


Sustainable high-performance materials: The role of bamboo and glass fibers in hybrid composites

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ABSTRACT

This study investigates the mechanical and structural properties of bamboo-glass fiber hybrid composites with the aim of optimizing strength-to-weight performance for advanced engineering applications. Composites were fabricated using the Vacuum-Assisted Resin Infusion (VARI) method to ensure uniform resin distribution and reduced void content. Four configurations—bamboo (BBBB), glass (GGGG), and hybrids (BGGB, GBBG)—were analyzed. GGGG exhibited the highest density (1.697 g/cm³) and tensile strength (125.86 MPa), while BBBB demonstrated the lowest density (0.954 g/cm³), highlighting bamboo lightweight advantage. Hybrid composites improved tensile strength by 24–30 % and flexural strength by 16–58 % compared to pure bamboo composites, with BGGB achieving superior tensile performance (87.24 MPa) and GBBG excelling in flexural strength (99.16 MPa). Specific tensile strength showed BGGB as the most efficient (86.39 MPa/g/cm³), followed by GBBG, while specific flexural strength revealed GGGG as the highest (108.76 MPa/g/cm³), with GBBG offering a balanced performance (97.4 MPa/g/cm³). The stacking sequence significantly influenced the performance, with BGGB optimizing the tensile stress distribution and GBBG enhancing the load transfer through glass fibers in the outer layers. Microstructural and FTIR analyses revealed that the hydrophilic and porous nature of bamboo weakened interfacial bonding, while glass fibers formed strong chemical bonds, improving rigidity and load transfer. These findings highlight the potential of bamboo-glass hybrid composites as sustainable, lightweight, and high-performance materials suitable for applications in sports equipment, automotive components, and other advanced engineering applications.

1. Introduction

The development of science and technology continues to evolve in line with lifestyle changes. One of the rapidly advancing fields that meet modern demands is materials science, where materials are expected to be not only strong but also lightweight [1]. The ability of composites to combine the mechanical and physical properties of different materials enables them to satisfy the requirements of modern materials. The evolution of composite materials has historically focused on achieving high-performance characteristics, such as strength, stiffness, and durability. Over the decades, advances in composite technology have broadened the scope of applications, ranging from aerospace to

automotive industries, highlighting the versatility and adaptability of these materials [2,3]. However, issues related to composite waste have emerged with the increased use of composites. Composite materials, often non-biodegradable and challenging to recycle, threaten the environment [4,5]. Therefore, the development of composite materials must consider environmental sustainability [6,7].

The growing demand for sustainable materials has brought natural fibers to the forefront as eco-friendly reinforcements in composite materials [8–10]. Natural fibers, such as bamboo, kenaf, jute, and sisal, are valued for their unique sustainability and eco-friendliness [11,12]. Natural fibers are lightweight, strong, cheaper, and have a lower environmental impact than synthetic fibers [13–15]. However, challenges in

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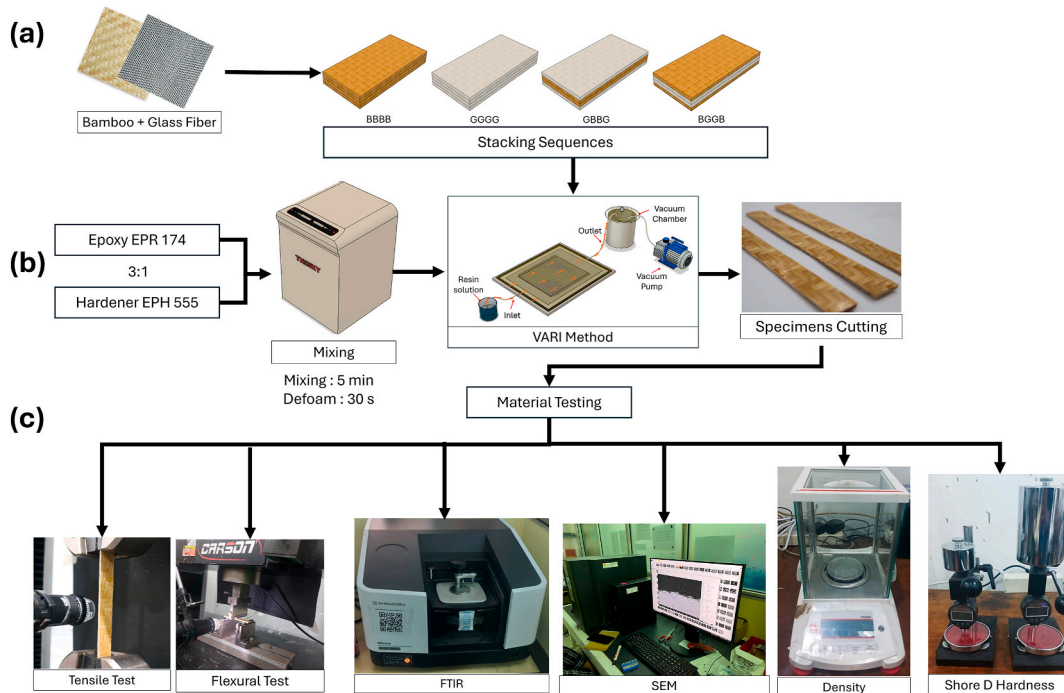


Fig. 1. Schematic overview, (a) stacking sequences, (b) composite fabrication, and (c) material testing.

integrating natural fibers into composite materials include poor compatibility between the fiber and matrix, leading to weak adhesion, high moisture absorption that affects durability and weakens the fiber-matrix interface, swelling, poor chemical resistance, and lower fire resistance compared to synthetic fibers [16–18]. Additionally, the lignin content in natural fibers creates a hydrophobic surface layer, reducing fiber-matrix interfacial bonding and requiring chemical treatment to improve adhesion [19,20]. Addressing these challenges requires techniques to modify the fiber surface, improve the fiber/matrix interface, and hybridize natural and synthetic fibers to achieve superior properties for advanced applications [21,22].

The integration of natural and synthetic fibers in hybrid composites not only optimizes the mechanical properties, but also addresses the limitations of using natural fibers alone [23,24]. Recent advancements in hybrid composites, such as the integration of natural fibers with synthetic fibers like glass and carbon, have demonstrated substantial potential to improve mechanical properties while reducing overall density and cost [25–27]. These innovations leverage the unique strengths of each fiber type natural fibers, such as bamboo, are combined with synthetic fibers, such as glass fibers, to create materials that leverage both advantages [28]. Glass fibers are well known for their high tensile strength, stiffness, and durability, making them an ideal choice for enhancing the mechanical properties of composite materials. However, their relatively high density, approximately 2.4 g/cm^3 , significantly increases the overall weight of the composite [29]. In contrast, bamboo fibers provide a sustainable and eco-friendly alternative due to their abundance and lower density, which ranges from 0.6 to 1 g/cm^3 [30]. This substantial difference in density highlights the potential of bamboo to reduce the overall weight of the hybrid composites while maintaining structural performance. Through the integration of glass fibers for their superior mechanical properties and bamboo fibers for their lightness and environmental benefits, hybrid composites provide a balanced approach to achieving high strength-to-weight ratios, making them suitable for advanced applications.

The properties of hybrid composites can be enhanced by optimizing the stacking sequence, which ensures better load distribution and improved structural integrity, thereby boosting overall performance and expanding their applicability in various advanced applications [31–33].

Previous studies have shown that the stacking sequence in hybrid composites significantly influences their mechanical properties. For instance, research on hybrid composites combining jute and hemp fibers demonstrated improvements in tensile and compressive strength through optimized stacking arrangements [34]. Similarly, investigations on jute/hemp hybrid composites revealed that optimized stacking sequences, with hemp placed on the outer skin, significantly improved flexural strength while reducing moisture absorption [33]. By carefully arranging the fiber layers, such as alternating bamboo and glass layers, the mechanical properties of the composite can be tailored for specific applications. Appropriate stacking sequences improve the load transfer, balance rigidity, and flexibility, and reduce stress concentrations, leading to superior strength-to-weight ratios and overall performance [35, 36]. This strategic layering also mitigates issues related to moisture uptake and weak bonding by distributing stresses more uniformly and enhancing fiber-matrix interaction [37,38]. This study aimed to evaluate the compatibility of bamboo and glass fibers in hybrid composites. The main focus was to understand how the interaction between these two fibers affects the mechanical performance of the composite. Additionally, microstructural characterization was conducted using SEM and FTIR to identify the failure mechanisms and material interactions within the composite.

2. Material and method

2.1. Materials

The materials used in this study consisted of woven glass fiber with a GSM of 185 g/m^2 , sourced from PT Justus Kimia Raya, Indonesia [39], and woven bamboo fiber with a GSM of 459 g/m^2 , sourced from local craftsmen in Yogyakarta. The matrix used was Epoxy Resin EPR 174 and Epoxy Hardener EPH 555 obtained from PT Justus Kimia Raya [40,41].

2.2. Method

The schematic overview of the study is shown in Fig. 1(a–c), including the stacking sequence of materials (Fig. 1(a)), the fabrication process using the VARI method (Fig. 1(b)), and the material testing

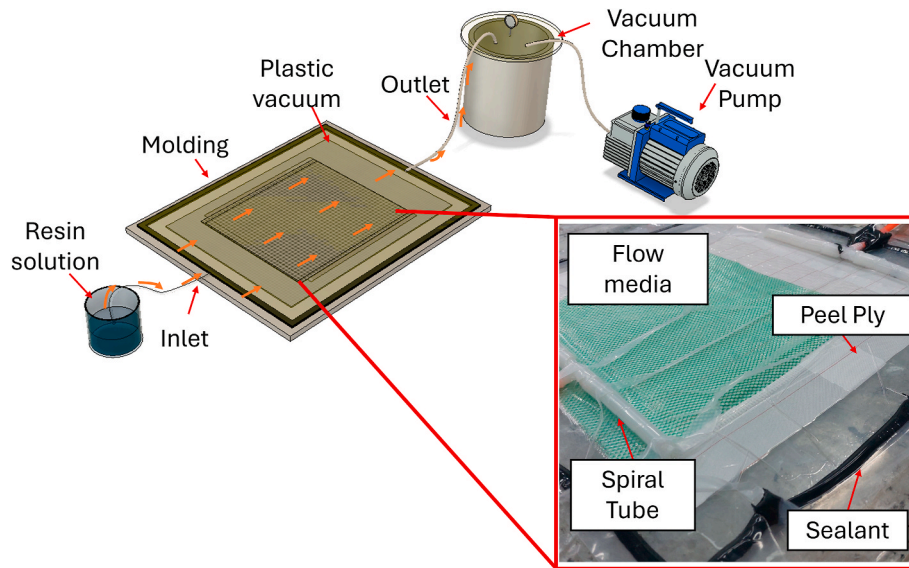


Fig. 2. Vacuum-Assisted Resin Infusion (VARI) method.

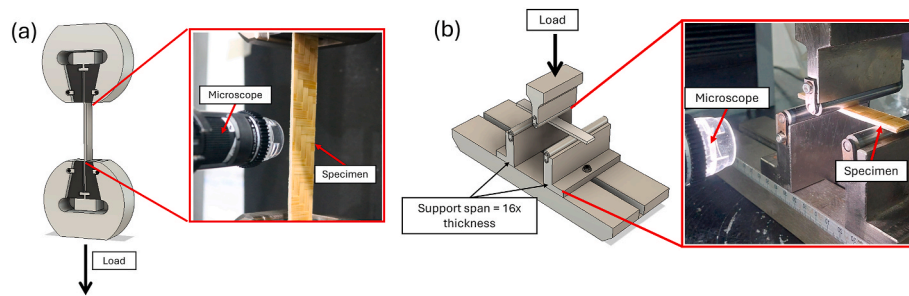


Fig. 3. Testing setup, (a) tensile testing setup, (b) flexural testing setup.

conducted to evaluate the mechanical performance and structural characteristics of the composites (Fig. 1(c)).

2.2.1. Composite fabrication

Fig. 1 (a) illustrates the arrangement of the layers in the bamboo composite (BBBB), glass fiber composite (GGGG), and hybrid composites (GBBG and BGGB). The composites were fabricated using the Vacuum-Assisted Resin Infusion (VARI) method [42], as shown in Fig. 2. Using vacuum pressure, VARI removes trapped air from the fiber layers and draws the resin uniformly through the reinforcement. This ensures consistent resin flow, reduces the void content, and prevents resin-rich or resin-deficient zones. The epoxy resin and hardener were mixed at a 3:1 ratio, and the mixture was stirred using a Thinky ARE-50 planetary centrifugal mixer to minimize voids during mixing. The mixing process lasted 5 min, followed by a 30-s defoaming step to further eliminate air entrapment. This combination ensures that the resin fully saturates the fiber layers, creating a dense and uniform composite structure. The composites were then cured for 48 h and cut into the specified dimensions using a water-cooled cutting machine.

2.2.2. Testing method

Mechanical testing was conducted using a universal testing machine Carson CRN-50 with a 50 kN load cell. The testing included a tensile test according to the ASTM D3039-08 standard [43], with specimen dimensions of 20 mm × 200 mm and a crosshead speed of 2 mm/min. The flexural test was conducted according to the ASTM D790-17 standard [44], with specimen dimensions of 15 mm × 100 mm and a crosshead speed of 2 mm/min. The support span length was set as 16 times the

thickness of the material. The tensile and flexural test setups are shown in Fig. 3. The hardness test was performed using Shore D, following the ASTM D2240-15 standard [45], designed to measure the hardness of the composite materials. Density measurements were performed using a precision balance (OHAUS PX224) at room temperature (23 °C). The weight of the composite was first measured in air, followed by a second measurement while submerged in distilled water. Each test was conducted using five samples for each composite variation to ensure the consistency and reliability of the results. Additionally, observations were made using a Dino-Lite AF4915 digital microscope during tensile and flexural tests. SEM observations were conducted using a Thermo Fisher Scientific Phenom ProX Desktop SEM to examine the fracture morphology after mechanical testing. The fracture samples were cut and coated with gold. Material characterization was performed using FT-IR with a SHIMADZU IRXross.

2.2.3. Density and volume fraction calculation

Density was calculated using the following equation:

$$\rho = \frac{w_c}{w_i} \rho_s \quad (1)$$

where ρ is the density, w_c is the weight of the composite in air, w_i is the weight of the composite when weighed in water and ρ_s is the density of the liquid solution. The volume fraction was measured by first determining the weight of the composite with dimensions of 50 mm × 50 mm and then calculated using the following equation:

$$w_c = w_{bamboo} + w_{glass} + w_{resin} \quad (2)$$

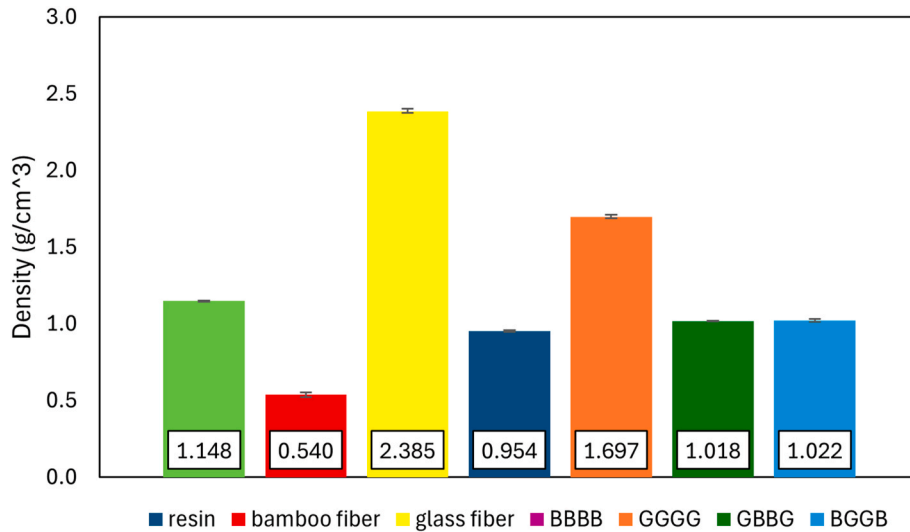


Fig. 4. Density measurement result.

Where w_c is the weight of the composite, and w_{bamboo} , w_{glass} , and w_{resin} are the weights of each component. The weight of each component was calculated using the following equation:

$$w_{bamboo} = n \times GSM_{bamboo} \times A \tag{3}$$

$$w_{glass} = n \times GSM_{glass} \times A \tag{4}$$

Where n is the number of layers, GSM_{bamboo} and GSM_{glass} are the weight per unit area of the bamboo and glass fibers, and A is the surface area of the specimen. The volume of each component was calculated using the following equation:

$$v_{bamboo} = \frac{w_{bamboo}}{\rho_{bamboo}} \tag{5}$$

$$v_{glass} = \frac{w_{glass}}{\rho_{glass}} \tag{6}$$

$$v_{resin} = \frac{w_{resin}}{\rho_{resin}} \tag{7}$$

$$v_c = v_{bamboo} + v_{glass} + v_{resin} \tag{8}$$

Where v is the volume and ρ is the density of each component. The

volume fraction of each component was calculated using the following equation:

$$V_{fbamboo} = \frac{v_{bamboo}}{v_c} \tag{9}$$

$$V_{fglass} = \frac{v_{glass}}{v_c} \tag{10}$$

Where V_{f_bamboo} and V_{f_glass} are the volume fractions of bamboo fiber and glass fiber in the composite.

3. Result and discussion

3.1. Density and volume fraction measurements

Fig. 4 shows the densities (g/cm³) of the various components and composites, revealing significant differences between the tested materials. Glass fiber has the highest density, at 2.385 g/cm³, indicating that glass fiber is much denser than the other materials. Previous studies have reported that the density of glass fibers typically ranges from 2.1 to 2.7 g/cm³ [46]. Resin has a density of 1.148 g/cm³, lower than glass fiber but higher than other materials, such as bamboo fiber and some hybrid composites. Bamboo fiber has the lowest density, at 0.540 g/cm³, indicating that bamboo fiber is significantly lighter than glass fiber and

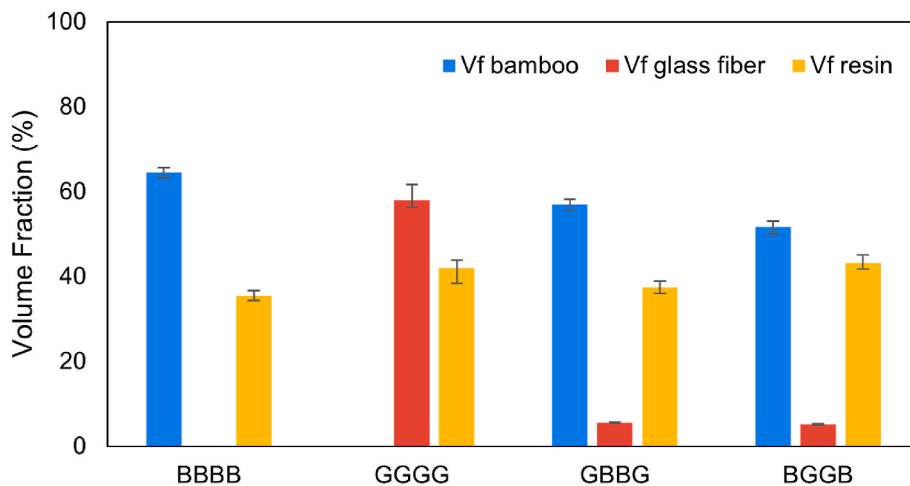


Fig. 5. Volume fraction calculation result.

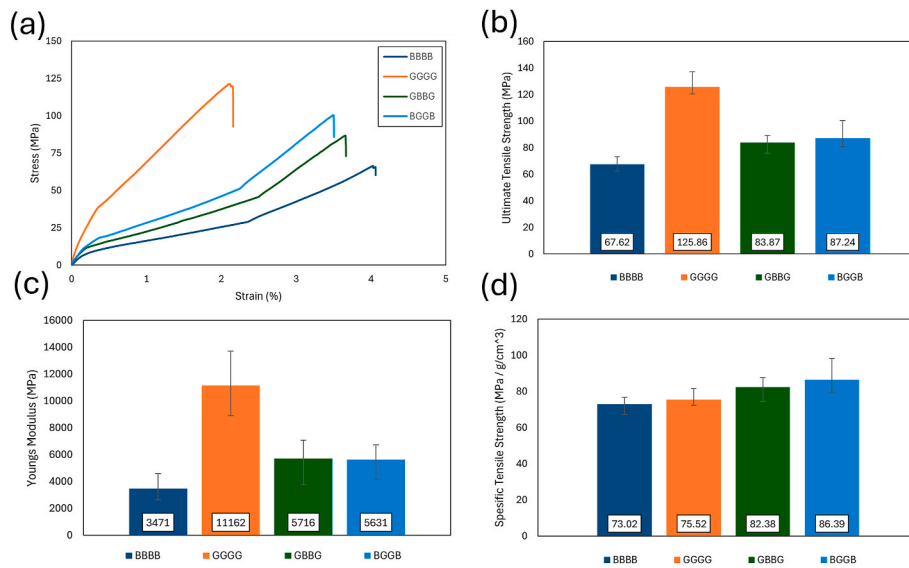


Fig. 6. Tensile test result (a) stress-strain, (b) ultimate tensile strength, (c) youngs modulus, (d) specific tensile strength.

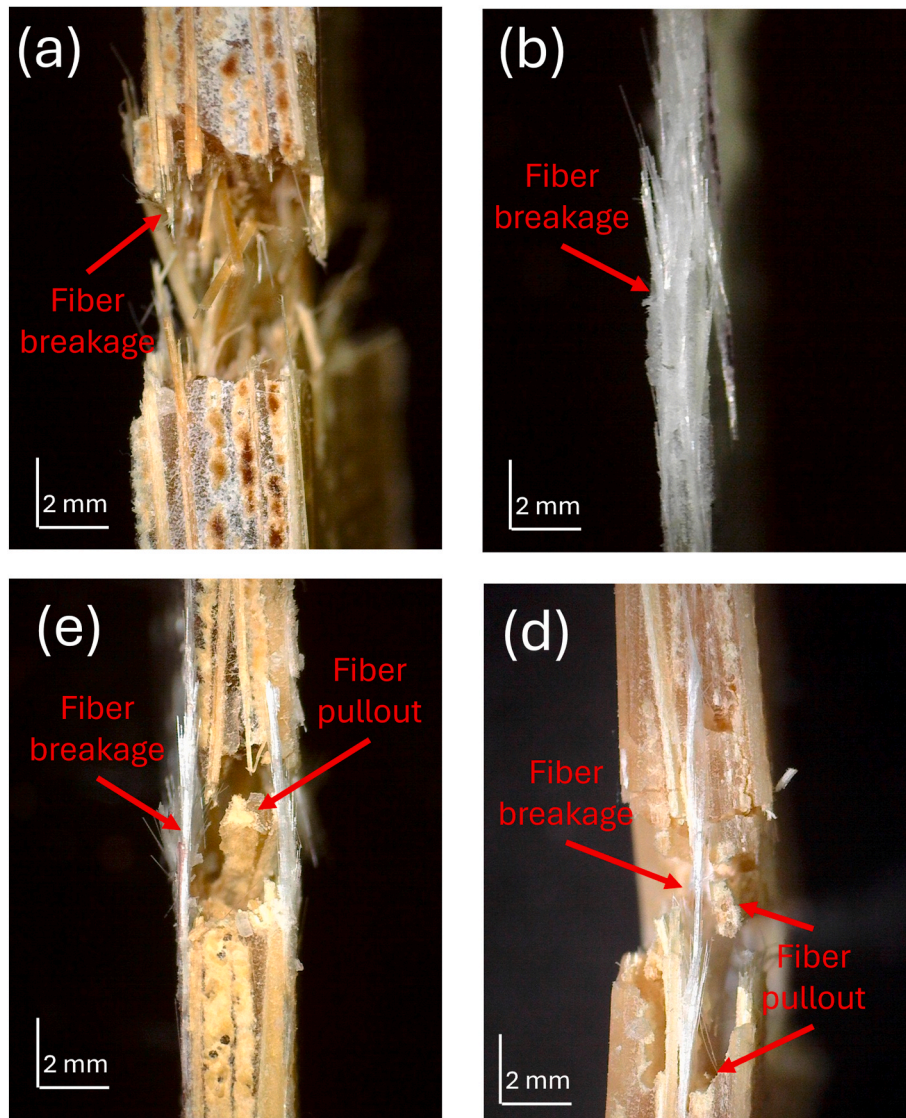


Fig. 7. Specimen failure modes during tensile test (a) BBBB, (b) GGGG, (c) GBBG, and (d) BGGG.

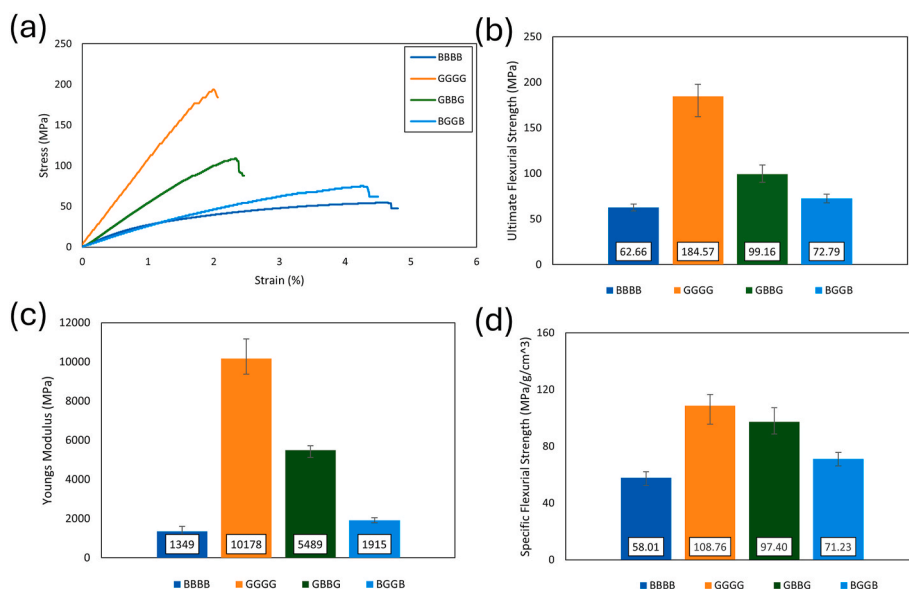


Fig. 8. Flexural test result (a) stress-strain, (b) ultimate flexural strength, (c) youngs modulus, (d) specific flexural strength.

resin. GGGG composite has a density of 1.697 g/cm³, lower than pure glass fiber but still shows that glass fiber contributes significantly to the density of the composite. The BBBB composite, with a density of 0.954 g/cm³, indicated that the bamboo-based composites were lighter than those using glass fibers. The hybrid composites, GBBG and BGGB, had densities of 1.018 and 1.022 g/cm³, respectively. Density measurements revealed that the GGGG composites possess the highest density due to their mass and compact structure, indicating that these composites are more rigid but also heavier. In contrast, BBBB composites are significantly lighter, making them advantageous for weight-sensitive applications, where low density is essential for performance. The hybrid composites BGGB and GBBG demonstrated intermediate densities, balancing the strength contribution from the glass fibers with the lightweight characteristics of bamboo. This balance makes them suitable for applications where both reduced weight and structural integrity are desired.

Based on the volume fraction test results (Fig. 5), the BBBB composite had a fiber volume fraction of 64.6 %. This indicates that bamboo fibers with resin as the matrix dominate the BBBB composite. The GGGG composite contained 58 % glass fibers and 42 % resin. The BGGB hybrid composite consisted of 51.6 % bamboo fiber, 5.1 % glass fiber, and 43.2 % resin, where bamboo fiber was the main component, with a small amount of glass fiber added for additional reinforcement. Another hybrid composite, GBBG, contained 56.93 % bamboo fibers, 5.6 % glass fibers, and 37.4 % resin, indicating that bamboo fibers were the dominant component. The volume fraction analysis further showed that the hybrid composites BGGB and GBBG consisted mainly of bamboo fibers, with only a small proportion of glass fibers. This composition aids in reducing the overall weight of the composite while preserving the eco-friendly qualities of bamboo. Lower density in a composite indicates a lighter structure, which is beneficial for applications that require weight efficiency.

3.2. Mechanical properties

Fig. 6(a)–(d) shows the tensile test results for the composite configurations. Fig. 6(a) shows the stress-strain curves illustrating the material response under a tensile load. The GGGG composite exhibits the lowest strain before failure, indicating high rigidity. In contrast, the BBBB composite shows the highest strain, reflecting the greater flexibility of bamboo fibers. The hybrid composites GBBG and BGGB exhibit improved tensile resistance compared to the BBBB composite,

suggesting that the addition of glass fibers enhances the mechanical properties of the composite. The stacking sequence also influences strain behavior, with the BGGB configuration showing slightly lower strain than GBBG, suggesting that positioning bamboo layers around glass fibers can enhance rigidity while retaining some flexibility. This variation in strain response highlights how stacking sequences can be optimized to achieve the desired mechanical properties in hybrid composites. Fig. 6(b) presents the Ultimate Tensile Strength (UTS), where the GGGG composite achieved the highest value at 125.86 MPa, followed by the hybrid BGGB at 87.24 MPa and GBBG at 83.87 MPa, while BBBB displayed the lowest UTS at 67.62 MPa. The hybrid composites showed higher tensile strength than BBBB, indicating that combination bamboo and glass fibers improves the tensile strength. Notably, the stacking sequence of BGGB enhances the tensile strength more effectively than that of GBBG, indicating that arranging bamboo layers around glass can optimize load transfer. This aligns with research on jute-glass composites, where stacking sequences such as JGGJ showed higher strength than GJJG and JGJG [47]. Fig. 6(c) shows youngs modulus, with GGGG achieving the highest modulus at 11162 MPa, signifying greater stiffness, while the hybrid composites also showed improved stiffness over BBBB but remained below GGGG. Fig. 6(d) illustrates Specific Tensile Strength, with hybrid composites demonstrating superior strength-to-weight efficiency, particularly BGGB, which achieved the highest value at 86.39 MPa/g/cm³, followed by GBBG. These results suggest that while GGGG provides the highest overall tensile strength and stiffness, the hybrid composites effectively balance the strength and weight. BGGB achieves higher tensile strength than GBBG, highlighting the impact of stacking sequence on mechanical performance.

The various failure types that occurred during tensile testing of the composites were examined using a microscope. Fig. 7(a)–(e) shows the results of observations using a digital microscope with 24× magnification. As shown in Fig. 7(a), the BBBB composite experienced fiber breakage, where the bamboo fibers detached from the matrix due to their inability to withstand the tensile stress. Fig. 7(b) shows that the GGGG composite exhibited fiber breakage, indicating that the glass fibers continued to carry some load despite matrix fracture. As shown in Fig. 7(c), the GBBG hybrid composite displayed bamboo fiber pull-out, while the glass fibers showed fiber breakage. A similar pattern was observed in Fig. 7(d) for the BGGB composite, with bamboo fibers showing fiber pull-out and glass fibers displaying fiber breakage. These differences in the failure patterns highlight how bamboo and glass fibers react differently to tensile stress. Bamboo fibers tend to pull out due to

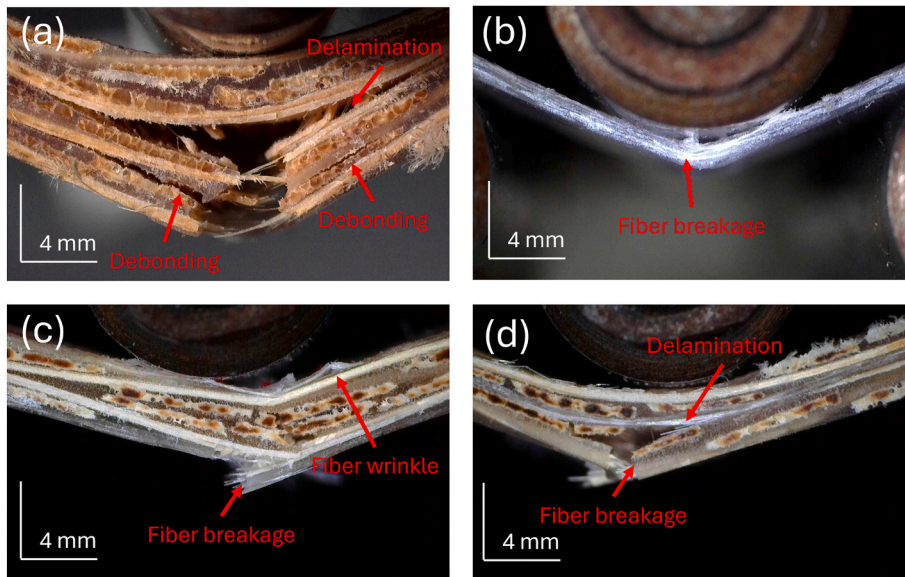


Fig. 9. Specimen failure modes during flexural tests (a) BBBB, (b) GGGG, (c) GBBG, and (d) BGGB.

their lower tensile strength and weaker interfacial bonding with the matrix, whereas glass fibers bridge across the fractured areas, reflecting their higher load-carrying capacity and better interfacial adhesion. This behavior is attributed to the distinct mechanical properties of bamboo and glass fibers, which result in uneven stress distribution within hybrid composites and lead to more complex failure mechanisms [48,49].

The flexural test results in Fig. 8(a)–(d) illustrate the effects of the stacking sequence on the mechanical behavior of the bamboo and glass fiber composites. In Fig. 8(a), the stress-strain curves show that the GGGG composite exhibits the lowest strain before failure, indicating high rigidity due to the stiffness of pure glass fiber. In contrast, the BBBB composite shows the highest strain, reflecting the flexibility of bamboo fibers. The hybrid composites, GBBG and BGGB, demonstrated strain values between GGGG and BBBB, showing a balanced response between rigidity and flexibility. The stacking sequence significantly affects the strain behavior, GBBG exhibits lower strain than BGGB, indicating that the layer arrangement influences flexural response, with GBBG providing greater rigidity under flexural loading. Fig. 8(b) presents the Ultimate Flexural Strength, where the GGGG composite achieved the

highest strength at 184.57 MPa, followed by the BBBB composite at 62.66 MPa. Both hybrid composites displayed improved flexural strength compared to BBBB, indicating that incorporating glass fibers in the hybrid configuration enhanced the flexural strength. Among the hybrid composites, GBBG exhibits a higher flexural strength at 99.16 MPa compared to BGGB at 72.79 MPa, suggesting that the GBBG stacking sequence better leverages the combination of glass and bamboo layers to enhance strength. In Fig. 8(c), the Young's modulus shows the stiffness of each configuration, with GGGG displaying the highest modulus at 10178 MPa. The GBBG configuration, with a modulus of 5489 MPa, significantly improved over BBBB at 1349 MPa, while remaining below the GGGG modulus. BGGB, with a modulus of 1915 MPa, demonstrated lower stiffness than GBBG, indicating that the stacking sequence of GBBG can significantly enhance the young's modulus under flexural loading conditions. Lastly, Fig. 8(d) shows the Specific Flexural Strength, with GGGG achieving the highest efficiency at 108.76 MPa/g/cm³, followed by GBBG at 97.4 MPa/g/cm³. BGGB exhibits a lower specific flexural strength of 71.23 MPa/g/cm³, while BBBB has the lowest at 58.01 MPa/g/cm³. These results highlight that in

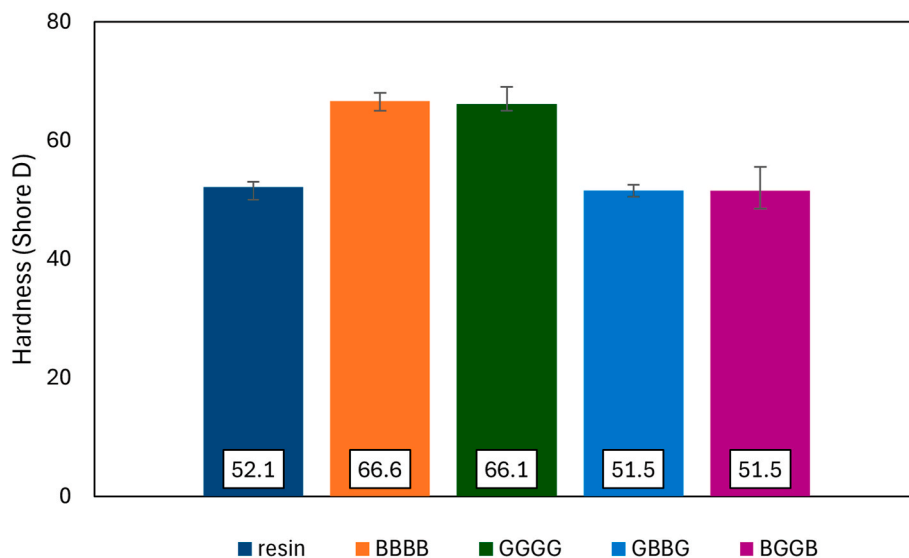


Fig. 10. Hardness test result.

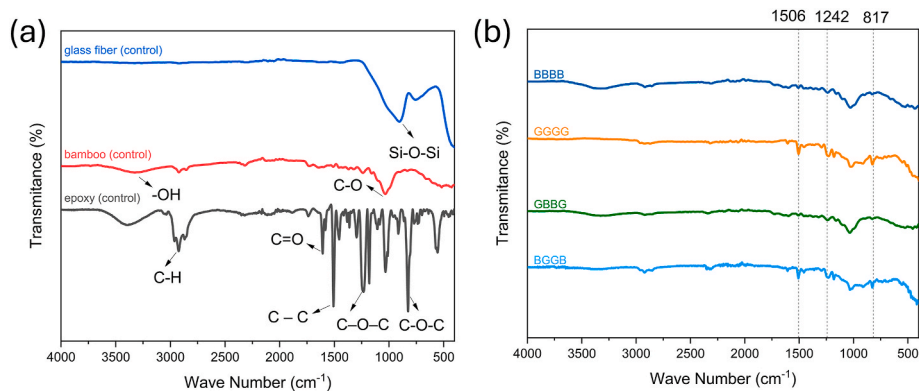


Fig. 11. FTIR results of specimens a) Control specimen b) Composite specimen.

terms of the flexural strength-to-weight ratio, GGGG provides the best efficiency, and GBBG achieves a more balanced performance among the hybrid configurations. Overall, the stacking sequence significantly impacts the mechanical response under flexural loading, with GBBG showing better flexibility, strength, and stiffness balance than BGGB in the hybrid composites.

Fig. 9(a)–(d) shows the failure modes of the specimens during the flexural tests for various composite variations. In Fig. 9(a), the BBBB composite displays delamination, indicating bond failure between the bamboo fiber layers and matrix caused by flexural stress, leading to layer separation. In Fig. 9(b), the GGGG composite shows brittle fracture under flexural stress, which is a common failure mode for single-material composites with uniform stiffness. Fig. 9(c) shows that the hybrid GBBG composite experienced compression failure, where the glass fibers wrinkled under compressive stress during the flexural test. Additionally, fiber breakage was visible under tensile stress, indicating that the glass fibers in the outer layers were unable to fully withstand the tensile forces applied during the test, leading to structural failure. This fiber breakage further propagated into delamination between the glass fibers and bamboo. Fig. 9(d) shows the hybrid BGGB composite, where the fiber fracture is clearly visible, indicating that the bamboo fibers in the outer layers cannot withstand the applied flexural load. Additionally, delamination was observed between the bamboo and glass fiber layers, highlighting weak interfacial bonding under flexural stress. These failure modes in the composite variations reveal weak interfacial bonding between the glass fibers and bamboo under flexural stress [50, 51].

Fig. 10 shows the results of the hardness tests. Based on the Shore D hardness test results shown in the graph, the BBBB composite exhibited the highest hardness value at 66.6 Shore D, slightly higher than the pure glass fiber composite (GGGG), which recorded a hardness of 66.1 Shore D. This indicates that both composites, despite being composed of different materials, had nearly identical hardness values. On the other hand, the hybrid composites, GBBG and BGGB, had a hardness value of 51.5 Shore D, which is lower than BBBB and GGGG. This suggests that the combination of bamboo and glass fibers in this configuration did not significantly increase hardness.

The lower Shore D hardness in hybrid composites compared to pure bamboo (BBBB) and pure glass (GGGG) composites is due to differences in the matrix reinforcement. In GGGG, the rigid and dense glass fibers strongly reinforce the matrix, resulting in higher hardness, while in BBBB, the bamboo fibers provide moderate reinforcement due to their cellular structure. Hybrid composites with alternating bamboo and glass fiber layers have a less uniform reinforcement structure. The softer, porous bamboo fibers reduce the overall rigidity, and the differing properties and weaker interfacial bonding between bamboo and glass fibers lead to uneven stress distribution, further lowering the hardness. These factors explain the reduced Shore D hardness in the hybrid composites, despite their optimized mechanical properties.

Table 1

FTIR characteristic peaks of epoxy, glass fiber, and bamboo [52–54].

Material	Characteristic Peaks (cm ⁻¹)	Functional Group	Assignment
Epoxy (control)	2926	C-H	stretching vibrations
	1608	C=O	(carbonyl) stretching vibrations
	1509	C-C	stretching vibrations of the aromatic ring
	1243	C-O-C	stretching of the oxirane ring
Glass fiber	906	Si-O-Si	stretching vibrations
	3400	-OH	stretching vibrations
Bambo fiber	1037	C-O	stretching vibrations
	821	C-O-C	bending vibrations of the oxirane ring

3.3. SEM and FTIR

The FTIR spectra of the composite materials are shown in Fig. 11(a) and (b). Fig. 11(a) shows that the control specimen epoxy exhibits significant peaks around 3000–2800 cm⁻¹, indicating the presence of C-H groups, and peaks at 1750–1600 cm⁻¹ correspond to the carbonyl (C=O) groups. Bamboo fiber shows dominant peaks around 3400 cm⁻¹, indicating the presence of -OH groups from water or moisture, and peaks at 1000–1100 cm⁻¹, indicating C-O groups from the lignin and hemicellulose structures. The spectrum shows weak peaks for glass fiber due to its inorganic nature, which is not highly active in FTIR, with peaks around 1000–500 cm⁻¹ associated with Si-O-Si bonds. Table 1 presents the characteristic FTIR peaks of these materials, supported by Refs. [52–54], providing a detailed assignment of functional groups and their corresponding vibrations.

In Fig. 11(b), the FTIR spectrum of the BBBB composite is dominated by bamboo characteristic -OH and C-O peaks, indicating minimal chemical interactions between bamboo and the epoxy matrix. This weak interaction is attributed to the hydrophilic properties of bamboo, which reduce compatibility with the hydrophobic epoxy matrix, leading to poor load transfer and adhesive failure. In contrast, the GGGG composite spectrum was dominated by glass fiber Si-O peaks, reflecting strong matrix adhesion, but limited chemical modifications. Additional peaks observed at 1509 cm⁻¹, 1243 cm⁻¹, and 821 cm⁻¹ in the GGGG and BGGB composites correspond to interactions between the epoxy matrix and the oxirane ring, suggesting potential chemical bonding, while no such additional peaks were found in BBBB and GBBG. The hybrid composites BGGB and GBBG display spectra with peaks from both bamboo -OH groups and glass fiber Si-O-Si bonds, indicating the coexistence of bamboo and glass fiber characteristics. The reduced intensity of -OH peaks in BGGB and GBBG suggests a partial reduction in the bamboo moisture content and improved interfacial bonding due to

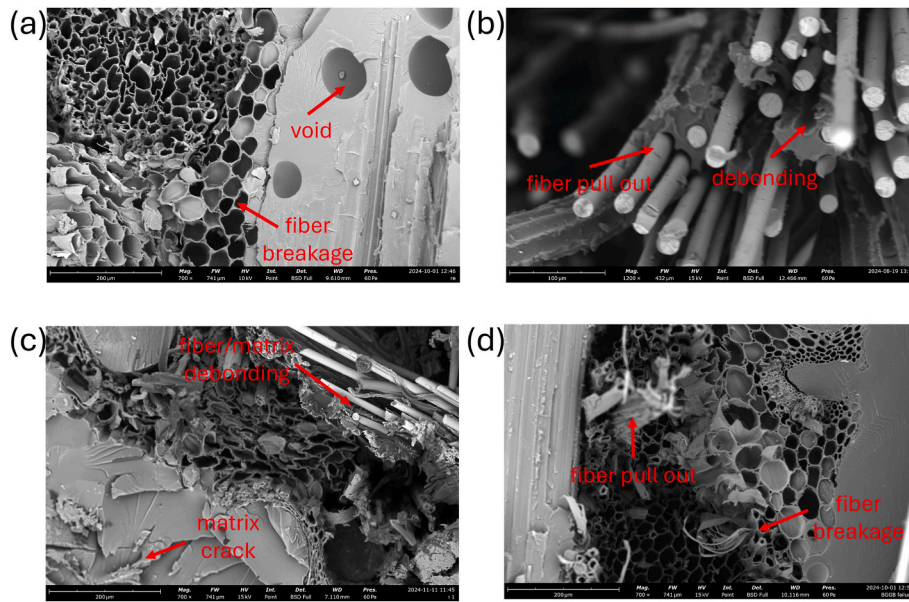


Fig. 12. SEM observation results of (a) BBBB, (b) GGGG, (c) GBBG, (d) BGGB.

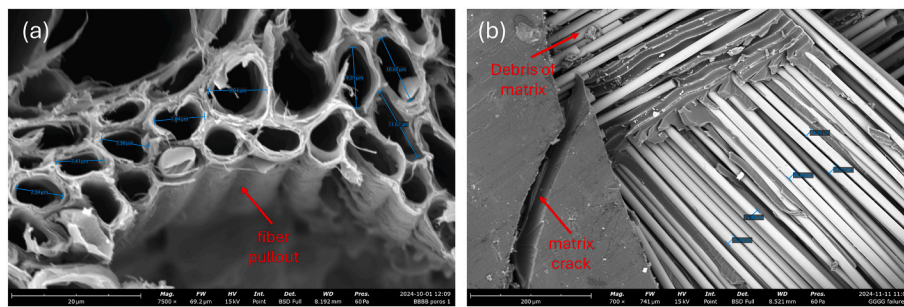


Fig. 13. SEM images of composite failure modes: (a) BBBB composite and (b) GGGG composite.

hybridization. These FTIR results provide valuable insights into the chemical composition, compatibility, and fiber-matrix interactions in bamboo-glass hybrid composites.

After tensile testing, Fig. 12(a)–(d) illustrate the fracture morphologies of BBBB, GGGG, GBBG, and BGGB composites. Fig. 12(a) shows the porous bamboo structure in BBBB, with visible voids that reduce tensile and flexural strength, while smooth areas suggest adhesive failure at the bamboo-matrix interface, explaining BBBB higher strain but lower tensile strength compared to GGGG. Fig. 12(b) highlights the dense glass fiber arrangement in GGGG, ensuring superior tensile strength and stiffness through uniform load distribution, although fiber-matrix debonding remains a primary failure mechanism. Fig. 12(c) reveals fiber-matrix debonding and matrix cracks in GBBG, particularly at the bamboo-glass interface, indicating stress concentrations and challenges in adhesion between materials with differing properties, despite glass fibers enhancing the rigidity. Fig. 12(d) shows the fiber pull-out and breakage in BGGB, particularly in bamboo layers, reflecting the weaker adhesion and lower tensile strength of bamboo fibers due to their hydrophilic and porous nature, leading to ineffective load transfer and early failure under tensile stress.

For further analysis, Fig. 13(a) and (b) provide insights into the structural characteristics and interfacial bonding of the composites. In Fig. 13(a), the BBBB composite shows bamboo fiber pull-out with pore sizes ranging from 7 to 11.67 μm , highlighting the presence of voids and a porous structure. The clean pull-out observed on the bamboo fibers indicates poor interfacial bonding between the bamboo and epoxy matrix, which can be attributed to the potential impact of hydrophobic

interactions between the bamboo fibers and epoxy matrix. These interactions weaken the adhesion at the interface, reducing the load-transfer efficiency. In contrast, Fig. 13(b) shows matrix cracking and debris around the glass fibers in the GGGG composite, where the glass fibers measured 14–16 μm in diameter. The matrix debris visible around the fibers suggests strong adhesion prior to failure, as the matrix material adhered to the fiber surfaces during the fracture. This behavior reflects the brittle nature of the composite and the high load-carrying capacity of the glass fibers, which can withstand significant stress before interface debonding becomes the dominant mode of failure. The observed matrix debris and cracking alongside intact glass fibers indicate that the failure primarily occurs within the matrix rather than the fibers, underscoring the robust nature of glass fibers under applied loads.

Overall, the SEM images support the mechanical findings, indicating that pure bamboo composites offer greater flexibility with lower strength, pure glass composites provide higher rigidity and strength, and hybrid composites strike a balance, with the stacking sequence influencing the efficiency of this balance.

3.4. Discussion

The GGGG composite exhibited the highest tensile strength, while BBBB showed the lowest strength, highlighting the superior reinforcing effect of the glass fibers. Although bamboo composites have lower tensile strength, their lightweight nature makes them ideal for weight-sensitive applications. In hybrid configurations, such as BGGB and GBBG, the addition of glass fibers increased the tensile strength by

24–30 % and flexural strength by 16–58 %, demonstrating their significant contribution to rigidity and overall mechanical performance. The high stiffness of the glass fibers significantly enhanced the overall rigidity of the hybrid composites. With their superior tensile strength and elastic modulus, glass fibers act as a structural backbone, reinforcing the composite matrix and improving load transfer. The stacking sequence significantly influences the rigidity, strength, and stiffness of hybrid composites under tensile and flexural loading [55–57]. In tensile tests, BGGB achieves higher tensile strength (87.24 MPa) than GBBG (83.87 MPa) due to bamboo fibers on the outer layers providing more uniform stress distribution, though failures include bamboo fiber pull-out and glass fiber breakage. Conversely, GBBG, with glass fibers on the outer layers, offers higher stiffness but shows less uniform stress distribution and failure at bamboo-glass interfaces due to the higher volume fraction of bamboo compared to glass fibers. In flexural tests, BGGB outperforms GBBG with a flexural strength of 99.16 MPa compared to 72.79 MPa, due to the placement of glass fibers in the outer layers. These layers endure the highest stress during bending, benefiting from the high stiffness and compressive strength of the glass fibers, which enables better load distribution and resistance to failure. Conversely, BGGB with bamboo fibers in the outer layers are more prone to deformation and early failure because of their lower compressive strength. The stacking sequence of bamboo and glass layers significantly influences the mechanical performance, with glass fibers in the outer layers bearing the highest stresses, while bamboo fibers in the core enhance energy absorption and reduce the overall weight of the composite [58].

Hybrid composites offer a unique combination of lightweight properties and high mechanical performance, making them well suited for applications requiring strength and weight efficiency. BGGB and GBBG exceed the specific strength of GGGG in tensile testing because of their lower density, whereas GBBG approaches the specific strength of GGGG in flexural tests. The integration of bamboo fibers reduces the overall weight of the composite, resulting in a higher strength-to-weight ratio compared to pure glass fiber composites. This balance of properties highlights the potential of hybrid composites for weight-sensitive applications [59]. Their specific tensile and flexural strengths make them particularly advantageous for sports equipment, such as hiking backpack frames, bicycle frames, and protective gear, such as helmets and shin guards, where lightweight durability is critical. By combining lightweight bamboo flexibility with glass fiber rigidity, these composites provide excellent performance, durability, and ergonomics, thereby meeting the demands of modern sports and outdoor applications.

Microscopic and SEM observations provided detailed insights into the failure mechanisms and structural characteristics of bamboo, glass fiber, and hybrid composites. In the BBBB composite, SEM analysis revealed large pores and voids inherent to the bamboo cellular structure, contributing to its low density and high flexibility but reducing its tensile and flexural strengths. Bamboo porous cellular structure creates stress concentration points that weaken its tensile strength by promoting crack initiation and propagation under tensile loads. However, the porosity also contributes to its strain capacity and flexibility, as the hollow and thin-walled fibers allow for greater deformation before failure, explaining the BBBB higher strain but lower tensile strength and stiffness compared to GGGG. The smooth fracture surfaces further indicate adhesive failure at the bamboo-matrix interface, which is attributed to its hydrophilic nature and porous structure that weakens the interfacial bonding and load transfer efficiency [60]. In contrast, the GGGG composite exhibited a densely packed, uniform fiber arrangement with minimal porosity, as observed in the SEM images. This structure supports superior tensile strength and stiffness, with failure occurring primarily through fiber-matrix debonding rather than fiber breakage. Microscopic observations during flexural tests confirm this, showing that GGGG maintains load sharing after fiber breakage, enhancing its flexural strength. For the hybrid composites BGGB and GBBG, SEM and microscopic analyses revealed mixed characteristics and failure modes. The fiber pull-out observed in the BGGB and GBBG tensile tests

highlights the weaker adhesion of bamboo fibers compared to glass fibers, disrupting the tensile stress distribution and leading to pull-outs. During flexural testing, BGGB exhibited delamination due to poor bamboo-glass bonding, whereas GBBG demonstrated better flexural performance but experienced fiber wrinkling during compression and breakage in tension, with failure concentrated at the bamboo-glass interface. Cracks are frequently initiated in bamboo fibers owing to their low tensile strength and porous structure, making them prone to failure. Unlike single-material composites with uniform stress distributions and simpler failure modes, hybrid composites exhibit localized stress concentrations and mixed failure mechanisms due to material heterogeneity. The buckling or fiber wrinkles observed in GBBG during flexural tests are primarily caused by a mismatch between the mechanical properties of glass and bamboo fibers [61]. Glass fibers, with high stiffness, are less adaptable to compressive stress, while bamboo fibers, being more flexible, deform more easily. This difference creates an uneven stress distribution, leading to localized buckling in stiffer glass fibers. This buckling phenomenon reduces the energy absorption capacity of the composite because it decreases the stress that the material can withstand before failure. Consequently, the structural integrity and energy-dissipation efficiency of the hybrid composite were compromised. These mixed failure modes underscore the challenge of achieving uniform stress distribution in hybrid composites, complicating their mechanical performance compared with single-fiber composites such as GGGG. At the microscopic level, the interaction between bamboo and glass fibers in hybrid composites creates a synergistic balance that mitigates the limitations of each fiber. Bamboo fibers, with their lightweight and flexible nature, benefit from their low density and cellular structure, allowing them to absorb energy during deformation. However, bamboo fibers are limited by their weak tensile strength and matrix adhesion, making them prone to pull-out under stress. Glass fibers, by contrast, provide high tensile strength and stiffness, acting as a structural backbone with strong matrix bonding for efficient load transfer and crack bridging. These limitations can be addressed by optimizing the bamboo-matrix interface. Bamboo hydrophilic nature and porous structure, which weaken adhesion and reduce load transfer, can be improved through surface treatments like alkali or silane to enhance bonding. The strategic placement of glass fibers in high-stress zones improves load distribution and stiffness. Additionally, matrix modifications with compatibilizers or nanofillers further strengthen the interfacial bonding, while functional coatings reduce delamination and fiber pull-out [12]. These optimizations enable hybrid composites to achieve tensile strength and modulus comparable to those of GGGG composites while retaining the lightweight benefits of bamboo, making them ideal for strength-sensitive and weight-efficient applications. Overall, the findings highlight that bamboo porosity, although beneficial for reducing density, negatively impacts mechanical integrity, making the stacking sequence critical for optimizing hybrid composite performance.

The FTIR analysis highlights bamboo fibers natural moisture content, as indicated by the strong –OH stretching peak at 3400 cm^{-1} . This moisture, inherent to bamboos lignin and hemicellulose composition, adversely affects its compatibility with the hydrophobic epoxy matrix. The hydrophilic nature of bamboo results in weak interfacial bonding, leading to adhesive failure mechanisms, such as fiber pull-out, which reduce the tensile and flexural performance of bamboo-based composites by limiting effective stress transfer at the interface. Additional peaks observed at 1509 cm^{-1} , 1243 cm^{-1} , and 821 cm^{-1} in the GGGG and BGGB composites correspond to interactions between the epoxy matrix and the oxirane ring, indicating potential chemical bonding. These chemical bonds enhance matrix adhesion with glass fibers, as reflected in the Si–O stretching peak at 906 cm^{-1} , which underscores strong matrix-glass fiber interactions. This observation also emphasizes the weak chemical bonding between bamboo fibers and the matrix, as no such additional peaks were found in BBBB and GBBG. This lack of significant chemical interaction between bamboo fibers and the epoxy

Table 2
Mechanical properties of the bamboo-glass hybrid and other hybrid composites.

Fiber composition	Fabrication Method	Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus (GPa)	Density (g/cm ³)	Ref.
Bamboo-Glass Fiber	Vacuum Infusion	87.24	99.74	5.4	1.018	[this work]
Jute-Glass Fiber	Hand-Lay Up	83.02	157.31	21.234	1.27	[24]
Ramie-Glass Fiber	Compression Molding	78–95	130	11	–	[62]
Banana-Glass Fiber	Hand-Lay Up + Vacuum Bag	72.5	167.3	7.1	0.96	[63]

matrix further highlights the critical role of glass fibers in reinforcing hybrid composites through robust chemical bonding.

Table 2 presents a comparative analysis of the mechanical properties of bamboo-glass hybrid composites with other hybrid composites reported in the literature, including jute-glass, ramie-glass, and banana-glass composites. The bamboo-glass composite fabricated using the Vacuum-Assisted Resin Infusion (VARI) method demonstrates tensile and flexural strengths of 87.24 MPa and 99.74 MPa, respectively, which are superior to those of ramie-glass and banana-glass composites. Additionally, the bamboo-glass composite achieved an optimal density of 1.018 g/cm³, highlighting its lightweight advantage over higher-density composites, such as jute-glass (1.27 g/cm³). The superior properties are attributed to the VARI method, which ensures uniform resin distribution and minimizes void content, providing an advantage over the hand lay-up or compression molding methods used in other studies. These findings emphasize the significance of bamboo-glass hybrid composites as lightweight, high-performance materials, and demonstrate the importance of advanced fabrication techniques and fiber hybridization for achieving a balance of strength, stiffness, and reduced weight in composite applications.

The application of composite laminates in industry and daily life has been reported [39,64]. The hybrid laminates that consist of (natural and synthetic fibers) improved mechanical and thermal properties while remaining cost-effective and environmentally friendly [65,66]. In specific, the application of hybrid laminates is applicable to be applied in various sectors such as in civil construction and furniture, and specific part in automotive applications [67]. This approach requires extra treatment, such as mercerization and silane coating, which can enhance the compatibility with matrices and boost the bonding performance between natural and synthetic fibers. In structural applications, bamboo composites are proven can be used in different sections such as: beams, flooring, and even retrofitting infrastructure [68,69]. Several researchers reported that the hybridization of bamboo with synthetic fibers such as glass fiber improves durability in harsh environments, making it suitable for coastal or humid climates [70]. Although hybrid bamboo and synthetic fibers can be applied in different applications, limitations related to their uniformity, presence in large-scale applications, complex fabrication and treatment, high investment, and a lack of standardized testing protocols for hybrid composites, especially those involving natural fibers, limit their adoption in regulated industries such as aerospace [68,71].

4. Conclusion

This study investigated the mechanical behavior of bamboo-glass fiber hybrid composites, focusing on the effects of fiber type, density, volume fraction, and stacking sequence under tensile and flexural loads. The findings highlight the following key observations and implications.

- **Performance Enhancement:** Bamboo-glass hybrid composites showed 24–30 % higher tensile strength and 16–58 % improved flexural strength compared to pure bamboo composites.
- **Stacking Sequence Effect:** BGGB exhibited superior tensile strength, while GBBG exhibited higher flexural strength, highlighting the importance of the fiber arrangement.

- **Microstructural Findings:** SEM revealed bamboo porous structure and weak matrix bonding as failure points, while glass fibers provided strong reinforcement and better load transfer.
- **FTIR Insights:** Glass fibers formed strong chemical bonds with the matrix, while bamboo fibers showed weak adhesion due to hydrophilicity.
- **Comparative Advantage:** VARI-fabricated bamboo-glass composites outperformed jute-glass and banana-glass composites in terms of strength and density, demonstrating suitability for lightweight and high-performance applications.
- **The hybrid composites lightweight and high strength-to-weight ratio** make them suitable for applications requiring optimized mechanical performance, such as sports equipment and automotive components.

In summary, bamboo-glass fiber hybrid composites offer a promising balance between weight reduction and mechanical strength. By optimizing the stacking sequences and addressing interfacial bonding challenges, these composites have emerged as sustainable and high-performance materials suitable for advanced engineering applications. Future studies should explore surface treatments, such as alkali or silane, to improve bamboo fiber-matrix adhesion. Matrix modifications, including the incorporation of nanofillers or compatibilizers, can further enhance load transfer efficiency. Moreover, evaluating the environmental durability of these composites under humidity, temperature, and UV exposure will ensure their performance and longevity for practical applications.

CRedit authorship contribution statement

Nugroho Karya Yudha: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Alvin Dio Nugroho:** Writing – review & editing, Investigation, Formal analysis. **Wahyu Erlangga:** Investigation. **Jamasri:** Supervision, Writing – review & editing. **Bodo Fiedler:** Writing – review & editing, Supervision. **Muhammad Akhsin Muflikhun:** Writing – original draft, Writing – review & editing, Supervision, Resources, Conceptualization.

Data availability

The raw data and datasets supporting the findings of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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