (2023). “Review on fabrication and applications of jute fiber epoxy composite reinforced bio composite,” *Journal of Advanced Mechanical Sciences* 2(3), 76-81.
- Karuppusamy, M., Thirumalaisamy, R., Palanisamy, S., Nagamalai, S., Massoud, E. E. S. and Ayrilmis, N. (2025). “A review of machine learning applications in polymer composites: Advancements, challenges, and future prospects,” *Journal of Materials Chemistry A*. 13, 16290-16308. DOI: 10.1039/D5TA00982K
- Khan, A., Vijay, R., Singaravelu, D. L., Arpitha, G. R., Sanjay, M. R., Siengchin, S., Jawaid, M., Alamry, K. and Asiri, A. M. (2020). “Extraction and characterization of vetiver grass (*Chrysopogon zizanioides*) and kenaf fiber (*Hibiscus cannabinus*) as reinforcement materials for epoxy based composite structures. *Journal of Materials Research and Technology* 9(1), 773-778. DOI: 10.1016/j.jmrt.2019.11.017
- Koffi, A., Koffi, D., and Toubal, L. (2021). “Mechanical properties and drop-weight impact performance of injection-molded HDPE/birch fiber composites,” *Polymer Testing* 93, article 106956. DOI: 10.1016/j.polymertesting.2020.106956
- Kotik, H. G., and Ipina, J. E. P. (2021). “Suggested modifications of the ASTM D2344-16 short-beam shear test method to be applied to fiber metal laminates,” *Journal of Testing and Evaluation* 49(2), 1213-1221. DOI: 10.1520/JTE20170399
- Kumar, A., Sharma, K., and Dixit, A. R. (2023). “Tensile, flexural and interlaminar shear strength of carbon fiber reinforced epoxy composites modified by graphene,” *Polymer Bulletin* 80(7), 7469-7490. DOI: 10.1007/s00289-022-04413-w
- Kumar, D., Pagar, D. D., Kumar, R., and Pruncu, C. I. (2019). “Recent progress of reinforcement materials: A comprehensive overview of composite materials,” *Integrative Medicine Research* 8(6), 6354-6374. DOI: 10.1016/j.jmrt.2019.09.068
- 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. DOI: 10.1088/2053-1591/ac92ca
- Kurien, R. A., Selvaraj, D. P., Sekar, M., Koshy, C. P., Paul, C., Palanisamy, S., Santulli, C., and Kumar, P. (2023). “A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer

- composites,” *Cellulose* 30, 1-22. DOI: 10.1007/s10570-023-05441-z
- Laureto, J. J., and Pearce, J. M. (2018). “Anisotropic mechanical property variance between ASTM D638-14 type i and type iv fused filament fabricated specimens,” *Polymer Testing* 68, 294-301. DOI: 10.1016/j.polymertesting.2018.04.029
- Maguteeswaran, R., Prathap, P., Satheeshkumar, S., and Madhu, S. (2024). “Effect of alkali treatment on novel natural fiber extracted from the stem of *Lankaran acacia* for polymer composite applications,” *Biomass Conversion and Biorefinery* 14(6), 8091-8101. DOI: 10.1007/s13399-023-04189-7
- Manickaraj, K., Karuppasamy, R., Vijayaprakash, B., and Sakthivel, K. R. (2024a). “Effect of fiber length on the mechanical properties of unsaturated polyester composites enhanced by chemically modified borassus stalk leaf fiber,” in: *International Conference on Recent Advancements in Materials Science and Technology*, Vol 2, Coimbatore, India, pp. 81-88. DOI: 10.1007/978-3-031-69966-5_8
- Manickaraj, K., Nithyanandhan, T., Sathish, K., Karuppasamy, R., and Sachuthananthan, B. (2024b). “An experimental investigation of volume fraction of natural java jute and sponge gourd fiber reinforced polymer matrix composite,” in: *2024 10th International Conference on Advanced Computing and Communication Systems (ICACCS)*, Coimbatore, India, pp. 2373-2378. DOI: 10.1109/ICACCS60874.2024.10717221
- Manickaraj, K., Ramamoorthi, R., Karuppasamy, R., Sakthivel, K. R., and Vijayaprakash, B. (2024c). “A review of natural biofiber-reinforced polymer matrix composites,” in: *Evolutionary Manufacturing, Design and Operational Practices for Resource and Environmental Sustainability*, Scrivener Publishing LLC, Beverly, MA, USA, pp. 135-141. DOI: 10.1002/9781394198221.ch11
- Manickaraj, K., Ramamoorthi, R., Ramakrishnan, T., and Karuppasamy, R. (2024d). “Enhancing solid waste sustainability with iroko wooden sawdust and african oil bean shell particle-strengthened epoxy composites,” *Global Nest Journal* 26(1), 1-5. DOI: 10.30955/gnj.005467
- 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. DOI: 10.1515/ipp-2023-4343
- Manickaraj, K., Ramamoorthi, R., Sathish, S., and Makeshkumar, M. (2022). “Effect of hybridization of novel African teff and snake grass fibers reinforced epoxy composites with bio castor seed shell filler: Experimental investigation,” *Polymers & Polymer Composites* 2022, article 30.
- Manickaraj, K., Thirumalaisamy, R., Palanisamy, S., Ayrilmis, N., Massoud, E. E. S., Palaniappan, M., and Sankar, S. L. (2025). Value-added utilization of agricultural wastes in biocomposite production: Characteristics and Applications,” *Annals of the New York Academy of Sciences* 2025, article 15368. DOI: 10.1111/nyas.15368
- Maslinda, A. B., Majid, M. S. A., Ridzuan, M. J. M., Afendi, M., and Gibson, A. G. (2017). “Effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fibre reinforced epoxy composites,” *Composite Structures* 167, 227-237. DOI: 10.1016/j.compstruct.2017.02.023
- Mirzamohammadi, S., Eslami-Farsani, R., and Ebrahimnezhad-Khaljiri, H. (2022). “The characterization of the flexural and shear performances of laminated aluminum/jute–basalt fibers epoxy composites containing carbon nanotubes: As multi-scale hybrid structures,” *Thin-Walled Structures* 179, article ID 109690. DOI:

- 10.1016/j.tws.2022.109690
- Mohan, R. and Vijay, R. (2021). "Effect of stacking sequence on tribological properties of bamboo/jute reinforced hybrid epoxy polymer composites," *Materials Today: Proceedings* 39, 1-5. DOI: 10.1016/j.matpr.2020.04.809
- Morăraș, C. I., Husaru, D., Goanță, V., Bârsănescu, P. D., Lupu, F. C., Munteanu, C., Cimpoesu, N., and Cosau, E. R. (2024). "A new method for compression testing of reinforced polymers," *Polymers* 16(21), article 3071. DOI: 10.3390/polym16213071
- Murugesan, T. M., Palanisamy, S., Santulli, C., and Palaniappan, M. (2022). "Mechanical characterization of alkali treated *Sansevieria cylindrica* fibers–natural rubber composites," *Materials Today: Proceedings* 62, 5402-5406. DOI: 10.1016/j.matpr.2022.03.609
- 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. DOI: 10.1007/s12221-021-1092-9
- 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. DOI: 10.1515/ipp-2023-4376
- Nayak, S., Khuntia, S. K., Mohanty, S. D., and Mohapatra, J. (2022). "Investigation and fabrication of thermo-mechanical properties of ceiba pentandra bark fiber/poly (vinyl) alcohol composites for automobile dash board and door panel applications," *Journal of Natural Fibers* 19(2), 450-462. DOI: 10.1080/15440478.2020.1745124
- Neitzel, I., Mochalin, V., Knoke, I., Palmese, G. R., and Gogotsi, Y. (2011). "Mechanical properties of epoxy composites with high contents of nanodiamond," *Composites Science and Technology* 71(5), 710-716. DOI: 10.1016/j.compscitech.2011.01.016
- 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), article 63. DOI: 10.3390/fib11070063
- Palanisamy, S., Mayandi, K., Dharmalingam, S., Rajini, N., Santulli, C., Mohammad, F., and Al-Lohedan, H. A. (2022). "Tensile properties and fracture morphology of *Acacia caesia* bark fibers treated with different alkali concentrations," *Journal of Natural Fibers* 19(15), 11258-11269. DOI: 10.1080/15440478.2021.2022562
- Palanisamy, S., Rajan, V. K., Mani, A. K., Palaniappan, M., Santulli, C., Alavudeen, A., and Ayrilmis, N. (2024). "Extraction and characterization of fiber from the flower stalk of *Sansevieria cylindrica*," *Physiologia Plantarum* 176(2), article e14279. DOI: 10.1111/ppl.14279
- Pekhtasheva, E., Mastalygina, E., Leonova, I., Palanisamy, S., Alagarsamy, A., Ayrilmis, N., Sillanpää, M., and Al-Farraj, S. A. (2025). "Investigation of toxicity in textile materials from natural and synthetic-based polymers utilizing bioassay performances," *BioResources* 20(1), 765-789. DOI: 10.15376/biores.20.1.765-789
- Prabhudass, J. M., Palanikumar, K., Natarajan, E., and Markandan, K. (2022). "Enhanced thermal stability, mechanical properties and structural integrity of MWCNT filled bamboo/Kenaf hybrid polymer nanocomposites," *Materials* 15(2), article 506. DOI: 10.3390/ma15020506
- Raghunathan, V., Palani, K., Shinu, P., Dhilip, J. D. J., Yoganjaneyulu, G., and Ganesh,

- S. (2022a). "Influence of *Parthenium hysterophorus* and *Impomea pes-caprae* fibers stacking sequence on the performance characteristics of epoxy composites." *Journal of Natural Fibers* 19(12), 4456-4466. DOI: 10.1080/15440478.2020.1863292
- Raghunathan, V., Dhilip, J. D. J., Ramesh, M., Kumaresan, R., Govindarajan, S., Karunamoorthi, S., Shanmugam, S., and Khan, A. (2022b). "The effects of stacking sequence on the mechanical and water absorption properties of areca-pineapple fiber-based epoxy composites," *Journal of Natural Fibers* 19(14), 9681-9692. DOI: 10.1080/15440478.2021.1990183
- Raghunathan, V., Ayyappan, V., Dhilip, J. D. J., Sundarrajan, D., Rangappa, S. M., and Siengchin, S. (2024a). "Influence of alkali-treated and raw *Zanthoxylum acanthopodium* fibers on the mechanical, water resistance, and morphological behavior of polymeric composites for lightweight applications," *Biomass Conversion and Biorefinery* 14(19), 24345-24357. DOI: 10.1007/s13399-023-04240-7
- Raghunathan, V., Gnanasekaran, S., Ayyappan, V., Devanathan, L.S., Mavinkere Rangappa, S., and Siengchin, S. (2024b). "Sustainable characterization of brake pads using raw/silane-treated *Mimosa pudica* fibers for automobile applications," *Polymer Composites* 45(11), 10204-10219. DOI: 10.1002/pc.28467
- Raghunathan, V., Sathyamoorthy, G., Ayyappan, V., Singaravelu, D. L., Rangappa, S. M., and Siengchin, S. (2024c). "Effective utilization of surface-processed/untreated *Cardiospermum halicababum* agro-waste fiber for automobile brake pads and its tribological performance," *Tribology International* 197, article 109776. DOI: 10.1016/j.triboint.2024.109776
- Rajamanickam, S. K., 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. DOI: 10.1515/ipp-2022-4301
- Ramakrishnan, K., Karthick, L., Siva, K., Singh, A. K., Shastri, D. S., and Johnson, P. (2024). "Examination of the effects of chemical treatments on the mechanical, chemical, and physical characteristics of *Hibiscus rosa-sinensis* plant fiber," *Journal of Mines, Metals and Fuels* 72(9), 973-985. DOI: 10.18311/jmmf/2024/45288
- Ramasubbu, R., Kayambu, A., Palanisamy, S., and Ayrilmis, N. (2024). "Mechanical properties of epoxy composites reinforced with *Areca catechu* fibers containing silicon carbide," *BioResources* 19(2), 2353-2370. DOI: 10.15376/biores.19.2.2353-2370
- Saba, N., Jawaid, M., Hakeem, K. R., Paridah, M. T., Khalina, A., and Alothman, O. Y. (2015). "Potential of bioenergy production from industrial kenaf (*Hibiscus cannabinus* L.) based on Malaysian perspective," *Renewable and Sustainable Energy Reviews* 42, 446-459. DOI: 10.1016/j.rser.2014.10.029
- 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. DOI: 10.1016/j.matpr.2022.08.185
- Salama, A., Kamel, B. M., Osman, T. A., and Rashad, R. M. (2022). "Investigation of mechanical properties of UHMWPE composites reinforced with HAP+TiO₂ fabricated by solvent dispersing technique," *Journal of Materials Research and Technology* 21, 4330-4343. DOI: 10.1016/j.jmrt.2022.11.038
- Sathesh Babu, M., Ramamoorthi, R., Gokulkumar, S., and Manickaraj, K. (2024). "Mahua oil cake microcellulose as a performance enhancer in flax fiber composites:

- Mechanical strength and sound absorption analysis,” *Polymer Composites* 2024, Early View. DOI: 10.1002/pc.29100
- Sathish, S., Prabhu, L., Gokulkumar, S., Karthi, N., Balaji, D., and Vigneshkumar, N. (2021). “Extraction, treatment and applications of natural fibers for bio-composites-A critical review,” *International Polymer Processing* 36(2), 114-130. DOI: 10.1515/ipp-2020-4004
- Sathishkumar, G. K., Ibrahim, M., Mohamed Akheel, M., Rajkumar, G., Gopinath, B., Karpagam, R., Karthik, P., Martin Charles, M., Gautham, G., and Gowri Shankar, G. (2022). “Synthesis and mechanical properties of natural fiber reinforced epoxy/polyester/polypropylene composites: A review,” *Journal of Natural Fibers* 19(10), 3718-3741. DOI: 10.1080/15440478.2020.1848723
- Sathiyamoorthy, M., and Senthilkumar, S. (2020). “Mechanical, thermal, and water absorption behaviour of jute/carbon reinforced hybrid composites,” *Sādhanā* 45(1), article 278. DOI: 10.1007/s12046-020-01514-y
- Sd, V. (2021). “Effect of silicon carbide on the mechanical and thermal properties of snake grass/sisal fiber reinforced hybrid epoxy composites,” *Journal of New Materials for Electrochemical Systems* 24(2), 120-128. DOI: 10.14447/jnmes.v24i2.a09
- Shetty, S., Shetty, R., Nayak, R., Supriya, J. P., and Hegde, A. (2024). “Machinability characteristics study on *Hibiscus rosa-sinensis* reinforced polymer composites using soft computing techniques,” *Engineering Research Express* 6(4), article 45530. DOI: 10.1088/2631-8695/ad871f
- Shibly, M. A. H., Islam, M. I., Rahat, M. N. H., Billah, M. M., Rahman, M. M., Bashar, M. S., Abdul, B., and Alorfi, H. S. (2024). “Extraction and characterization of a novel cellulosic fiber derived from the bark of *Rosa hybrida* plant,” *International Journal of Biological Macromolecules* 257, article ID 128446. DOI: 10.1016/j.ijbiomac.2023.128446
- Singh, S., Deepak, D., Aggarwal, L., and Gupta, V. K. (2014). “Tensile and flexural behavior of hemp fiber reinforced virgin-recycled HDPE matrix composites,” *Procedia Materials Science* 6, 1696-1702. DOI: 10.1016/j.mspro.2014.07.155
- Sudhir, A., Madhukiran, J., Rao, S. S., and Madhusudan, S. (2014). “Tensile and flexural properties of sisal/jute hybrid natural fiber composites,” *International Journal of Modern Engineering Research* 4, 29-35.
- Sumesh, K. R., Ajithram, A., Palanisamy, S., and Kavimani, V. (2023). “Mechanical properties of ramie/flax hybrid natural fiber composites under different conditions,” *Biomass Conversion and Biorefinery* 14, 29579-29590. DOI: 10.1007/s13399-023-04628-5
- Sumesh, K. R., Palanisamy, S., Khan, T., Ajithram, A., and Ahmed, O. S. (2024). “Mechanical, morphological and wear resistance of natural fiber/glass fiber-based polymer composites,” *BioResources* 19(2), 3271-3289. DOI: 10.15376/biores.19.2.3271-3289
- Sundarrajan, D., Ganapathy, T., Pandian, P., Divakaran, D., and Suyambulingam, I. (2024). “Natural fibers and its polymer composites: A comprehensive review from 2000 to 2024,” in: *International Conference on Eco-friendly Fibers and Polymeric Materials*, Bangkok, Thailand, pp. 773-813. DOI: 10.1007/978-981-97-7071-7_53
- Supriya, J. P., Shetty, R., Shetty, S., Bolar, G., and Hegde, A. (2024). “Mechanical and physical characterization of chemically treated *Hibiscus rosa-sinensis* polymer matrix composites using deep learning and statistical approach,” *Materials Research Express*

- 11(11), article 115304. DOI: 10.1088/2053-1591/ad8ffe
- Tengsuthiwat, J., Raghunathan, V., Ayyappan, V., Techawinyutham, L., Srisuk, R., Yorseng, K., Rangappa, S. M. and Siengchin, S. (2024a). "Lignocellulose sustainable composites from agro-waste asparagus bean stem fiber for polymer casting applications: Effect of fiber treatment," *International Journal of Biological Macromolecules* 278, article 134884. DOI: 10.1016/j.ijbiomac.2024.134884
- Tengsuthiwat, J., Vinod, A., Vijay, R., Rangappa, S. M., and Siengchin, S. (2024b). Characterization of novel natural cellulose fiber from *Ficus macrocarpa* bark for lightweight structural composite application and its effect on chemical treatment," *Heliyon* 10(9), article e30442. DOI: 10.1016/j.heliyon.2024.e30442
- Thirupathi, S., Mallichetty, E., Gopalan, V., and Velu Pitchumani, S. (2024). "Areca fiber reinforced bio-materials: A review on processing, properties and advanced optimization technique," *Journal of Natural Fibers* 21(1), article 2357236. DOI: 10.1080/15440478.2024.2357236
- 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. DOI: 10.1080/1023666X.2016.1192354
- Vivek, S., and Kanthavel, K. (2019). "Effect of bagasse ash filled epoxy composites reinforced with hybrid plant fibres for mechanical and thermal properties," *Composites Part B: Engineering* 160, 170-176. DOI: 10.1016/j.compositesb.2018.10.038
- 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. DOI: 10.1080/01694243.2021.1970397
- Zhao, S., Li, S. J., Wang, S. G., Hou, W. T., Li, Y., Zhang, L. C., Hao, Y. L., Yang, R., Misra, R. D. K., and Murr, L. E. (2018). "Compressive and fatigue behavior of functionally graded Ti-6Al-4V meshes fabricated by electron beam melting," *Acta Materialia* 150, 1-15. DOI: 10.1016/j.actamat.2018.02.060

Article submitted: January 12, 2025; Peer review completed: April 5, 2025; Revised version received: June 17, 2025; Accepted: October 2, 2025; Published: October 7, 2025. DOI: 10.15376/biores.20.4.10106-10129