Mechanical and Hygrothermal Evaluation of Natural Fiber Hybrid Epoxy Composites Using *Borassus flabellifer* Fruit Fiber and Snake Grass Fiber with Gum Enhancement

Murugesan Palaniappan

Mechanical, microstructural, and hygrothermal behaviours were studied for hybrid epoxy composites reinforced with *Borassus flabellifer* fruit fiber (BFF), snake grass fiber (SGF), and gum Arabic. Six composites were fabricated with varying BFF-SGF ratios while maintaining constant epoxy (60%) and gum Arabic (10%) content. The composites were evaluated for tensile, flexural, impact, hardness, interlaminar shear strength (ILSS), density, water absorption, thickness swelling, and microstructural morphology using scanning electron microscopy (SEM). Hybridization significantly improved the overall structural performance of the composites. Among all compositions, the C3 composite (15% BFF / 15% SGF / 10% gum Arabic) exhibited the highest tensile strength (72 MPa), flexural strength (89 MPa), impact strength (28 kJ/m²), hardness (79 Shore D), ILSS (42 MPa), and density (1.21 g/cm³), and the lowest water absorption (6.1%) and minimum thickness swelling (1.53%) after 72 h. SEM analysis revealed improved fiber-matrix interfacial bonding, reduced void content, and uniform gum dispersion in the hybrid composites, which contributed to their superior performance. In contrast, single-fiber and gum-free composites demonstrated lower mechanical and hygrothermal performance due to weaker interfacial adhesion and non-uniform stress transfer. These findings indicate that BFF-SGF hybrid composites are promising materials for lightweight structural and semi-structural applications.

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INTRODUCTION

Natural fiber-reinforced polymer composites (NFPCs) have gained increasing attention over the past few decades due to their unique combination of environmental, economic, and mechanical advantages (Singh and Rout 2023). The widespread use of synthetic fiber composites, such as glass and carbon fiber-reinforced polymers, has raised concerns about environmental sustainability, recyclability, and the carbon footprint associated with their production and disposal. In contrast, natural fibers offer renewable, biodegradable, and low-density alternatives that contribute to reducing the overall environmental impact of composite materials (Ramu *et al.* 2024; Chen *et al.* 2025). Additionally, NFPCs demonstrate high specific strength, good toughness, and relatively low processing costs, making them attractive for applications ranging from automotive and construction to aerospace and consumer goods (Mohammed *et al.* 2024). These properties have prompted extensive research into the development of high-performance composites using various lignocellulosic fibers, natural gums, and environmentally friendly matrices (Palanisamy *et al.* 2023; Rahman *et al.* 2025). Among the numerous natural fibers explored, *Borassus flabellifer* fruit fiber (BFF), obtained from the husk of the Palmyra palm, has emerged as a promising reinforcement. BFF has a rich lignocellulosic composition, including cellulose, hemicellulose, and lignin, which contributes to its inherent strength, rigidity, and durability. Its rough surface morphology and high aspect ratio facilitate good mechanical interlocking with polymer matrices, enhancing stress transfer and load-bearing capability. Previous studies have shown that BFF exhibits good tensile strength and modulus, making it suitable for structural applications where moderate stiffness and toughness are required (Sinha and Devnani 2023; Guo *et al.* 2025). Moreover, BFF is abundant in tropical regions and represents an agricultural waste product, adding to its sustainability and cost-effectiveness as a reinforcement material. Its use in composites not only improves mechanical performance but also provides a valuable outlet for biomass that would otherwise contribute to environmental waste.

Snake grass fiber (SGF), another natural reinforcement, has also gained attention in recent years due to its high stiffness, strong tensile properties, and compatibility with polymer matrices. SGF is derived from the stems or leaves of specific grass species and is characterized by its fibrous, elongated structure with a high cellulose content (Palaniappan *et al.* 2025b). This structural configuration imparts rigidity, tensile strength, and good load-bearing capability when incorporated into polymer matrices. In addition, SGF exhibits relatively low moisture absorption compared to other natural fibers, making it advantageous in applications where dimensional stability under humid or wet conditions is critical. The combination of high stiffness and moderate ductility makes SGF a suitable candidate for hybrid reinforcement, as it can complement other fibers that provide toughness and flexibility (Pachiappan and Santhanam 2023; Wan *et al.* 2025).

Hybridization of natural fibers (the usage of two different fiber types simultaneously) is recognized as a promising strategy to optimize the mechanical, thermal, and moisture-resistant properties of polymer composites. The rationale behind hybrid composites is based on the principle of combining two or more fibers with complementary mechanical and physical characteristics to achieve synergistic reinforcement (Natarajan *et al.* 2023). While single-fiber composites may suffer from limitations such as brittleness, insufficient stiffness, or high moisture uptake, hybrid systems can balance these properties. For instance, a combination of a ductile fiber with a rigid fiber can simultaneously improve toughness and stiffness, enhance impact resistance, and mitigate the risk of brittle failure (Kumar *et al.* 2022; Su *et al.* 2025). In addition, hybridization can influence the fiber-matrix interfacial adhesion, stress distribution, and the overall morphology of the composite, resulting in improved structural performance. Hybrid composites have been extensively studied in synthetic systems; however, the development of natural fiber-based hybrid composites is gaining momentum due to the combined benefits of sustainability, cost-effectiveness, and tunable mechanical properties (Dev *et al.* 2024; Yang *et al.* 2026a).

The incorporation of gums, such as gum Arabic, provides an additional avenue for enhancing the performance of natural fiber composites. Gum Arabic, a natural polysaccharide obtained from the exudates of acacia trees, is recognized for its film-forming ability, water solubility, and adhesive properties (Ravichandran *et al.* 2025). When incorporated into polymer composites, gum Arabic can fill microvoids, improve fiber-matrix contact, and act as a natural bonding enhancer. This not only strengthens the interfacial adhesion but also limits moisture ingress, thereby reducing water absorption and thickness swelling (Aruchamy *et al.* 2025). Improved interfacial bonding is particularly critical in natural fiber composites, where the hydrophilic nature of fibers can create weak points at the fiber-matrix interface, leading to premature failure or reduced load transfer efficiency. The synergistic effect of fiber hybridization combined with gum addition can result in composites with superior mechanical strength, toughness, and hygrothermal stability (Manickaraj *et al.* 2025b).

Several studies have reported on the individual effects of BFF or SGF reinforcement in polymer matrices; however, research on their combined effect as hybrid reinforcement is limited. Exploring hybrid BFF/SGF composites can provide valuable insights into the optimization of fiber proportions for balanced mechanical and physical performance (Ahmed and Ali 2023). The use of equal or varying proportions of the two fibers allows the investigation of synergistic interactions, stress transfer efficiency, and the effect on properties such as tensile strength, flexural behavior, impact resistance, hardness, interlaminar shear strength (ILSS), density, water absorption, and thickness swelling (Salpriyan *et al.* 2025). In particular, understanding the relationship between fiber composition, fiber-matrix adhesion, and the resulting microstructure is essential for designing composites with tailored properties for specific engineering applications (Gurusamy *et al.* 2025).

Gum Arabic is a natural exudate mainly composed of highly branched polysaccharides, particularly arabinogalactan, together with arabinogalactan–protein complexes, minor glycoprotein fractions, and small amounts of naturally associated mineral salts. Because of this composition, it exhibits good film-forming ability, emulsifying characteristics, biocompatibility, and strong hydrophilicity (Prasad *et al.* 2022; Mudgil and Mudgil 2024; Zheng *et al.* 2026). These features make gum Arabic attractive as a sustainable adhesive or modifier in polymer composites. In an epoxy-based composite, gum Arabic may improve dispersion and interfacial interaction with natural fibers due to the presence of multiple hydroxyl-containing polysaccharide chains, which can support adhesion and mechanical interlocking. However, because it is not a low-molecular-weight flexible additive, it is not expected to behave as a conventional plasticizer for epoxy. Instead, it is more likely to function as an interfacial agent, while its hydrophilic character may also increase the tendency for moisture interaction if dispersion and matrix encapsulation are not sufficient. These considerations are consistent with review literature on gum Arabic composition and functionality (Patel and Goyal 2015; Iqbal *et al.* 2020).

Moreover, the environmental and sustainability aspects of natural fiber composites should not be overlooked. Both BFF and SGF are renewable, biodegradable, and abundantly available, and their use in hybrid composites promotes the utilization of agricultural waste. Incorporating such fibers into epoxy matrices not only improves material performance but also supports sustainable material development and circular economy principles (Al-Hamayda *et al.* 2023; Liu *et al.* 2026). These composites have the potential to replace conventional synthetic fiber composites in applications such as automotive interiors, furniture boards, and construction panels, where both mechanical strength and environmental sustainability are important (Manickaraj *et al.* 2025a).

The selection of reinforcing fibers in hybrid composites should be based not only on their individual properties but also on their ability to provide complementary performance when combined (NagarajaGanesh *et al.* 2025).

In the present study, *Borassus flabellifer* fruit fiber (BFF) and snake grass fiber (SGF) were chosen with the hypothesis that their hybridization would generate a synergistic reinforcement effect in the epoxy matrix. SGF was expected to contribute higher stiffness and rigidity, thereby improving load-bearing capacity and dimensional stability, whereas BFF was anticipated to enhance ductility and energy absorption, helping to improve toughness and reduce brittle failure. Thus, the balanced incorporation of these two natural fibers, together with gum Arabic, was expected to improve stress transfer, interfacial bonding, and overall mechanical and hygrothermal performance of the composite (Ramasamy *et al.* 2025; Hindi *et al.* 2025).

This work aimed to systematically investigate the combined effect of *Borassus flabellifer* fruit fiber and snake grass fiber in epoxy composites, with gum Arabic added as a natural bonding enhancer. The study evaluated the influence of different fiber ratios on tensile, flexural, and impact properties, as well as hardness, ILSS, density, water absorption, and thickness swelling (Palaniappan *et al.* 2025a). In addition, scanning electron microscopy (SEM) was used to examine the fractured surfaces and fiber-matrix interface, providing insight into the microstructural mechanisms responsible for the observed composite behaviour.

The main objective was to identify the optimal hybrid fiber combination that provides a balanced improvement in mechanical strength, stiffness, toughness, interlaminar integrity, moisture resistance, and dimensional stability. In particular, the study aimed to enhance the load-bearing capability and structural performance of the composite through the synergistic hybridization of *Borassus flabellifer* fruit fiber and snake grass fiber, together with gum Arabic (Ramesh *et al.* 2022a).

By exploring hybridization strategies and gum incorporation, this study contributes to the growing body of knowledge on sustainable composite materials and demonstrates the potential of BFF/SGF-based epoxy composites as environmentally responsible alternatives to traditional synthetic fiber composites (Cozic *et al.* 2009; Yang *et al.* 2026b; Xiang *et al.* 2026). The findings are expected to benefit material scientists, mechanical engineers, and researchers working on natural fiber composites, as well as industries seeking lightweight, high-strength, and moisture-resistant materials for structural and non-structural applications (Hasan *et al.* 2021).

EXPERIMENTAL

Borassus flabellifer fruit fiber (BFF)

BFF was obtained from the husk of *Borassus flabellifer* (Palmyra) fruits, a widely available agro-waste source in tropical regions. The fiber is rich in lignocellulosic constituents such as cellulose, hemicellulose, and lignin, which contribute to its moderate tensile strength, good toughness, and biodegradability (Kavitha *et al.* 2023). Its rough surface morphology and porous structure facilitate mechanical interlocking with the epoxy matrix, making BFF a suitable reinforcement for hybrid polymer composites. Additionally, its low density supports lightweight composite development. Figure 1 shows the *Borassus flabellifer* fruit and its fibers.

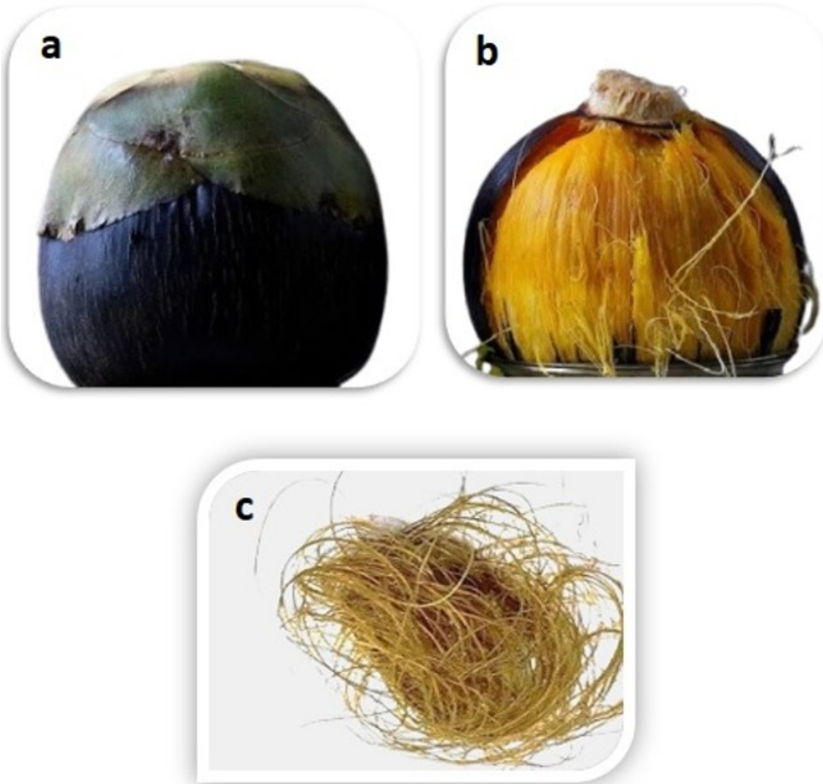

Fig. 1. (a) *Borassus flabellifer* fruit, (b) *Borassus flabellifer* fruit fiber, (c) separated *Borassus flabellifer* fruit fiber

Snake Grass Fiber (SGF)

Snake grass fiber (SGF), obtained from *Sansevieria roxburghiana*, is considered a promising reinforcement material mainly because of its relatively high cellulose content, which contributes significantly to its tensile strength and stiffness.

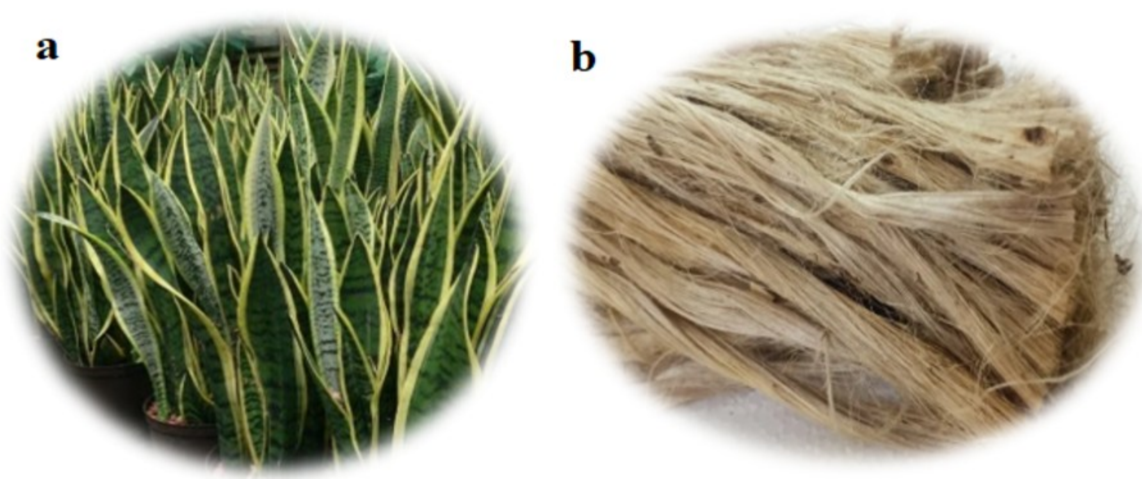

Fig. 2. (a) Snake grass plant and (b) extracted snake grass fiber

In addition, its superior axial rigidity, long continuous fiber structure, and well-aligned microfibrillar arrangement support efficient stress transfer and improved dimensional stability in composite materials. SGF also exhibits good thermal stability, making it suitable for hybrid composite applications. Owing to these characteristics, SGF is widely used in hybridization to enhance load-bearing performance and compensate for the lower stiffness or strength of other natural fibers (Babayo *et al.* 2022). Figure 2a shows the snake grass plant, and Fig. 2b shows the snake grass fiber.

Gum Arabic

Gum Arabic, a natural exudate obtained from *Acacia* species, was used at 10 wt.%. It is mainly composed of highly branched arabinogalactan polysaccharides, arabinogalactan–protein complexes, and minor glycoprotein fractions, along with small amounts of naturally associated mineral salts. These constituents provide abundant hydroxyl-containing functional groups, which can improve fiber-matrix compatibility by promoting better wetting, interfacial adhesion, and mechanical interlocking in the epoxy system (Karimah *et al.* 2021). The gum particles may also help achieve more uniform fiber dispersion and reduce void formation, thereby contributing to better dimensional stability and moisture resistance. In addition, the biodegradable and non-toxic nature of gum Arabic makes it an environmentally friendly additive for green composite fabrication. Figure 3a shows the gum Arabic, and Fig. 3b shows the gum Arabic powder.

Fig. 3. (a) Gum Arabic and (b) Gum Arabic powder

Epoxy Resin

A commercial-grade epoxy resin system, Araldite LY556, was selected as the matrix owing to its excellent mechanical properties, high chemical resistance, and good dimensional stability. Epoxy provides strong adhesion to natural fibers, thereby ensuring effective load transfer within the composite. Its relatively low viscosity facilitates uniform mixing with the reinforcements, while its cured network structure offers high tensile, flexural, and impact strength (Nanthakumar *et al.* 2025). Aradur HY951 was used as the amine-based hardener. Based on commonly reported practice in the literature, the epoxy and hardener were mixed in a 10:1 weight ratio and allowed to cure at room temperature to obtain adequate cross-linking and stable composite properties.

Chemical Treatment of Fibers

Borassus flabellifer fruit fiber (BFF) and Snake Grass Fiber (SGF) were alkali-treated to enhance their compatibility with the epoxy matrix. The fibers were first washed with distilled water and then immersed in a 5 wt.% NaOH solution for 2 h at room temperature. This treatment removed surface impurities, waxes, hemicellulose, and part of the lignin, increasing surface roughness and exposing cellulose for better mechanical interlocking (Sinha and Devnani 2023). After treatment, the fibers were rinsed repeatedly until neutral pH and oven-dried at 60 °C for 24 h. The cleaned, dried fibers were then cut to the required lengths before composite fabrication. The alkali treatment improved fiber-matrix adhesion, enhanced wetting, reduced amorphous components, and promoted better load transfer (Soni *et al.* 2024). SEM observations confirmed improved interfacial bonding and reduced voids in the treated fiber composites

Methods / Fabrication Process

Hybrid composites were prepared using the hand lay-up method followed by compression molding. Cleaned and dried *Borassus flabellifer* fruit fiber (BFF), snake grass fiber (SGF), and gum Arabic (10 wt.%) were weighed according to the formulation (Srinivasan *et al.* 2020). Epoxy resin and hardener were mixed in a 10:1 ratio, after which the fibers and gum were gradually added and stirred to ensure uniform dispersion without air entrapment. A release agent was applied to the mold before pouring the mixture. The filled mold was then placed in a compression molding unit to achieve proper fiber wetting and uniform laminate thickness. The composites were cured at room temperature for 24 h and post-cured at 60 °C for 2 h (Ramesh *et al.* 2022b). Finally, the cured panels were demolded and cut into test specimens as per relevant ASTM standards.

Composite Formulations

Six hybrid epoxy composite panels were prepared by varying the proportions of *Borassus flabellifer* fruit fiber (BFF) and snake grass fiber (SGF), while maintaining epoxy resin (60%) and gum Arabic (10%) constant. The formulations included C1 (30% BFF/0% SGF), C2 (20% BFF/10% SGF), C3 (15% BFF/15% SGF), and C4 (10% BFF/20% SGF), enabling a systematic evaluation of the effect of hybrid fiber ratios on the mechanical and moisture-related properties of the composites (Ramesh *et al.* 2023). Table 1 shows that six composite panels were fabricated with varying BFF and SGF ratios:

Table 1. Composite Formulations

No.	Composite Code	BFF (%)	SGF (%)	Gum Arabic (%)	Epoxy (%)
1	C1 (30% BFF/0% SGF)	30	0	10	60
2	C2 (20% BFF/10% SGF)	20	10	10	60
3	C3 (15% BFF/15% SGF)	15	15	10	60
4	C4 (10% BFF/20% SGF)	10	20	10	60
5	C5 (0% BFF/30% SGF)	0	30	10	60
6	C6 (30% BFF/30% SGF)	30	30	0	60

Testing Procedure

The fabricated composites were evaluated through a series of mechanical, physical, and moisture-related tests to determine their structural performance and environmental stability. Before testing, all specimens were conditioned to equilibrium under controlled laboratory conditions for 24 h prior to evaluation. This pre-conditioning step was carried out to minimize the effect of ambient moisture and temperature variations on the test results.

Tensile Testing (ASTM D638 2022)

Dog-bone-shaped specimens were tested using a universal testing machine (UTM) to measure tensile strength and tensile modulus (Shao *et al.* 2023). The crosshead speed was maintained as per standard requirements, and stress-strain curves were recorded to evaluate load-bearing capability and stiffness.

Flexural Testing (ASTM D790 2017)

A three-point bending setup was used to determine the flexural strength and flexural modulus of the composites. Specimens were loaded at a constant span rate until failure, allowing assessment of bending resistance and rigidity (Tripathi *et al.* 2016).

Impact Strength (Izod Method)

Notched specimens were subjected to Izod impact testing to determine their ability to absorb energy during sudden loading. This test provides insight into the toughness and crack propagation resistance of each composite formulation (Arasu and Manickaraj 2025; Pandiarajan *et al.* 2025).

Hardness (Shore D)

Surface hardness was measured using a Shore D durometer. Multiple readings were taken on each sample to ensure consistency, providing an indication of surface resistance to indentation and wear (Li *et al.* 2021).

Interlaminar Shear Strength (ILSS)

ILSS was evaluated using the short-beam shear method, where specimens were loaded at a small span-to-thickness ratio. This test reflects fiber-matrix bonding quality and resistance to delamination under shear stresses (Arukalam *et al.* 2020).

Density (ASTM D792 2020)

Composite density was measured using the water displacement method based on Archimedes' principle. This test helps correlate material composition with overall mass efficiency and structural performance (Greeley *et al.* 2006).

Water Absorption (ASTM D570 2022)

Samples were immersed in distilled water for 24, 48, and 72 h. The percentage of water uptake was calculated from the weight gain at each interval, indicating moisture diffusivity and hydrophilicity of the composites (Alshammari *et al.* 2019).

Thickness Swelling

After immersion, specimen thickness was measured to determine the percentage increase relative to the original thickness. Thickness swelling reflects dimensional stability, matrix integrity, and fiber-matrix compatibility under moisture exposure (Nagamadhu *et al.* 2023).

Scanning Electron Microscopy (SEM)

SEM analysis was performed on alkali-treated fibers and on the fractured surfaces of tensile and flexural test specimens (Karuppusamy *et al.* 2025). This examination provided insights into fiber surface morphology, fiber-matrix adhesion, void distribution, gum dispersion, and failure mechanisms such as fiber pull-out and matrix cracking. SEM observations were used to correlate microstructural features with the mechanical performance of each composite.

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical behavior of *Borassus flabellifer* fruit fiber/snake grass fiber/ gum Arabic (BFF/SGF/gum Arabic) reinforced epoxy composites was comprehensively evaluated through tensile, flexural, impact, hardness, and interlaminar shear strength tests (Hariram and Shankar 2024). The results clearly demonstrate the significant influence of hybrid fiber ratios and gum incorporation on mechanical performance. Table 2 shows the mechanical properties of the developed hybrid epoxy composites.

Table 2. Mechanical Properties of the Developed Hybrid Epoxy Composites

Composite Code	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Impact Strength (kJ/m²)	Hardness (Shore D)	ILSS (MPa)
C1	58	2.1	72	2.45	21	74	34
C2	66	2.5	81	2.75	24	77	38
C3	72	2.9	89	3.05	28	79	42
C4	68	2.7	85	2.9	26	78	40
C5	63	2.4	79	2.65	23	76	36
C6	55	1.9	68	2.3	18	70	30

Tensile Test Results

The tensile behavior of BFF/SGF/gum Arabic reinforced epoxy composites clearly demonstrated the critical role of fiber hybridization and gum incorporation in enhancing mechanical performance (Fig. 4). The tensile strength of the composites ranged from 55 MPa to 72 MPa, showing significant variation depending on the type and proportion of fibers used. Among the formulations, C3 (15% BFF / 15% SGF) exhibited the highest tensile strength of 72 MPa, indicating an optimal balance between fiber distribution and stress transfer within the matrix (Patel and Goyal 2015; Jiang *et al.* 2026). The nearly equal proportion of BFF and SGF allowed for a synergistic reinforcement effect, where the moderate stiffness and ductility of BFF complemented the high rigidity and tensile load-bearing capacity of SGF. This synergy facilitated more uniform stress distribution under tensile loading, reducing localized stress concentrations that can initiate failure. C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also exhibited high tensile strengths of 66 MPa and 68 MPa, respectively, confirming that hybrid composites generally outperformed single-fiber composites. In contrast, single-fiber composites C1 (30% BFF) and C5 (30% SGF) showed moderate tensile strengths of 58 and 63 MPa, highlighting that exclusive reliance on one fiber limits interfacial bonding efficiency and load-sharing capability. The fiber-free composite, C6, containing only epoxy and gum Arabic, recorded the lowest strength (55 MPa), which is consistent with the typical behavior of unreinforced polymers, where the matrix alone cannot sustain high tensile loads. A similar trend was observed in the tensile modulus values, which ranged from 1.9 to 2.9 GPa. C3 again showed the highest modulus of 2.9 GPa, which can be attributed to the stiffening effect of the balanced BFF-SGF reinforcement and the improved fiber-matrix adhesion resulting from alkali treatment. C2 and C4 demonstrated moderately high modulus values of 2.5 to 2.7 GPa, while C1 and C5 had lower moduli of 2.1 to 2.4 GPa, and C6 recorded the lowest value of 1.9 GPa. The increase in stiffness for hybrid composites can be linked to better stress transfer efficiency from the epoxy matrix to the reinforcing fibers, which is facilitated by the complementary mechanical properties of BFF and SGF. The underlying mechanism for the superior tensile performance of hybrid composites, particularly C3, is multifaceted. BFF contributes moderate stiffness and ductility, which helps accommodate deformation without brittle failure, while SGF provides high rigidity and enhances the composite's tensile load-bearing capacity. Gum Arabic acts as a natural compatibilizer, filling microvoids and improving interfacial bonding between fibers and the epoxy matrix. Furthermore, alkali treatment of the fibers increases surface roughness and exposes cellulose fibrils, which promotes mechanical interlocking and reduces fiber pull-out during loading (Mohamed *et al.* 2025). This combination of factors resulted in improved load transfer from matrix to fibers, reduced microvoid formation, and overall enhanced tensile properties. SEM analysis corroborated these observations, revealing fewer interfacial gaps, reduced void content, and stronger fiber-matrix adhesion in hybrid composites, particularly in C3, which explains the observed improvements in both tensile strength and modulus (Kim *et al.* 2011; Jiang *et al.* 2025).

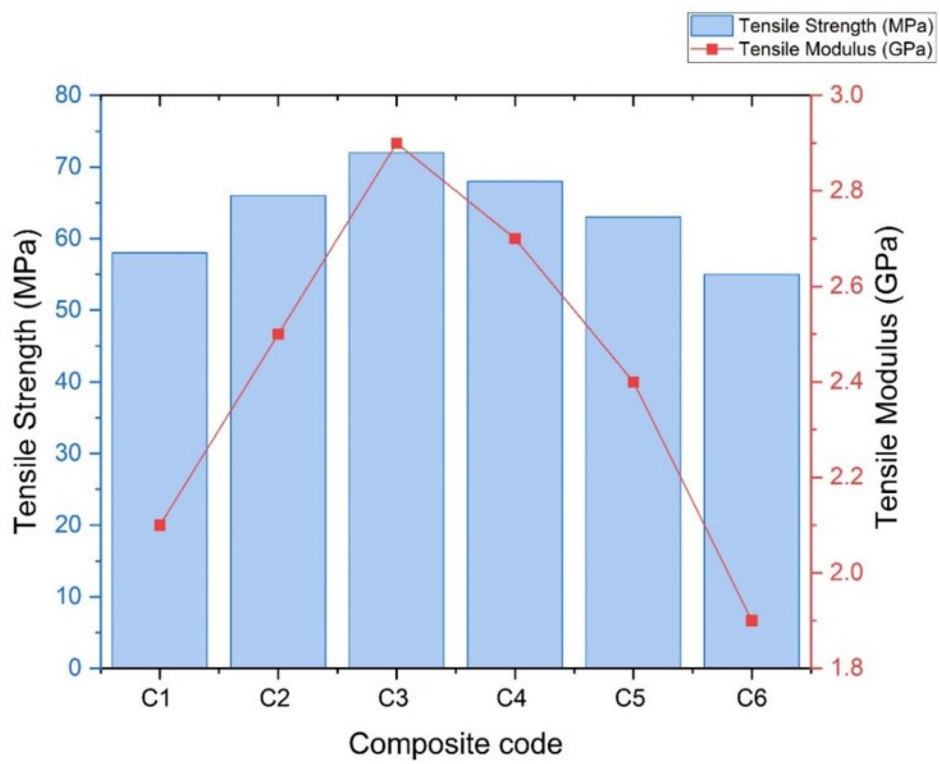

Fig. 4. Tensile strength and tensile modulus of the developed epoxy composites under six compositions: **C1** (30% BFF/0% SGF/10% gum Arabic/60% epoxy), **C2** (20% BFF/10% SGF/10% gum Arabic/60% epoxy), **C3** (15% BFF/15% SGF/10% gum Arabic/60% epoxy), **C4** (10% BFF/20% SGF/10% gum Arabic/60% epoxy), **C5** (0% BFF/30% SGF/10% gum Arabic/60% epoxy), and **C6** (30% BFF/30% SGF/0% gum Arabic/60% epoxy)

The results indicate that hybridization of BFF and SGF fibers, coupled with gum Arabic and alkali treatment, significantly enhances the tensile performance of epoxy composites by leveraging complementary fiber characteristics, improving interfacial bonding, and reducing microstructural defects (Thangavel *et al.* 2024). This makes such hybrid composites promising candidates for structural applications requiring both strength and stiffness.

Flexural Test Results

The flexural behavior of BFF/SGF/gum Arabic reinforced epoxy composites clearly illustrates the significant impact of hybrid fiber reinforcement and filler incorporation on bending performance (Fig. 5). The flexural strength of the composites ranged from 68 to 89 MPa, highlighting the importance of both fiber type and proportion in resisting bending loads. Among the tested formulations, C3 (15% BFF / 15% SGF) exhibited the highest flexural strength of 89 MPa, indicating an optimal balance between the two fiber types, which allows for an efficient distribution of bending stress throughout the composite. The nearly equal proportion of BFF and SGF enables a synergistic reinforcement effect: BFF, with moderate stiffness and inherent ductility, contributes to deformation accommodation under bending, while SGF, being highly rigid, enhances the composite's ability to resist load without significant deflection or failure. This complementary interaction ensures effective stress transfer from the epoxy matrix to the reinforcing fibers, thereby improving overall flexural performance. Other hybrid composites, such as C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF), also demonstrated high flexural strengths of 81 and 85 MPa, respectively. These values confirm that even when the hybrid ratio was not perfectly balanced, the combination of fibers still significantly enhanced bending resistance compared to single-fiber systems. Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), showed moderate flexural strengths of 72 and 79 MPa, respectively. The moderate performance in these cases can be attributed to limited load-sharing and stress distribution, as the absence of complementary fibers reduces the efficiency of fiber-matrix interaction during bending (Musa *et al.* 2024). The fiber-free epoxy composite containing only gum Arabic, C6, exhibited the lowest flexural strength of 68 MPa, which is consistent with the typical behavior of polymer matrices that rely solely on the gum to resist bending stresses; without fibrous reinforcement, the matrix alone cannot sustain high loads or prevent localized deformation. A similar trend was observed in flexural modulus, which ranged from 2.3 GPa (C6) to 3.05 GPa (C3). C3 displayed the highest modulus of 3.05 GPa, reflecting increased stiffness due to the balanced hybrid reinforcement and improved interfacial adhesion promoted by alkali treatment of fibers and the presence of gum Arabic. The moderately high modulus values of C2 (2.75 GPa) and C4 (2.9 GPa) further highlight the beneficial effect of partial hybridization on rigidity, while C1 (2.45 GPa) and C5 (2.65 GPa) exhibited lower stiffness, confirming that the single-fiber composites were less efficient in stress transfer. The lowest modulus in C6 (2.3 GPa) emphasizes the critical role of fibrous reinforcement in providing structural rigidity under flexural loading. The superior flexural performance of hybrid composites, particularly C3, is explained by several synergistic mechanisms (Manickaraj *et al.* 2024a). BFF fibers offer moderate stiffness and good ductility, allowing the composite to accommodate bending deformation without premature failure, whereas SGF fibers contribute high rigidity and load-bearing capacity, thereby enhancing resistance to bending stress. The inclusion of gum Arabic serves as a natural compatibilizer, filling microvoids within the matrix, improving fiber-matrix adhesion, and reducing the likelihood of crack initiation and propagation (Al Kiey *et al.* 2022; Luo *et al.* 2026). Moreover, alkali treatment of both BFF and SGF fibers increases surface roughness and exposes cellulose fibrils, which improves mechanical interlocking and reduces fiber pull-out during bending. SEM observations support these findings by showing fewer voids and tighter fiber-matrix interfaces in hybrid composites, particularly in C3, which explains the observed improvements in both flexural strength and modulus (Shao *et al.* 2024).

The results demonstrate that careful selection and hybridization of BFF and SGF fibers, along with the incorporation of gum Arabic and alkali treatment, significantly enhance the bending performance of epoxy composites. The improved stress transfer, reduced microstructural defects, and synergistic interaction between fibers make these hybrid composites promising candidates for applications that require superior strength and stiffness under flexural loading, such as automotive panels, furniture boards, and structural laminates (Nalini *et al.* 2024). The study highlights that optimal fiber ratios are crucial to achieving maximum mechanical efficiency, with balanced hybridization yielding the best combination of flexural strength and rigidity.

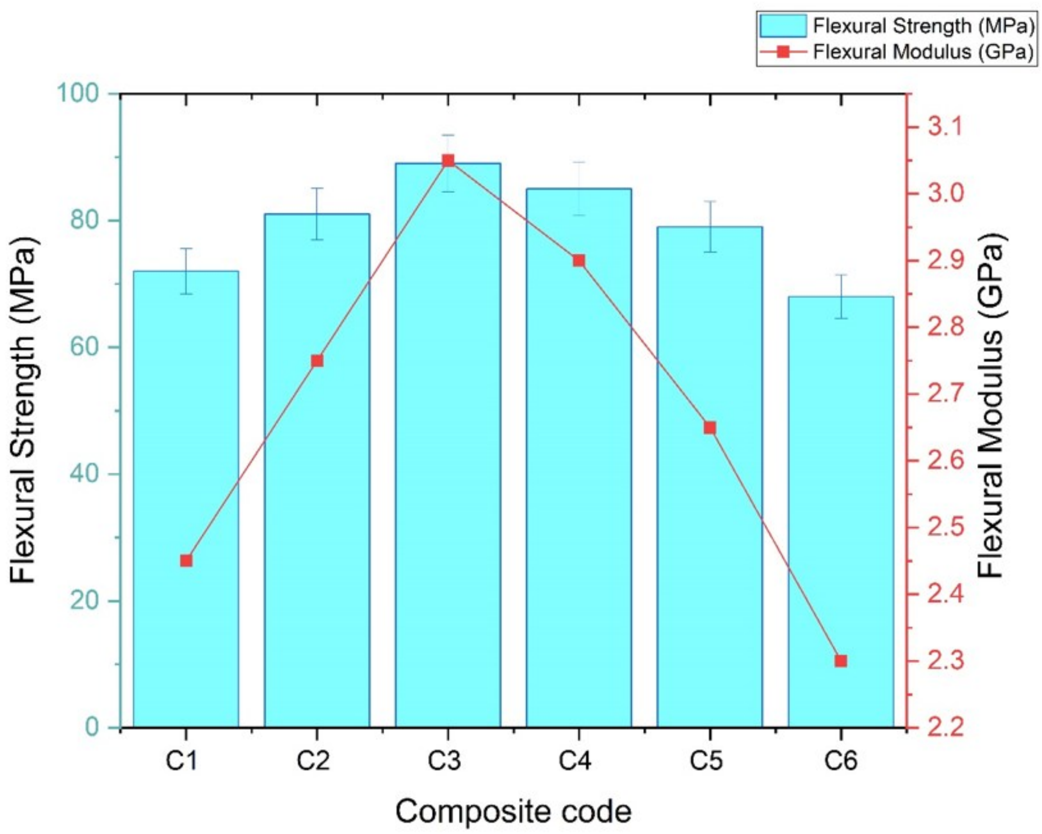

Fig. 5. Flexural strength and flexural modulus

Impact Test Results

The impact strength of BFF/SGF/gum Arabic reinforced epoxy composites reflects the material's ability to absorb sudden energy without fracturing, which is critical for applications involving dynamic or shock loading (Fig. 6). The measured impact strength ranged from 18 to 28 kJ/m², with C3 (15% BFF / 15% SGF) exhibiting the highest value of 28 kJ/m², indicating an optimal balance between the two fibers for energy dissipation.

The synergistic combination of BFF and SGF allows the composite to resist crack initiation and propagation under impact. BFF contributes ductility and toughness, permitting controlled deformation, while SGF provides high rigidity and load-bearing capability, collectively enabling the composite to absorb greater energy. Hybrid formulations C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also showed enhanced impact strengths of 24 and 26 kJ/m², respectively, demonstrating that even partial hybridization significantly improves energy absorption compared to single-fiber composites. Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), displayed moderate impact strengths of 21 and 23 kJ/m², reflecting the limitations of relying on a single fiber type, where the absence of complementary mechanical properties reduces the ability to arrest crack propagation. The epoxy-only composite with gum Arabic, C6, recorded the lowest impact strength of 18 kJ/m², consistent with unreinforced polymer behavior, as the matrix alone lacks sufficient mechanisms to dissipate sudden loads. The improvement in impact strength for hybrid composites can be attributed to enhanced fiber-matrix adhesion, facilitated by gum Arabic filling microvoids and promoting effective stress transfer, and alkali treatment, which increases fiber surface roughness and mechanical interlocking (Quintanilha *et al.* 2014). SEM observations support this interpretation, showing minimal void content and improved interfacial bonding in hybrid composites, particularly in C3, which collectively contribute to superior toughness and resistance to impact-induced fracture. Overall, these results indicate that balanced hybridization of BFF and SGF fibers, along with proper gum content and surface treatment, is essential for developing epoxy composites with enhanced impact resistance suitable for dynamic structural applications (Gurukarthik Babu *et al.* 2021).

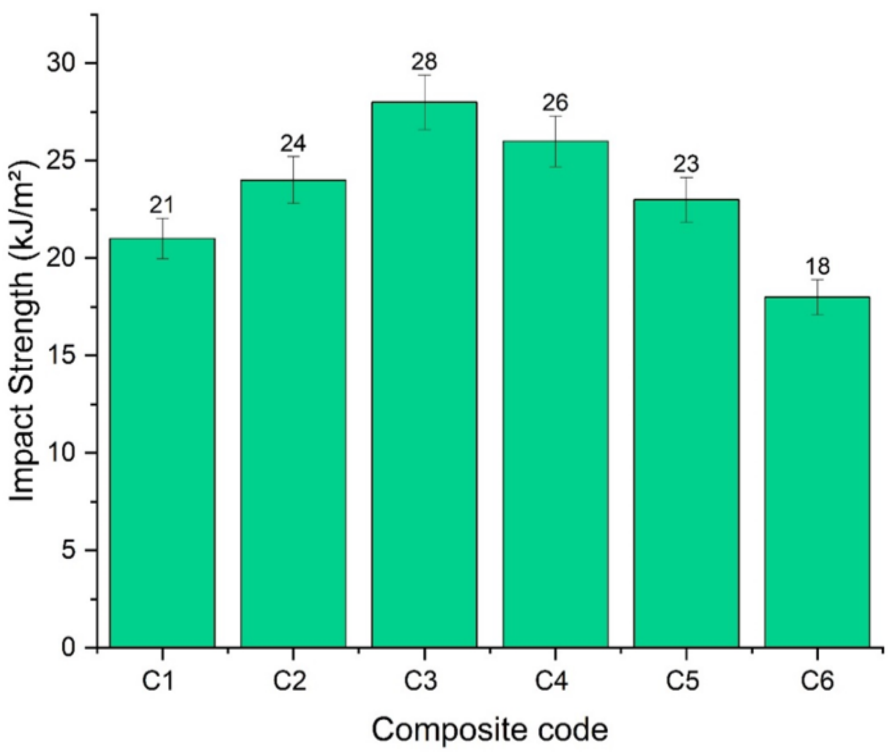

Fig. 6. Impact strength

Shore D Hardness

The Shore D hardness of BFF/SGF/gum Arabic reinforced epoxy composites provides an indication of surface resistance to indentation, which is critical for wear resistance and dimensional stability in structural applications (Fig. 7). The measured hardness values ranged from 70 (C6) to 79 (C3), showing a clear dependence on fiber type and hybridization. Among the formulations, C3 (15% BFF / 15% SGF) exhibited the highest hardness of 79, indicating that a balanced combination of BFF and SGF fibers produced a dense and mechanically robust surface.

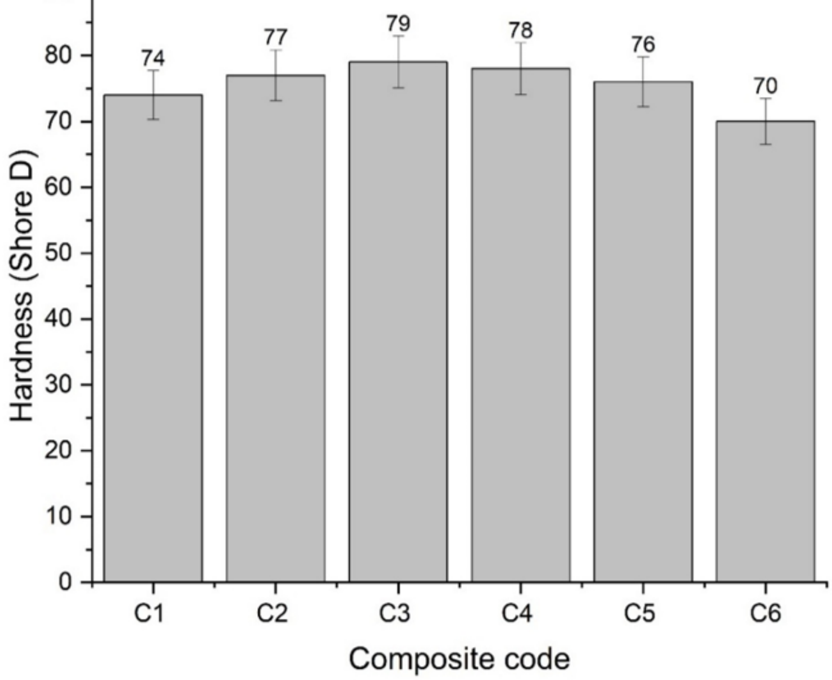

Fig. 7. Hardness

The synergistic effect arose because BFF provided moderate stiffness and toughness, while SGF contributed higher rigidity, resulting in enhanced surface resistance when subjected to indentation. Hybrid composites C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also showed elevated hardness values of 77 and 78, respectively, confirming that even partial hybridization can improve surface integrity compared to single-fiber composites. Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), displayed moderately high hardness values of 74 and 76, respectively, suggesting that although single fibers can reinforce the matrix, they are less effective than hybrid combinations in resisting localized deformation. The fiber-free composite, C6, containing only gum Arabic, recorded the lowest hardness of 70, highlighting the essential role of fibrous reinforcement in improving surface rigidity. Mechanistically, the improved hardness in hybrid composites can be attributed to enhanced fiber-matrix interaction facilitated by gum Arabic, which fills microvoids and reduces stress concentration at the interface, and alkali treatment, which increases fiber roughness and promotes mechanical interlocking (Abdin *et al.* 2022). SEM analysis supports these findings, revealing a more compact and void-free microstructure in hybrid composites, particularly in C3, which contributes to superior hardness. Overall, the results indicate that carefully balanced hybridization of BFF and SGF fibers, combined with gum incorporation and surface treatment, significantly enhances the surface strength of epoxy composites, making them suitable for applications requiring high wear resistance, dimensional stability, and mechanical durability (Abuarra *et al.* 2014).

Interlaminar Shear Strength

The ILSS of BFF/SGF/gum Arabic reinforced epoxy composites provides insight into the resistance of the material to delamination under transverse shear loading, which is critical for laminated composites in structural applications (Fig. 8). The ILSS values ranged from 30 MPa (C6) to 42 MPa (C3), indicating a significant dependence on fiber type and hybridization. Among the tested composites, C3 (15% BFF / 15% SGF) showed the highest ILSS of 42 MPa, reflecting an optimal combination of fibers that enhances interfacial bonding and shear load transfer between layers. The synergistic effect of BFF and SGF contributes to effective stress distribution: BFF fibers offer moderate stiffness and ductility, which helps accommodate shear deformation without microcracking, while SGF fibers provide high rigidity, increasing the composite's resistance to layer separation. Hybrid composites C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) exhibited ILSS values of 38 and 40 MPa, respectively, demonstrating that even partial hybridization significantly improves resistance to interlaminar shear compared to single-fiber composites.

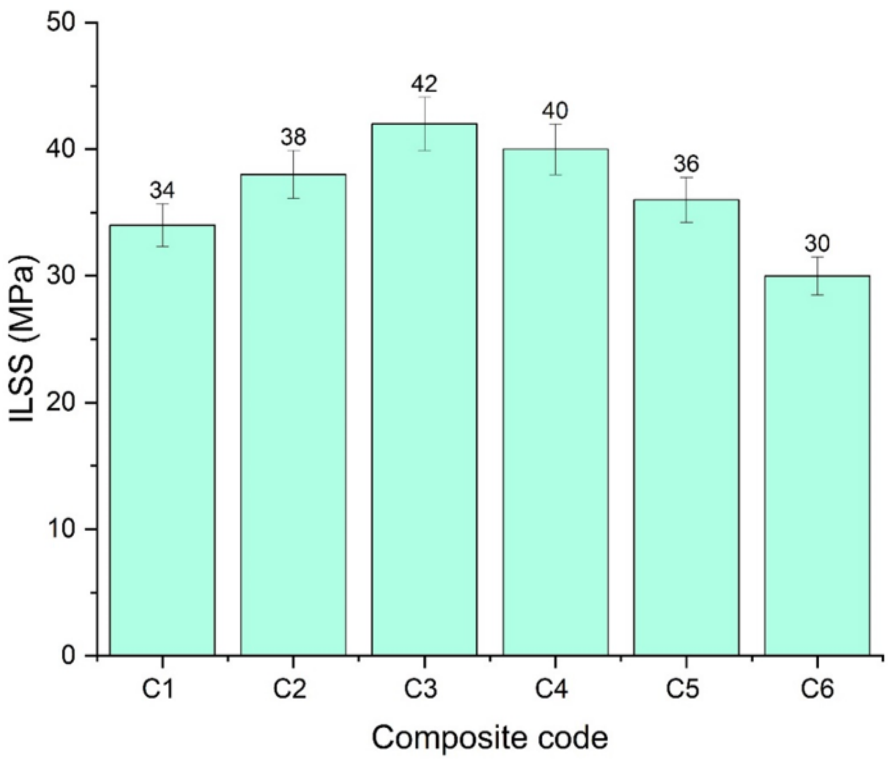

Fig. 8. ILSS

Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), recorded moderately high ILSS values of 34 and 36 MPa, respectively, indicating that while single fibers enhance shear strength compared to fiber-free matrices, they are less effective than hybrid composites in distributing interlaminar stresses. The fiber-free epoxy composite containing gum Arabic, C6, showed the lowest ILSS of 30 MPa, consistent with the reduced ability of unreinforced polymer matrices to resist shear-induced delamination. The improved ILSS in hybrid composites can be attributed to the combined effect of enhanced fiber-matrix adhesion facilitated by gum Arabic, which fills microvoids and reduces stress concentration, and alkali treatment, which increases fiber surface roughness and promotes mechanical interlocking (Suresh *et al.* 2016). SEM observations support these findings, showing minimal interfacial gaps, improved fiber-matrix bonding, and reduced microvoids in hybrid composites, particularly in C3, which explains the superior resistance to interlaminar shear failure. Overall, these results indicate that balanced hybridization of BFF and SGF fibers, together with gum Arabic and alkali treatment, significantly enhances the ILSS of epoxy composites, making them more suitable for structural applications that require resistance to delamination and transverse shear stresses, such as laminated panels, automotive components, and aerospace structures (Alrasheedi *et al.* 2026).

Density

The density of BFF/SGF/gum Arabic reinforced epoxy composites provides critical information about the compactness, fiber-matrix packing, and overall structural integrity of the laminates (Fig. 9).

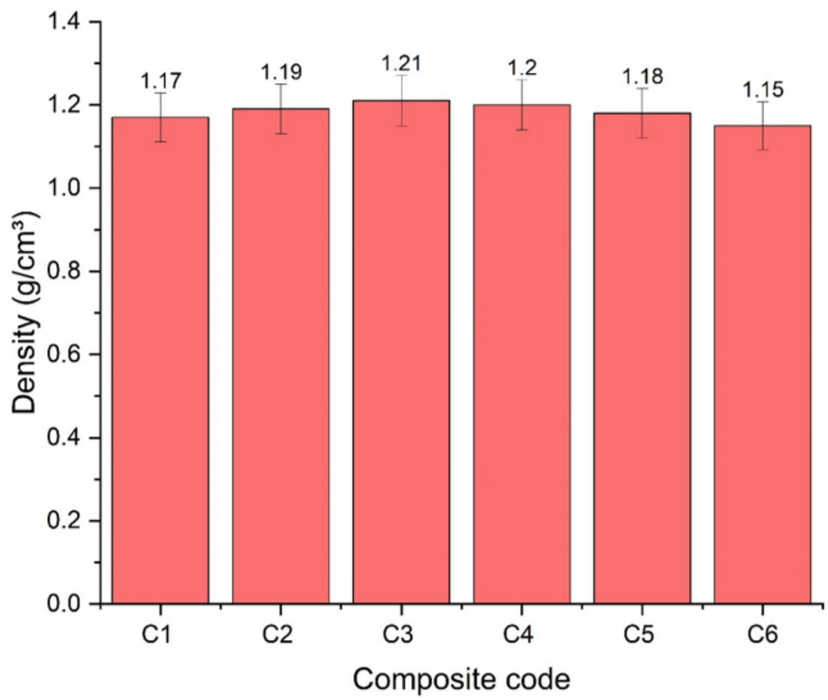

Fig. 9. Density

The measured densities ranged from 1.15 g/cm³ (C6) to 1.21 g/cm³ (C3), reflecting the influence of fiber content, hybridization, and gum incorporation. Among the formulations, C3 (15% BFF / 15% SGF) exhibited the highest density of 1.21 g/cm³, indicating that a balanced combination of BFF and SGF fibers results in efficient packing within the epoxy matrix, reducing void content and enhancing structural compactness. Hybrid composites C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also showed relatively high densities of 1.19 and 1.20 g/cm³, respectively, confirming that the inclusion of both fiber types contributed to a denser composite structure compared to single-fiber systems. Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), exhibited moderate densities of 1.17 g/cm³ and 1.18 g/cm³, respectively, suggesting that while these fibers enhanced structural reinforcement, the absence of complementary fibers led to less efficient matrix filling and slightly higher void fractions.

The lowest density was observed in C6 (1.15 g/cm³), the fiber-free epoxy composite containing only gum Arabic, highlighting the reduced packing efficiency and the absence of fibrous reinforcement, which typically contributes to increased composite mass and compactness. The increased density observed in hybrid composites can be mechanistically explained by the synergistic effect of BFF and SGF fibers, which fill interstitial spaces more effectively, combined with the role of gum Arabic in occupying microvoids, thereby minimizing porosity and enhancing interfacial bonding. Additionally, alkali treatment of the fibers improves fiber-matrix adhesion, ensuring uniform distribution of fibers and further contributing to composite densification (Krishnadas *et al.* 2024). Higher densities in hybrid composites are associated with improved mechanical properties, as compact microstructures facilitate better stress transfer and resistance to deformation. Overall, these results indicate that the balanced hybridization of BFF and SGF fibers, along with the inclusion of gum Arabic and surface treatment, enhances the density and structural integrity of epoxy composites, making them suitable for load-bearing and structural applications where both mechanical strength and dimensional stability are required (Sathish *et al.* 2024).

Water Absorption Test

The water absorption behavior of BFF/SGF/gum Arabic reinforced epoxy composites provides insight into the hydrophilicity, fiber-matrix interfacial bonding, and long-term durability of the laminates when exposed to moisture (Fig. 10). The composites were tested over 24, 48, and 72 h, with absorption values ranging from 4.8% to 8.4%, showing a clear dependence on fiber composition and hybridization. Among the tested formulations, C3 (15% BFF / 15% SGF) exhibited the lowest water absorption across all time intervals (4.8% at 24 h, 5.7% at 48 h, and 6.1% at 72 h), indicating superior resistance to moisture uptake due to the balanced hybridization of BFF and SGF fibers, which optimizes packing density and reduces the presence of microvoids within the matrix (Govindarajan *et al.* 2024; Sumesh *et al.* 2023). Hybrid composites C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also showed relatively low water absorption values (5.4 to 7.2% and 5.0 to 6.7%, respectively), demonstrating that even partial hybridization helped to limit water penetration by enhancing fiber-matrix adhesion and minimizing capillary pathways. In contrast, single-fiber composites, C1 (30% BFF) and C5 (30% SGF), displayed higher water absorption (C1: 6.2 to 8.4%; C5: 5.3 to 7.0%), reflecting the increased hydrophilic nature of individual fibers and the presence of microvoids or weakly bonded regions that facilitate moisture ingress. Interestingly, the fiber-free composite with just gum Arabic, C6, exhibited water absorption values (5.6 to 7.5%) slightly higher than some hybrid composites, highlighting that while gum Arabic can fill microvoids, the absence of fibrous reinforcement limits the structural network necessary to effectively resist water penetration (Gokul *et al.* 2024). Mechanistically, the reduced water absorption in hybrid composites is attributed to the synergistic interaction between BFF and SGF fibers, which improves packing density, reduces void content, and enhances fiber-matrix adhesion, while alkali treatment of fibers further decreases moisture affinity by removing surface impurities and exposing cellulose fibrils that bond more effectively with the epoxy matrix. The trend also indicates that water uptake increases with immersion time but stabilizes as saturation approaches, suggesting that hybrid composites, particularly C3, possess enhanced dimensional stability and durability under prolonged moisture exposure (Manickaraj *et al.* 2024b). Overall, these results confirm that balanced hybridization of BFF and SGF fibers, combined with gum Arabic and alkali treatment, not only enhances mechanical properties but also effectively reduces water absorption, making these composites suitable for applications in humid or wet environments, such as automotive interiors, furniture, and building panels (Fiber 2024).

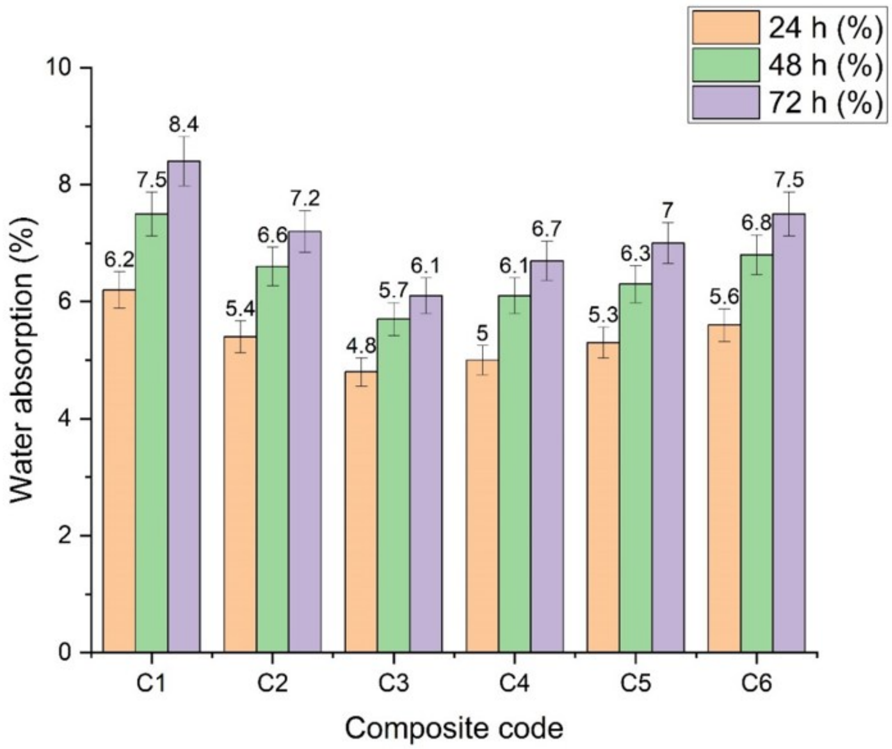

Fig. 10. Water absorption test

Thickness Swelling

The thickness swelling behavior of BFF/SGF/gum Arabic reinforced epoxy composites provides important information about dimensional stability and the resistance of the laminates to moisture-induced deformation (Fig. 11). Thickness swelling was measured over 24, 48, and 72 h, with values ranging from 1.2% to 2.1%, indicating that fiber composition and hybridization significantly influenced moisture-related expansion. Among the composites, C3 (15% BFF / 15% SGF) exhibited the lowest thickness swelling (1.2% at 24 h, 1.43% at 48 h, and 1.53% at 72 h), suggesting that balanced hybridization of BFF and SGF fibers created a denser and more compact microstructure that limited water ingress and minimized dimensional changes. Hybrid composites C2 (20% BFF / 10% SGF) and C4 (10% BFF / 20% SGF) also displayed relatively low swelling values (C2: 1.35 to 1.8%; C4: 1.25 to 1.68%), indicating that even partial hybridization improved dimensional stability compared to single-fiber composites (Chiang *et al.* 2014). Single-fiber composites, C1 (30% BFF) and C5 (30% SGF), recorded higher swelling (C1: 1.55 to 2.1%; C5: 1.33 to 1.75%), which can be attributed to increased hydrophilicity and the presence of microvoids that allow moisture penetration, leading to fiber expansion and matrix deformation. The fiber-free composite containing only gum Arabic, C6, exhibited intermediate swelling (1.4 to 1.88%), demonstrating that while gum can reduce void content, the absence of reinforcing fibers limits the ability to resist dimensional changes under prolonged water exposure. Mechanistically, the lower thickness swelling in hybrid composites can be explained by the synergistic effect of BFF and SGF fibers, which improves matrix packing and interfacial bonding, while alkali treatment reduces the hydroxyl content of fibers and enhances mechanical interlocking with the epoxy, thereby limiting water absorption and swelling. The results also showed a gradual increase in thickness swelling with immersion time, approaching saturation, which is typical for natural fiber composites (Barik *et al.* 2015). Overall, these findings indicate that optimized hybridization of BFF and SGF fibers, together with gum Arabic incorporation and fiber surface treatment, significantly improves the dimensional stability of epoxy composites, making them suitable for applications in humid or wet environments, including furniture, paneling, and interior automotive components (Nawaz *et al.* 2021).

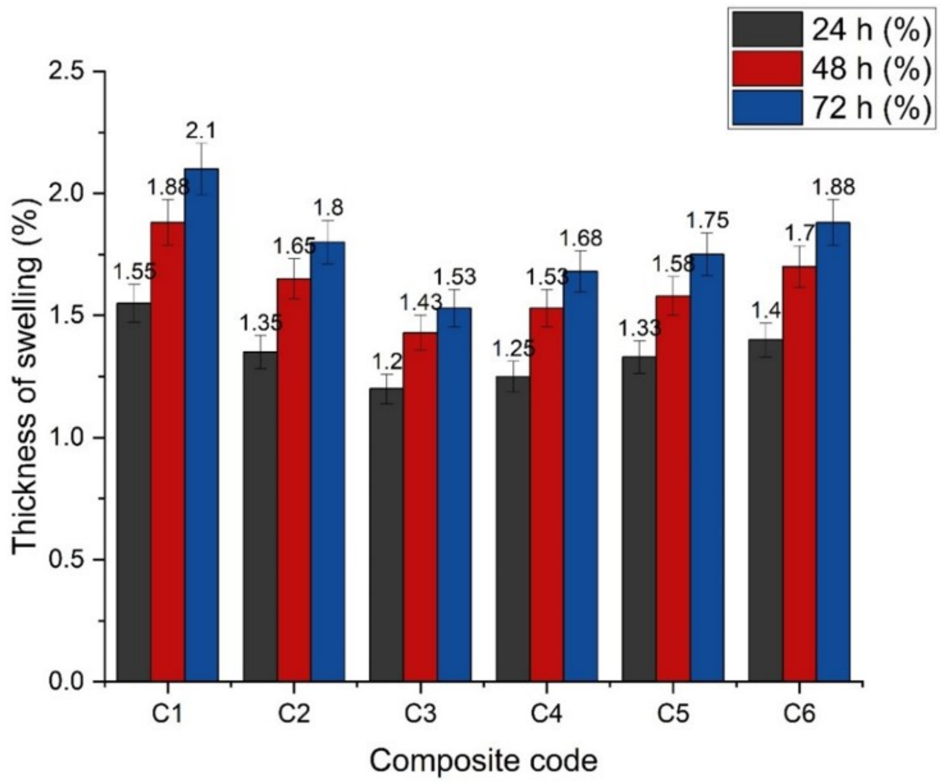

Fig. 11. Thickness swelling

Scanning Electron Microscopic Analysis

The SEM observations of the fractured surfaces of BFF/SGF/gum Arabic reinforced epoxy composites provide valuable insight into the microstructural features that govern their mechanical and physical properties (Palanisamy *et al.* 2022). The SEM images revealed significant differences between single-fiber, hybrid, and fiber-free composites, highlighting the role of fiber hybridization, gum incorporation, and alkali treatment in determining interfacial adhesion, void content, and fiber-matrix interaction (Fig. 12).

In single-fiber composites (C1 and C5), SEM micrographs showed relatively uniform fiber dispersion; however, some microvoids and small interfacial gaps were evident. These defects can act as stress concentrators under mechanical loading, explaining the moderate tensile, flexural, impact, and ILSS values observed for C1 and C5. Fiber pull-out and matrix debonding were occasionally observed, indicating suboptimal stress transfer from the epoxy matrix to the fibers (Hirwani and Sinha 2021). The presence of microvoids also accounts for the higher water absorption and thickness swelling observed in these composites, as voids create pathways for moisture ingress. In contrast, hybrid composites (C2, C3, and C4) exhibited a more compact and interconnected microstructure, with fibers uniformly embedded in the epoxy matrix and fewer voids. Notably, C3 (15% BFF / 15% SGF) showed excellent fiber-matrix adhesion with minimal interfacial gaps, consistent with its superior mechanical performance across all tests, including tensile (72 MPa), flexural (89 MPa), impact (28 kJ/m²), hardness (79 Shore D), and ILSS (42 MPa). The improved adhesion is attributed to the synergistic effect of hybrid fiber reinforcement, where the moderate ductility of BFF complements the high rigidity of SGF, allowing effective stress distribution and minimizing localized fiber pull-out. SEM also revealed that the gum Arabic filled microvoids and irregularities at the fiber-matrix interface, further enhancing interfacial bonding (Prasetya and Putri 2024).

Alkali treatment of fibers increased surface roughness and exposed cellulose fibrils, which promoted mechanical interlocking with the epoxy matrix, resulting in more efficient load transfer and higher resistance to delamination and deformation. C6, the fiber-free epoxy composite with gum Arabic, displayed a relatively smooth fracture surface with some gum agglomeration but lacked fibrous reinforcement. The absence of fibers led to lower mechanical properties, as reflected in the tensile, flexural, and impact results, and allowed slightly higher water absorption and thickness swelling due to limited structural reinforcement (Rejab *et al.* 2023).

The micrographs showed occasional microcracks, which can initiate failure under stress, explaining the lower stiffness, strength, and interlaminar shear resistance in C6. Overall, SEM analysis confirmed the trends observed in the mechanical and physical tests: hybridization of BFF and SGF fibers produces a dense, well-bonded microstructure with minimal voids, enhanced fiber-matrix adhesion, and reduced fiber pull-out, directly correlating with superior tensile, flexural, impact, hardness, ILSS, and moisture resistance properties. In addition, the presence of gum Arabic and alkali-treated fibers contributed to uniform stress transfer, reduced microvoid content, and improved dimensional stability (Rajamanickam *et al.* 2022). These microstructural observations underscore the effectiveness of hybrid fiber reinforcement and surface treatment strategies in optimizing the performance of natural fiber-reinforced epoxy composites, making them suitable for high-strength, moisture-resistant, and structurally demanding applications (Farooq *et al.* 2022).

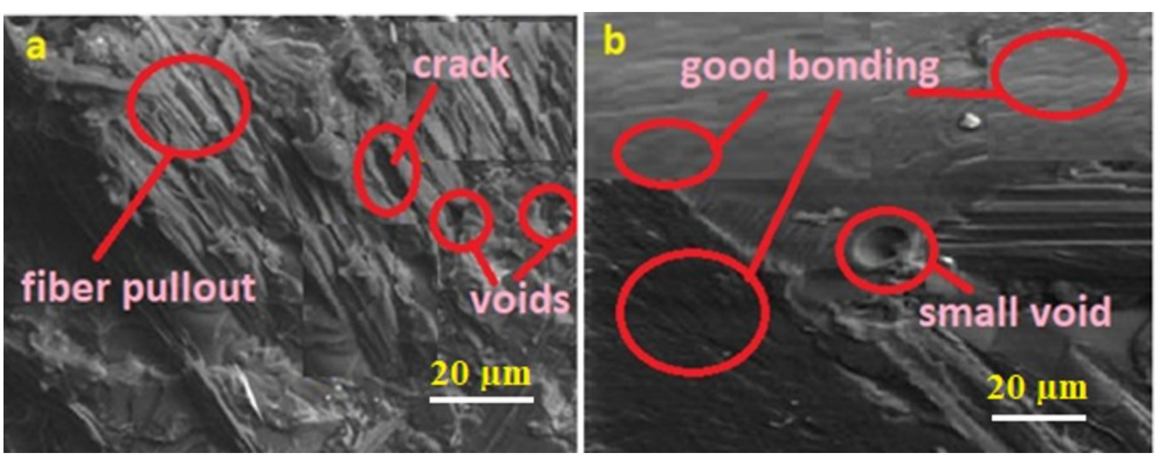

Fig. 12. (a) 20FL/25SWD; (b) 20FL/15SWD

CONCLUSIONS

1. The results of this study confirm that hybrid fiber reinforcement significantly improved the overall performance of epoxy composites. Among all the developed compositions, the balanced hybrid composite C3 (15% BFF / 15% SGF) exhibited the best mechanical performance, with the highest tensile strength (72 MPa), tensile modulus (2.9 GPa), flexural strength (89 MPa), flexural modulus (3.05 GPa), impact strength (28 kJ/m²), hardness (79 Shore D), and interlaminar shear strength (42 MPa). This superior behaviour indicates efficient stress transfer and effective load sharing between the fibers and the matrix.
2. The combination of the moderate ductility of BFF and the high rigidity of SGF created a synergistic reinforcement effect, which enhanced not only strength, but also stiffness, toughness, and delamination resistance. The partial hybrid composites, C2 and C4, also performed better than the single-fiber composites, further confirming the beneficial role of fiber hybridization.
3. In addition, the alkali treatment of fibers and the incorporation of gum Arabic reduced void content, improved fiber-matrix adhesion, and enhanced mechanical interlocking, as supported by SEM observations. These improvements led to reduced fiber pull-out, better stress distribution, and enhanced overall composite performance.
4. The hybrid composites, particularly C3, also showed superior hygrothermal performance, with the lowest water absorption (4.8 to 6.1%) and thickness swelling (1.2 to 1.53%) after 72 h of immersion. This behaviour can be attributed to improved interfacial bonding and a denser microstructure achieved through balanced hybridization and gum incorporation. In contrast, the single-fiber and fiber-free composites exhibited higher moisture uptake and thickness swelling due to the presence of microvoids and weaker interfacial interaction.
5. The hybrid composites also recorded relatively higher densities (1.19 to 1.21 g/cm³), indicating efficient fiber packing and reduced void formation, which directly contributed to their improved mechanical and hygrothermal properties. SEM analysis further confirmed uniform fiber distribution, strong fiber-matrix bonding, and minimal void content in the hybrid composites, explaining their enhanced mechanical strength, dimensional stability, and resistance to water-induced deformation. By comparison, the fiber-free composites showed smoother fracture surfaces and gum agglomeration, which corresponded to their lower performance.
6. Overall, the optimized hybridization of BFF and SGF fibers with gum Arabic reinforcement produced epoxy composites with superior mechanical strength, dimensional stability, and hygrothermal resistance. These characteristics make them promising materials for lightweight structural and semi-structural applications, including automotive panels, furniture boards, and other load-bearing or moisture-prone environments. In summary, the study demonstrates that balanced hybridization of natural fibers, together with suitable surface treatment and gum incorporation, is an effective approach for developing high-performance and environmentally friendly epoxy composites.

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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.

Use of Generative AI

The AI tool Quillbot was used to prepare this text.

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