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Tensile, Flexural, and Water Absorption Properties of Nano-Silica Enhanced Kenaf/Flax/Glass Fiber-Reinforced Epoxy Hybrid Biocomposites for Sustainable Development

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ABSTRACT

Fiber-reinforced composites are widely used in various industries. Hybridization improves the mechanical strength and versatility of these materials. Specifically, combining plant fibers with synthetic fibers enhances performance of biocomposites and environmental sustainability. This study fabricated five fiber-reinforced epoxy biocomposites (KKKKK, GKKKG, GKFKG, GFKFG, and GKGKG) from kenaf (K), flax (F), and glass (G) fibers using hand lay-up and vacuum bagging techniques. The epoxy matrix was mixed with nano-silica. These biocomposites were evaluated for tensile and flexural properties, water absorption, physical behavior, and specific strength. The results showed that hybrid fiber composites had significantly higher mechanical properties than pure kenaf composites. The tensile and flexural strengths of GFKFG were 103.79% and 196.32% higher than KKKKK, respectively. Additionally, hybrid biocomposites had superior moisture absorption, with GKFKG absorbing 45.59% and 48.52% less moisture in distilled water and artificial seawater, respectively, compared to KKKKK. Hybrid biocomposites also exhibited higher specific strength and thinner thickness, making them suitable for lightweight and compact structures. In conclusion, hybridizing kenaf fibers with flax and glass fibers enhances performance of biocomposites, promoting their use in marine, aerospace, and automotive applications, contributing to sustainable development.

摘要

纤维增强复合材料广泛应用于各个行业。混合提高了这些材料的机械强度和通用性. 具体而言，将植物纤维与合成纤维结合可以提高生物复合材料的性能和环境可持续性. 本研究使用手工铺层和真空袋技术，从红麻 (K)、亚麻 (F)和玻璃 (G)纤维中制备了五种纤维增强环氧生物复合材料 (KKKKKKK、GKKKG、GKFKG、GFKFG和GKGKG). 环氧树脂基质与纳米二氧化硅混合. 对这些生物复合材料的拉伸和弯曲性能、吸水率、物理行为和比强度进行了评估. 结果表明，混杂纤维复合材料的力学性能明显高于纯红麻复合材料. GFKFG的拉伸强度和弯曲强度分别比KKKKK高103.79%和196.32%. 此外，混合生物复合材料具有优异的吸湿性，与KKKKK相比，GKFKG在蒸馏水和人工海水中的吸湿性分别降低了45.59%和48.52%. 混合生物复合材料还表现出更高的比强度和更薄的厚度，使其适用于轻质紧凑的结构. 总之，红麻纤维与亚麻和玻璃纤维的杂交提高了生物复合材料的性能，促进了它们在海洋、航空航天和汽车应用中的应用，为可持续发展做出了贡献.

KEYWORDS
Kenaf fiber; flax fiber; mechanical properties; water absorption; nano-silica; sustainable materials

关键字
红麻纤维; 亚麻纤维; 机械性能; 吸水率; 纳米二氧化硅; 可持续材料

Introduction

The manufacturing of weight-sensitive products depends on lightweight materials, and the increasing market demand and environmental needs are accelerating the innovation of environmentally sustainable lightweight materials (Andoko et al. 2023; G. S. Kumar et al. 2023; Sreenivas, Krishnamurthy, and Arpitha

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2020). The most significant advantage of these materials lies in their capacity to reduce structural weight while simultaneously improving fuel efficiency, minimizing emissions, and enhancing operational maneuverability (Sathyanarayana et al. 2023). Fiber-reinforced composites, as lightweight materials characterized by their superior mechanical performance and low density, play a crucial role in applications where fuel efficiency and weight reduction are critical considerations, particularly in aerospace, marine, and automotive engineering (Huang et al. 2024; Rubino et al. 2020; Verma, Shukla, and Kumar Shukla 2022). Conventionally, fiber-reinforced composites employing synthetic fibers as the principal reinforcement demonstrate superior mechanical performance (Han et al. 2018; Rajak, Wagh, and Linul 2021; Sayam et al. 2022). However, the production of synthetic fibers depends on nonrenewable petroleum resources and presents significant environmental challenges related to disposal and waste management (Acharya et al. 2021; Yashas Gowda et al. 2022). The demand for environmentally sustainable alternatives in the industrial sector has become increasingly urgent (Hawary et al. 2023). Among the many available alternatives, natural fibers have proven to be a promising and viable substitute for synthetic fibers (Balakrishnan, Thariq Hameed Sultan, Syazwani Shahar, Yeshwant Nayak, et al. 2024; Lotfi et al. 2021). These natural fibers exhibit considerable potential in improving both the mechanical performance and thermal stability of composite materials (S. Kumar et al. 2023). In addition, natural fiber-based composites contribute to lower material density, facilitating overall weight reduction in structural components.

Kenaf demonstrates remarkable adaptability across diverse growing conditions (Al-Mamun et al. 2023). Typically, kenaf grows to a height of 3.5 to 4.5 m within a short growth cycle and has a high production of bast fiber (Adole et al. 2019; Xu et al. 2020). Kenaf bast fiber exhibits excellent mechanical properties, with a tensile strength ranging from 223 to 1191 MPa, a density of 1.2 to 1.5 g/cm^3, and a specific strength of 148.7 to 794 N m/g, making the fiber highly suitable as a reinforcement in composites (Huang et al. 2025). In addition, kenaf has broad applications in the automotive industry, food, and medical fields and is a significant commodity crop in Malaysia (Vayabari et al. 2023). Expanding its applications will positively impact the local economy and enhance farmers' confidence in cultivation. Moreover, these cellulose fiber-reinforced biocomposites made from natural fibers offer superior economic and environmental benefits while contributing to carbon footprint reduction (Bi et al. 2024; Crupi et al. 2023; Radoor et al. 2020). Therefore, many studies have been focused on the development of kenaf fiber-based biocomposites (A. Khan et al. 2023; Lee et al. 2021). Both the manufacturing method and matrix selection have a direct impact on the mechanical properties of the composite (Huang et al. 2025). For example, Mishra et al. (2024) employed the hand lay-up technique to fabricate 4-ply kenaf fiber-reinforced polyester laminates, reporting tensile and flexural strengths of 35.78 MPa and 42.91 MPa, respectively. However, Malik et al. (2024) utilized the vacuum infusion molding technique to fabricate 5-layer kenaf fiber laminates, achieving tensile and flexural strengths of 58.6 MPa and 100.1 MPa, respectively.

Evaluating the mechanical properties of kenaf fiber-reinforced composites is essential to determine their suitability for industrial applications. Mechanical testing is crucial for assessing the safety and reliability of these biocomposites (Huang et al. 2025). Normally, the mechanical properties of fiber composites include tensile testing, bending testing, compression testing, impact testing, etc (Saba, Jawaid, and Sultan 2019). However, the inherent strength limitations of single kenaf fiber-reinforced composites restrict their feasibility in practical applications (Malik et al. 2024). Fortunately, hybridization technology provides a viable solution to address the low strength of these biocomposites. The hybridization of natural and synthetic fibers, combined with adjustments in stacking sequence, significantly alters the physical and chemical properties of biocomposites (Andrew and Dhakal 2022; Zhao et al. 2023). Hybrid fiber-reinforced composites are attracting a lot of attention for their better balance between environmental preservation, cost control, and performance (Calabrese et al. 2019). Kenaf fiber demonstrates excellent compatibility in hybridization with other fibers, enhancing the overall performance of biocomposites. Additionally, strategic hybridization techniques facilitate the development of environmentally friendly and sustainable biocomposites. Moreover, incorporating multiple reinforcing materials together enhances the synergistic effect, significantly improving biocomposites' mechanical properties (Haris et al. 2022). The hybrid biocomposites incorporating plant fibers and particulate fillers exhibit significantly improved thermal, mechanical, and microstructural properties (Sari, Suteja, Hidayatullah, et al. 2025; Sari, Suteja, and Syafri 2025; Sari, Suteja, Mavinkere Rangappa, et al. 2025). Furthermore, hybridizing different types of fibers can also enhance the water resistance property of composites (Maslinda et al. 2017). Abidin et al. (2023) fabricated GKGKG and

KGKGK hybrid composites of kenaf and glass fibers using the hand lay-up method. Their findings revealed that altering the stacking order significantly influenced mechanical properties. The tensile strength of GKGKG and KGKGK composites reached 147.64 MPa and 121.45 MPa, while their flexural strength reached 188.99 MPa and 155.22 MPa, respectively. Observably, composites with glass fiber as the outer layer exhibited superior mechanical performance compared to those with kenaf as the outer layer. These values markedly exceed the mechanical performance of single kenaf fiber-reinforced composites reported by Mishra et al. (2024) and Malik et al. (2024). Composites incorporating kenaf fibers with other plant fibers also exhibit satisfactory performance; however, their mechanical properties remain inferior to those reinforced with synthetic fibers (T. Khan et al. 2021; Razali et al. 2021).

Plant fibers primarily consist of cellulose, hemicellulose, lignin, pectin, and wax (Zwawi 2021). Although these substances play a crucial role in keeping the structural integrity of plant fibers, they also restrict the mechanical performance of these fibers (Komuraiah, Shyam Kumar, and Durga Prasad 2014). Simultaneously, this constraint on mechanical performance may also be expressed in plant fiber-based composites. In addition, the cell walls of plant fibers contain a large number of hydroxyl groups, leading to the hydrophilicity of plant fibers (Kabir et al. 2012). Therefore, the removal of undesirable impurities from plant fiber's surface and the reduction of interfacial incompatibility between hydrophilic plant fibers and hydrophobic polymers become key challenges in improving the performance of biocomposites (Amiandamhen, Meincken, and Tyhoda 2020; Ramesh 2016). Pre-treating natural fibers to eliminate impurities before fabrication is crucial for improving the material properties of natural fiber-based composites. Soaking plant fibers in a sodium hydroxide solution serves as an effective and practical pretreatment method (Sari et al. 2018), which can remove impurities and hydroxyl groups from these cellulose fiber surfaces (Kenned, Sankaranarayanasamy, and Suresh Kumar 2021). Moreover, the alkali treatment strengthens the interfacial adhesion between cellulose fibers and matrix, thereby enhancing the mechanical properties and water resistance of biocomposites (Ganesan et al. 2020; Mohammed et al. 2023). However, prolonged exposure to high concentrations of NaOH solution can increase the risk of natural fiber structure deterioration (Fiore, Di Bella, and Valenza 2015; Ismail et al. 2021). NaOH treatment modifies the microstructure of natural fibers, rendering them more fibrillated and brittle (Ismail et al. 2021). Thus, carefully selecting appropriate alkali treatment parameters is essential for improving fiber quality. Feng et al. (2020) treated kenaf fibers with different concentration NaOH solutions (1%, 3%, 5%, and 7%) for 4 h and reported that the composite made from kenaf fibers treated with a 5% NaOH solution exhibited 15.35% and 12.82% higher tensile and flexural strengths than the composite made from untreated kenaf fibers. Ogunbode et al. (2022) observed that the water absorption of kenaf fibers decreased by 16% after treatment with a 5% NaOH solution, improving fiber surface adhesion. Mercerization also plays a comparably crucial role in the treatment process of flax fibers. The alkali treatment also exerts a substantial influence on the processing of flax fibers (Frącz, Janowski, and Bąk 2021). X. Xiao, Cheng, and Zhong (2022) investigated the pretreatment of plant fibers by applying NaOH solutions with four concentrations (1%, 5%, 10%, and 15%) and observed that flax/polypropylene composites produced from flax fibers treated with the 5 wt.% NaOH solution achieved the highest tensile strength.

Integrating nanoparticles or nano-components into composite materials is widely recognized as an effective strategy for improving their long-term durability (Nawaz et al. 2022, Sathish, Jayant Giri, and Makki 2024). These tiny components, with diameters between 1 and 100 nanometers, can create a powerful influence on composite materials (Mallakpour, Sirous, and Mustansar Hussain 2021; Tripathy and Biswas 2022; Zaghloul et al. 2021). Nanofillers at the fiber–polymer interface trigger an interlocking mechanism, optimizing interface binding and force transfer performance to enhance the overall performances of fiber-reinforced composites (Caldwell and Berg 2018; Zhou et al. 2022; X. Liu, Fang, and Gao 2023). Silicon dioxide is one of the economical and common nanofillers (Hassan et al. 2021; Hiremath et al. 2021). According to Jotiram et al. (2022), within the 1–5 wt.% silica filler range, the 2 wt.% silica nanofiller concentration led to the most significant improvements in the tensile, compressive, and impact strengths of kenaf/epoxy composites, increasing by 20.61%, 23.71%, and 22.88%, respectively. In another study, Chowdary et al. (2022) demonstrated that the addition of 4 wt.% of nano-silica substantially improved the mechanical properties of Sisal/Kevlar polyester composites, while the mechanical properties of the composites were reduced when adding more nanofillers. Arunkumar et al. (2023) investigated the effect of various concentrations of silica (0, 2.5, 5, 7.5, 10, and 12.5 wt.%) on the mechanical and water-absorbent properties of flax/silica-based hybrid polypropylene composites. Their findings indicated that the addition of silica nanoparticles significantly improved the mechanical properties of the composites. At a 10 wt.% nanoparticle concentration, the flexural and tensile strengths peaked at 50.97 MPa and 42.65 MPa, respectively, while the water absorption was concurrently reduced by 23.63% compared to the zero-added one. Yadav et al. (2022) fabricated epoxy/nano-silica composites and found that the composite exhibited peak tensile, bending, and impact strengths when the nanoparticle content reached 3%. Additionally, Emrahi, Rostamiyan, and Hashemi-Tilehnoee (2023) reported that the addition of nano-silica beyond 3 wt.% in composite materials led to localized agglomeration of nanoparticles, which in turn adversely affected the mechanical performance of the composites. Although the optimal addition of SiO_2 in the composite is still controversial, it is obvious that an excessive amount of the nanofiller will not be beneficial to the fiber composites.

Besides the above, the hygroscopic behavior of composites adversely affects the mechanical properties of fiber-reinforced composites (Dhakal et al. 2021; Fontaine, LeBlanc, and Shukla 2021; Pavan et al. 2019). The water molecules that penetrate into the interior of the composite material will weaken the bonding performance between the fibers and the matrix (Arul et al. 2024). It is imperative for the durability of biocomposites to efficiently limit and manage their water uptake throughout the cycle life. Previous studies have shown that both the alkaline treatment of natural fibers and the addition of nanofillers are effective methods for decreasing the water absorption of biocomposites (Chandrasekar et al. 2017; Raj et al. 2022; X. Liu, Fang, and Gao 2023). In this study, five types of five-ply fiber composite laminates were fabricated from kenaf, flax, and glass fiber fabrics using the hand lay-up method and vacuum bag molding process. A certain amount of nano-silica was added to the composite materials as a nano-filler to improve the bonding between the fibers and the matrix. Subsequently, these biocomposites were evaluated for their physical properties, mechanical performance, and moisture absorption characteristics using ASTM standardized test methods. To assess the benefits of hybridization, a pure kenaf fiber laminate was used as a control for comparison with the hybrid biocomposites. This research investigates the potential of kenaf fiber-based hybrid biocomposites. It lays a foundation for promoting the application of biocomposite materials. In addition, this study supports the wider use of natural fibers to replace synthetic ones, aiming to reduce the negative environmental impacts associated with man-made fibers.

Materials and methods

Fibers and matrix materials

In this study, natural fibers (kenaf and flax) and glass fibers were utilized to fabricate bio-laminates, as shown in Figure 1. Woven kenaf fabrics were purchased from Lembaga Kenaf dan Tembakau Negara (LKTN), Kota Bharu, Malaysia, with 0.68 mm thickness and 275 g/m^2 areal density. Woven glass fabrics were obtained from Shandong Fiberglass Group Co., Ltd., China, with 0.20 mm thickness and 220 g/m^2 of areal density. Woven flax fabrics, with a thickness of 0.40 mm and an areal density of 223 g/m^2, were procured from Zhanjiang Xuesong Weaving Factory, China. The 20 nm nano SiO_2 was purchased from Beesley New Materials (Suzhou) Co., Ltd., China, and exhibited bulk densities of 0.16 g/cm^3. The epoxy

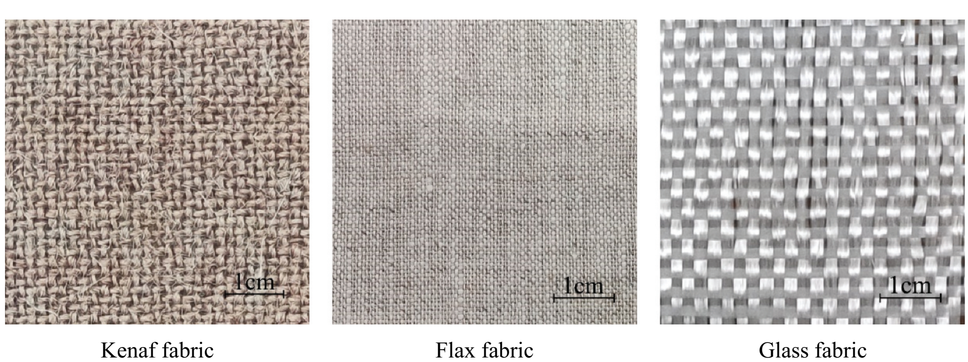


Figure 1. Appearance of kenaf, flax, and glass fabrics.

system used as the matrix in this research was supplied by IZE Solution SDN BHD, Malaysia, with a reported density of 1.10 g/cm^3.

Processing methods

Alkali treatment of plant fibers

All natural fibers underwent alkali treatment using NaOH solution to remove surface impurities and enhance the adhesion between the fibers and the matrix (Mahesh, Mahesh, and Harursampath 2022; X. Xiao, Cheng, and Zhong 2022). According to the designed laminate sizes, woven plant fabrics were cut into 450 mm × 350 mm. The cut fabrics were then treated with 5% NaOH solution for 4 h at room temperature (25℃). The alkali solution was prepared using solid sodium hydroxide pellets, supplied by Evergreen Engineering & Resources, Malaysia. In the alkali immersion period, the ratio of fabric to the solution is 1 to 20. Once the predetermined soaking time is reached, the natural fiber fabrics are removed from the NaOH solution and repeatedly washed with distilled water until the pH of the washing solution reaches a value within the range of 6.8 to 7.2. Subsequently, these fabrics are air-dried in the shade for 24 h and then placed in an oven at 60°C for 4 h to further the drying process.

Stacking sequence and sample nomenclature

All laminates used in this research were configured with five layers of woven fabric. KKKKK is a five-layer pure kenaf fabric composite laminate. However, these hybrid laminates were manufactured from multiple types of fiber fabrics, incorporating glass fiber as the exterior layers for enhanced performance. For instance, the reference laminate, GKKKG, uses three plies of kenaf fabrics as interior reinforcement, placed between two glass fabrics. Other hybrid laminates, such as GKFKG, GFKFG, and GKGKG, employed various stack sequences of kenaf and flax fiber fabrics placed between glass fabrics. Figure 2 shows the naming and stacking sequence structure of these laminates.

Fabrication of bio-laminates

Initially, following the processing steps, as shown in Figure 3(a-e), to prepare the matrix solution, add 3 wt.% nano-silica (the nanofiller was added in two steps, 1.5 wt.% each time to prevent agglomeration) and the hardener into epoxy resin. This process involves the following steps:

(i) Preparation of Mixture I:
- 1.5 wt.% nano-silica was added to the epoxy resin and stirred for 30 min to obtain Mixture I.

(ii) Preparation of Mixture II:
- 1.5 wt.% nano-silica was added to Mixture I and stirred again for 30 min to obtain Mixture II.

(iii) Preparation of the composite Matrix:

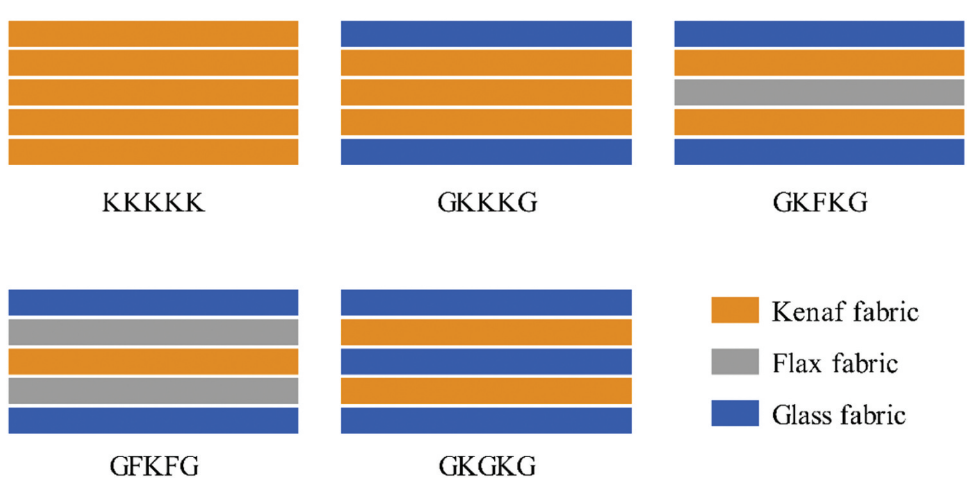
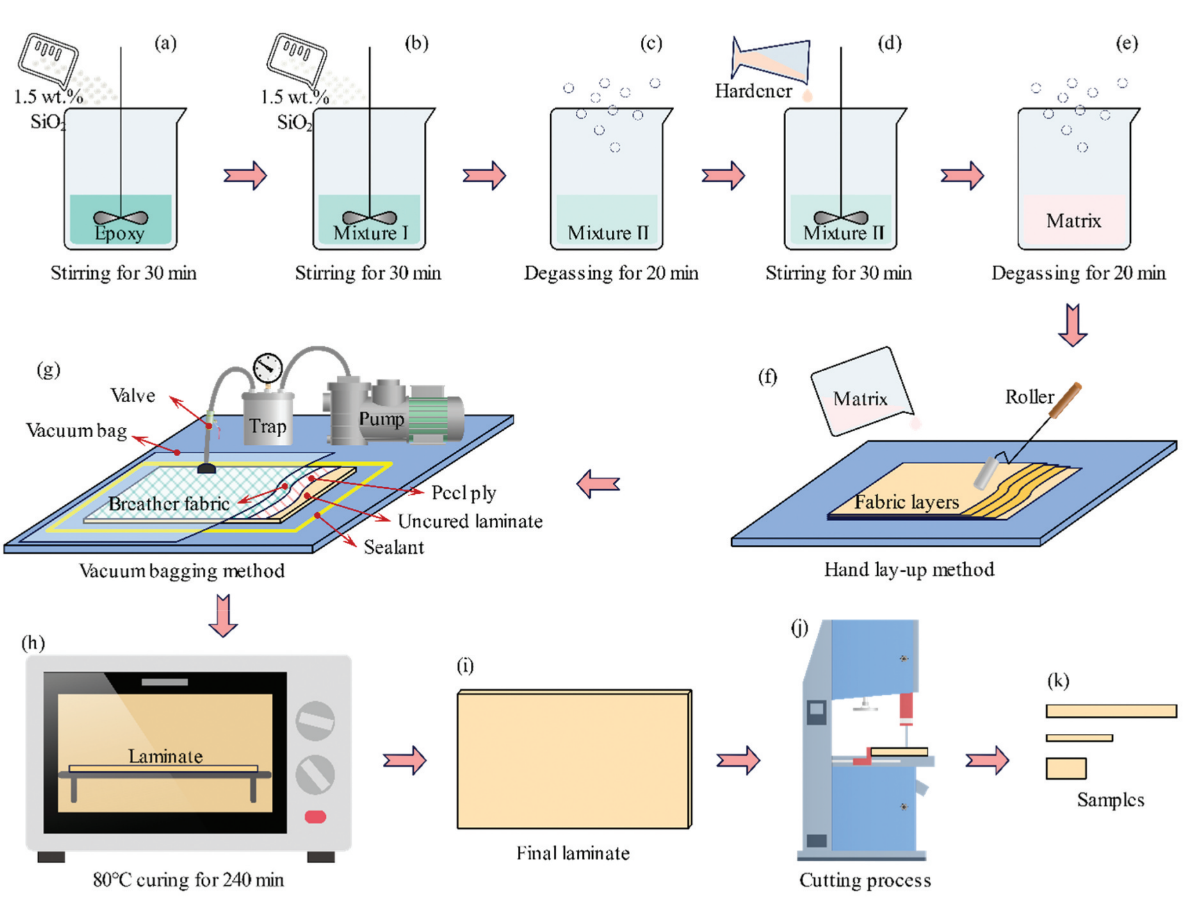


Figure 2. Kenaf fiber-based laminate types with different stack sequences.



Matrix fabrication and laminate processing.

- Mixture II was degassed for 20 min to remove air bubbles.
- The epoxy curing agent was added to Mixture II, maintaining a 3:1 weight ratio of epoxy resin to curing agent, and stirred for 30 min.
- The mixture with the curing agent was degassed for 20 min to obtain the composite matrix.

Subsequently, acetone was used to wipe the glass mold surface, ensuring the thorough cleaning of all contaminants before further processing. Then, a layer of release agent was evenly brushed onto the glass plate, achieving a dry thickness of 50–100 μm to aid in mold release and provide a smooth surface for the sample. Next, the fiber layers are sequentially stacked and fused to the matrix using a hand lay-up process and repeatedly rolled with a roller to eliminate air bubbles and promote fiber impregnation, as shown in Figure 3(f). Following this process, the vacuum bagging method was used to cure the laminate for 24 h at room temperature, as shown in Figure 3(g). The sealant tape was arranged around the perimeter of the laminate, and the peel ply and breather fabric were placed on top. Next, place the vacuum bag film over the assembly and press it firmly onto the sealant to establish an airtight area. A vacuum pump was used to evacuate the air within the sealed space. When reaching the desired vacuum pressure of −100 kPa, the valve on the hose was closed, and the condition was maintained during the curing period. Next, place the laminate in the oven for post-curing at 80°C for 240 min, as illustrated in Figure 3(h). Finally, the bio-laminates were collected, and then they were cut into specific sizes according to the ASTM standards for further research.

Experimental methods

ASTM standards were employed in this experiment, and five samples were prepared for each test to ensure data reliability.

Density measurement

Density is a fundamental property of composites, representing their unit weight. It is critical in calculating specific strength ratios and determining other material properties. The method for measuring the density of the composite samples in this study used Archimedes' principle, and the procedure followed ASTM D792 (Saba, Jawaid, and Sultan 2019). Composite samples were cut from laminates to dimensions of 76.2 × 25.6 mm. Samples were placed in a 25°C test environment for 48 h (Balakrishnan, Thariq Hameed Sultan, Syazwani Shahar, Azriff Basri, et al. 2024). The apparent weight of each sample was measured and recorded as a. Afterward, the sample was suspended on a wire and entirely immersed in distilled water, and the combined weight of the sample and wire was weighed and recorded as b. Subsequently, the sample was removed, and the weight of the partially submerged wire in water was measured and documented as w. Finally, the density of the test sample was calculated based on the following formula:

$$\rho_{composite} = \frac{a}{a + w - b}\rho_{water} \tag{1}$$

Where:
$\rho_{composite}$ = the density of the composite, g/cm^3,
ρ_{water} = the density of the distilled water, which is 0.997 at 25°C, g/cm^3.

Tensile testing

Tensile testing is commonly used to determine the tensile properties of composite laminates, such as tensile strength, modulus, and elongation at break. These properties are employed to evaluate the mechanical behavior of materials under axial tensile loading and are critical to the promotion and use definition of materials. In addition, tensile testing plays a crucial role in analyzing the failure-induced damage patterns in composite materials. These data will provide design ideas for the improvement of composite material. According to the ASTM D3039 standard demand, all the samples were prepared with a dimension of 250 × 25 mm cut from the laminates. Then, the MTS 810 system was employed to perform the tensile test, maintaining a crosshead speed of 2 mm/min (Manral et al. 2024).

Flexural testing

Flexural testing is widely used to evaluate the flexural mechanical properties of composite materials and is essential to analyze the material that needs to be applied for specific bending force applications. Flexural testing provides critical data for calculating flexural strength and modulus, enabling the evaluation of the composite material's stiffness and toughness, as shown in formulas 2 and 3. According to the requirements of ASTM D790, a three-point bending test system was used to evaluate the flexural behavior of the laminates. All the samples were prepared with dimensions of 127 × 13 mm cut from the laminates. Then, applying the MTS 810 system conducted the flexural test, adjusting the support span to specimen thickness ratio at 16:1. During the loading step, the rate of crosshead motion was controlled at 2 mm/min until the outer surface of the specimen fractured or the maximum strain reached 5.0%.

$$\sigma_f = \frac{3PL}{2bt^2} \tag{2}$$

$$E = \frac{L^3 m}{4bt^3} \tag{3}$$

Where:
σ_f = outer layer stress at loading point, MPa,
p = loading force, N,
L = support span, mm,
b = width of sample, mm,
t = thickness of sample, mm,
E = flexural modulus of elasticity, MPa,

m = Slope of the initial straight-line section of the load-deflection curve, N/mm.

Water absorption testing

Distilled water absorption

The hygroscopicity of natural fibers can significantly influence the performance of composite materials used in outdoor environments, especially when exposed to water. Water absorption in composite materials leads to volumetric swelling, surface distortion, and deterioration of mechanical properties (Abdurohman and Adhitya 2019). These effects are typically related to the rate of water absorption. In addition, water uptake may promote chemical degradation, lower electrical insulation, and encourage microbial growth, which negatively affects the material's durability and structural safety. Therefore, evaluating the water absorption behavior of biocomposites is essential for outdoor applications. By ASTM D570, water uptake specimens of 76.2 × 25.6 mm were fabricated. Their initial weight was measured before being submerged in distilled water, and their weight variations were systematically recorded until substantial saturation was achieved. The water absorption rate at moment t was subsequently calculated using the following formula:

$$Water\ Absorption(\%) = \frac{W_t - W_0}{W_0} \times 100 \tag{4}$$

Where:
W_0 = initial dry weight of the sample before immersion, g,
W_t = wet weight of sample at aging time t, g.

Artificial sea water absorption

To evaluate the suitability of composites for seawater applications, a seawater absorption test was performed under ASTM D570. The test procedure replicated the distilled water absorption test by substituting artificial seawater prepared following ASTM D1141. The various chemical components and weights required for the preparation of 10 l of artificial seawater are shown in Table 1.

Specific strength analysis

Specific strength is a key parameter that quantifies a material's load-bearing capacity relative to its mass. The index is in widespread use for assessing high-performance materials, which can be expressed as the ratio of the material's ultimate tensile strength to its density, as shown in the following formula.

$$Specific\ strength = \frac{Ultimate\ tensile\ strength}{Density} \tag{5}$$

Table 1. Chemical composition and weight in 10 L of artificial seawater.

S. No.	Chemical component	Weight (g)
1	$MgCl{\cdot}6H_20$	55.560
2	$CaCl_2$	5.790
3	$SrCl{\cdot}6H_20$	0.210
4	KCl	1.738
5	$NaHCO_3$	0.503
6	KBr	0.250
7	H_3BO_3	0.270
8	NaF	0.030
9	NaCl	245.340
10	Na_2SO_4	40.940

Table 2. Thickness, density, areal density, and component weight fractions of kenaf fiber-based biocomposites.

Sample	Thickness (mm)	Density (g/cm^3)	Areal density (g/cm^2)	Matrix weight fraction (wt.%)	Glass fiber weight fraction (wt.%)	Natural fiber weight fraction (wt.%)			Total fibers (wt.%)
						Kenaf	Flax	Total natural fibers	
KKKKK	3.748	1.195	0.448	69.3	–	30.7	–	30.7	30.7
GKKKG	3.455	1.244	0.430	70.6	10.2	19.2	–	19.2	29.4
GKFKG	3.277	1.267	0.415	70.8	10.6	13.2	5.4	18.6	29.2
GFKFG	2.597	1.284	0.333	65.2	13.2	8.2	13.3	21.6	34.8
GKGKG	2.861	1.298	0.371	67.4	17.8	14.8	–	14.8	32.6

Results and discussion

Physical properties

The fundamental physical properties of kenaf fiber-based laminates, including thickness, density, areal density, and material configuration weight fractions, are presented in Table 2. The thickness of the laminates in this study ranged from 2.60 to 3.75. Compared to hybrid laminates, single kenaf fiber laminate, KKKKK, has the greatest thickness. This is because the thickness of kenaf fabric is 0.675 mm, which is higher than that of flax fabric (0.402 mm) and glass fabric (0.200 mm). Also, benefitting from the lighter density of plant fibers than that of glass fibers, KKKKK has the lightest density. However, the thickness of the laminate makes for a high areal density character, reaching 0.448 g/cm^2. In addition, this composite has the highest level of plant fiber content of 30.7 wt.%. Comparing the weight of fibers in the laminate to the weight of the matrix, the more fiber content, the more matrix required. This is similar to previous research that the higher content of the natural fiber absorbed more epoxy resin when fabricating laminates (H. Xiao et al. 2023). Other hybrid composite laminates contain glass fibers, which significantly reduce the proportion of plant fibers. In the configuration, GKGKG, the plant fiber content is only 14.8 wt.%, representing a decrease of 51.79% compared to KKKKK. Moreover, the content of total natural fibers, including GKKKG, GKFKG, and GFKFG, is 19.2 wt.%, 18.6 wt.%, and 21.6 wt.%, respectively, demonstrating excellent biomaterial properties, although the results fall short compared to KKKKK. Furthermore, in contrast to the KKKKK, these hybrid configurations possess lighter areal densities and thinner thicknesses, which can reduce the weight and volume of the structures fabricated by them.

Tensile properties

All fabrics to fabricate samples were in plain-woven form with an equal number of fibers aligned in the warp and weft directions. During tensile loading, the applied force was aligned parallel to the warp fibers' direction. In the loading direction, the warp fibers bore the main load and ultimately fractured upon failure. The tensile strength, modulus, and elongation at break of pure kenaf fiber and hybrid kenaf fiber-based composites are pictured in Figure 4(a–c). KKKKK, the pure kenaf fiber-reinforced composite, exhibits the lowest tensile strength (50.56 MPa) and tensile modulus (4113.13 MPa) among all tested composites. However, the tensile behaviors of the hybrid composites are sharply increased by hybridizing glass fiber. A primary reason for this result is the inherently lower tensile strength of kenaf fibers relative to glass fibers. The hybrid composite, GKKKG, adopts a sandwich structure with glass fibers serving as the outer layers to enclose the kenaf fabric. GKKKG maintains the same total number of layers, and this configuration enhances the tensile strength by 62.70% compared to KKKKK, reaching 82.26 MPa. GKGKG is a variation of the GKKKG laminate, with a glass fiber fabric core layer substituting for the kenaf fiber fabric. Its tensile strength improves by 90.78% and 17.26% compared to KKKKK and GKKKG, respectively, reaching 96.46 MPa.

In Figure 4(a,b), GKFKG and GFKFG exhibit tensile strengths of 88.98 MPa and 103.38 MPa, respectively, along with tensile moduli of 6043.76 MPa and 6810.36 MPa. The tensile properties of GKFKG are between those of GKKKG and GKGKG. In addition, replacing two kenaf fabric layers with flax fabrics resulted in the composite with the highest tensile performance in the study. This discovery illustrated that using flax fabric as the core layer has a similar outcome as glass fiber, increasing tensile strength and

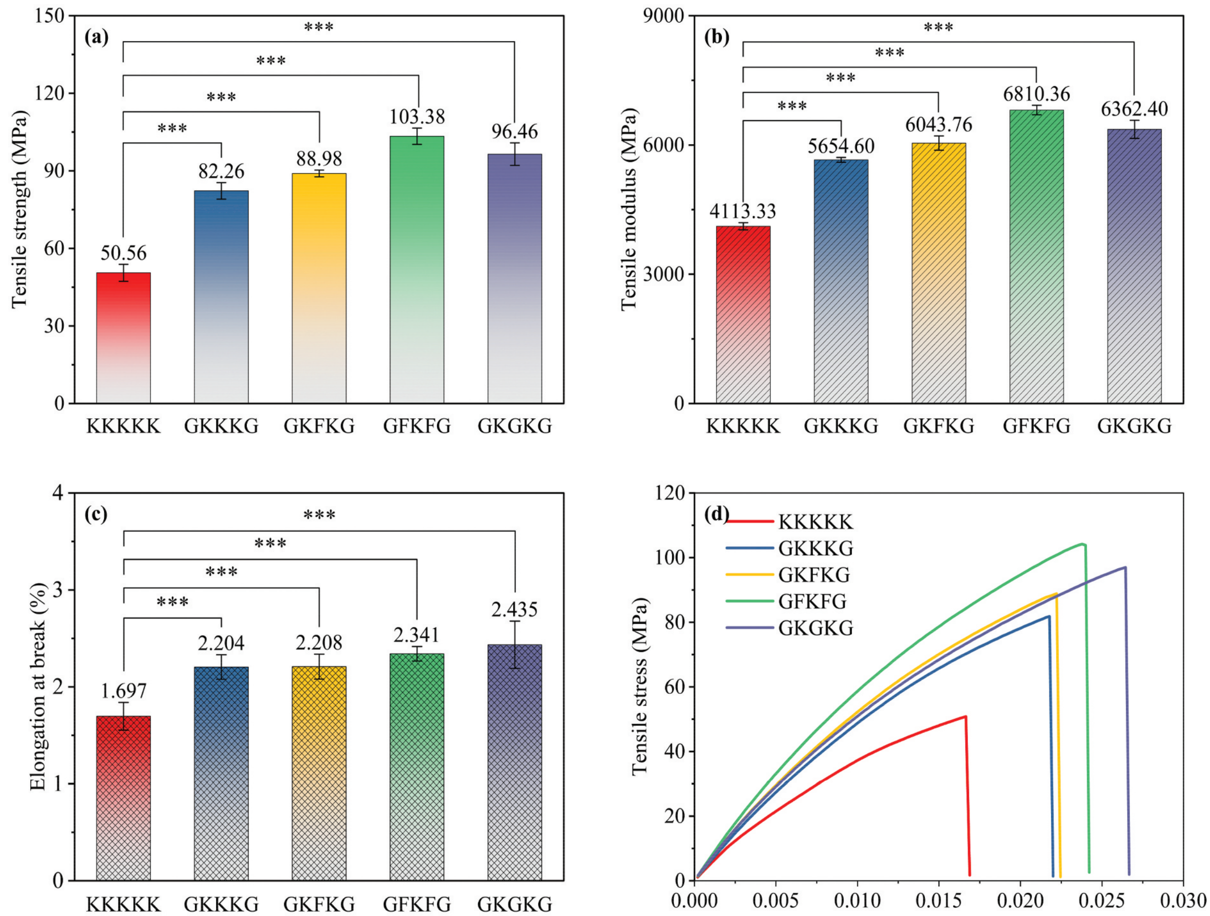


Figure 4. Tensile properties of kenaf fiber-based biocomposites: (a) tensile strength; (b) tensile modulus; (c) elongation at break; (d) stress–strain curve. Data are presented as mean±SD (n=5). Statistical significance was evaluated using one-way ANOVA and Tukey test (*$p \le .05$, **$p \le .01$, ***$p \le .001$).

modulus because of the flax fiber's extraordinary mechanical behavior. It has a positive effect on promoting the use of plant fiber materials in composites. For instance, the incorporation of flax fibers not only effectively enhances the tensile properties of the composite but also preserves or even increases the weight proportion of plant fiber in the laminates. The configuration of GFKFG displays the highest 21.8% plant fiber weight fraction and 13.2% glass fiber weight fraction, which is excellently stronger than the GKGKG with the highest 17.8% glass fiber weight fraction and 14.8% plant fiber weight fraction. However, the tensile strength and tensile modulus of GFKFG are 7.17% and 7.04% higher, respectively, than those of GKGKG.

The data in Figure 4(c) demonstrate that increasing the content of glass fibers in plant fiber composites improves the laminate ductility more significantly. KKKKK had the lowest elongation of 1.697% with 0% glass fiber, GKKKG had 2.204% with 10.2% glass fiber, and GKGKG had the highest elongation of 2.435% with 17.8% glass fiber. GKKKG and GKGKG exhibit increases of 29.41% and 42.94% in elongation at break, respectively, compared to KKKKK. Furthermore, the incorporation of flax fibers also contributed to a slight enhancement in elongation at break. For example, the elongation at break of GFKFG is 2% higher than that of GKKKG, reaching 2.341%, which is only minimally lower than that of GKGKG in this aspect.

Typical tensile stress–strain curves of kenaf fiber-based composites are presented in Figure 4(d). The figure demonstrates the progressive relationship between stress and strain in the fiber composites during the tensile process. At the initial stage of loading, the stress–strain curves show a linear progression. With increasing load, the stress–strain curve follows a nonlinear trajectory until the material ultimately fractures. The addition of glass fabric can significantly improve composites' tensile properties, increasing their load-bearing capacity. At the terminal stage, the curves abruptly drop to the baseline after reaching peak points. Specimens fracture entirely at this stage, accompanied by a loud cracking sound during experiments. The morphology of the stress–strain curve reveals a similar pattern consistent with the findings of Balakrishnan, Thariq Hameed Sultan, Syazwani Shahar, Azriff Basri, et al. (2024). When reaching peak tensile stress, fiber-reinforced composites fracture quickly.

The failure modes of all composite samples in this study vary depending on their composition. As illustrated in Figure 5, composite samples were completely fractured after tensile failure, and fiber pull-out and breakage are especially noticeable. At the fracture site, kenaf fibers and matrix in the pure natural fiber-reinforced composite, KKKKK, were destroyed simultaneously with a relatively flat fracture, as shown in Figure 6(a). The failure is exclusively localized at the fracture site, with the surrounding material on both sides retaining its original condition, exhibiting no fiber-matrix delamination. This is due to the excellent bonding properties of the epoxy resin to the kenaf fibers, the low tensile strength of the composites reinforced with pure plant fibers, and the similar breaking elongation of the kenaf fibers and the epoxy resin. However, compared to KKKKK, obvious debonding and delamination of the outer side glass fibers and matrix were observed on both near sides of the fracture in the other composites, as shown in Figure 5. At the fracture, the glass fibers that are parallel to the direction of the loading force are stretched and fractured, as shown in Figure 6(b-e). The glass fibers and resin at the fracture were detached, and the location of the glass fiber breakage was not uniform, as shown in Figure 6(f). In addition, these figures also illustrated that the fracture surfaces of the plant fiber and resin bonding area in hybrid laminates remain flat and aligned, as displayed in Figure 6(g).

Changing the stacking order and fiber type altered the tensile properties of the composites. The delamination phenomenon of the glass fibers and the matrix is due to the glass fibers having a higher tensile strength compared to the plant fibers and being able to withstand stress values beyond the bonding strength with the resin. From the fracture pattern, it is observed that the fracture of the fiber composites occurs first at the bonding site between the plant fibers and the matrix. As the plant fibers and their nearby matrix exited the work, the tensile stresses in the specimen were transferred by the glass fibers and their adhesion to the matrix. Debonding and delamination of the glass fibers from the matrix occur under load. When the stress value and elongation of the glass fibers at the fracture reached the limit and broke, the specimen fractured. Thus, fiber tensile strength as well as the fiber/matrix interfacial bond strength are crucial for the tensile strength of the composites.

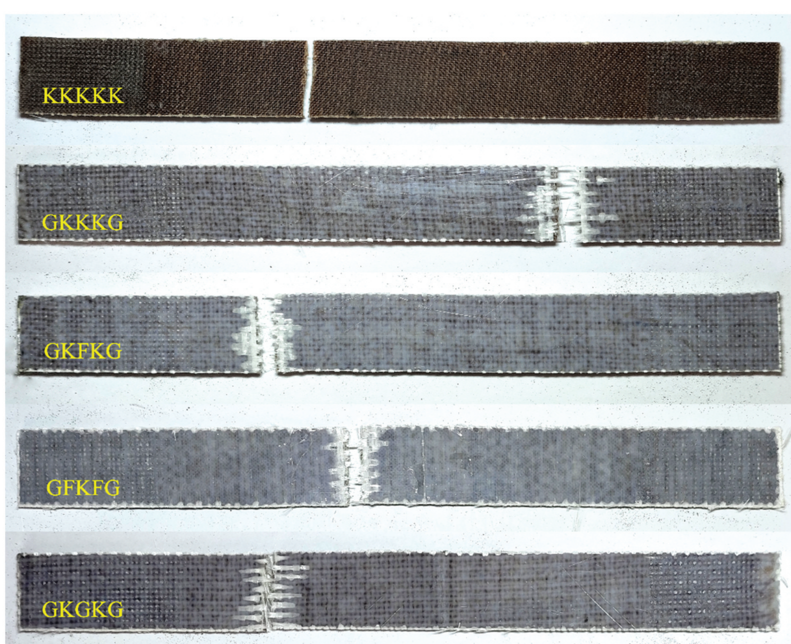


Figure 5. Fracture characteristics observed in kenaf fiber-based composites after tensile testing.

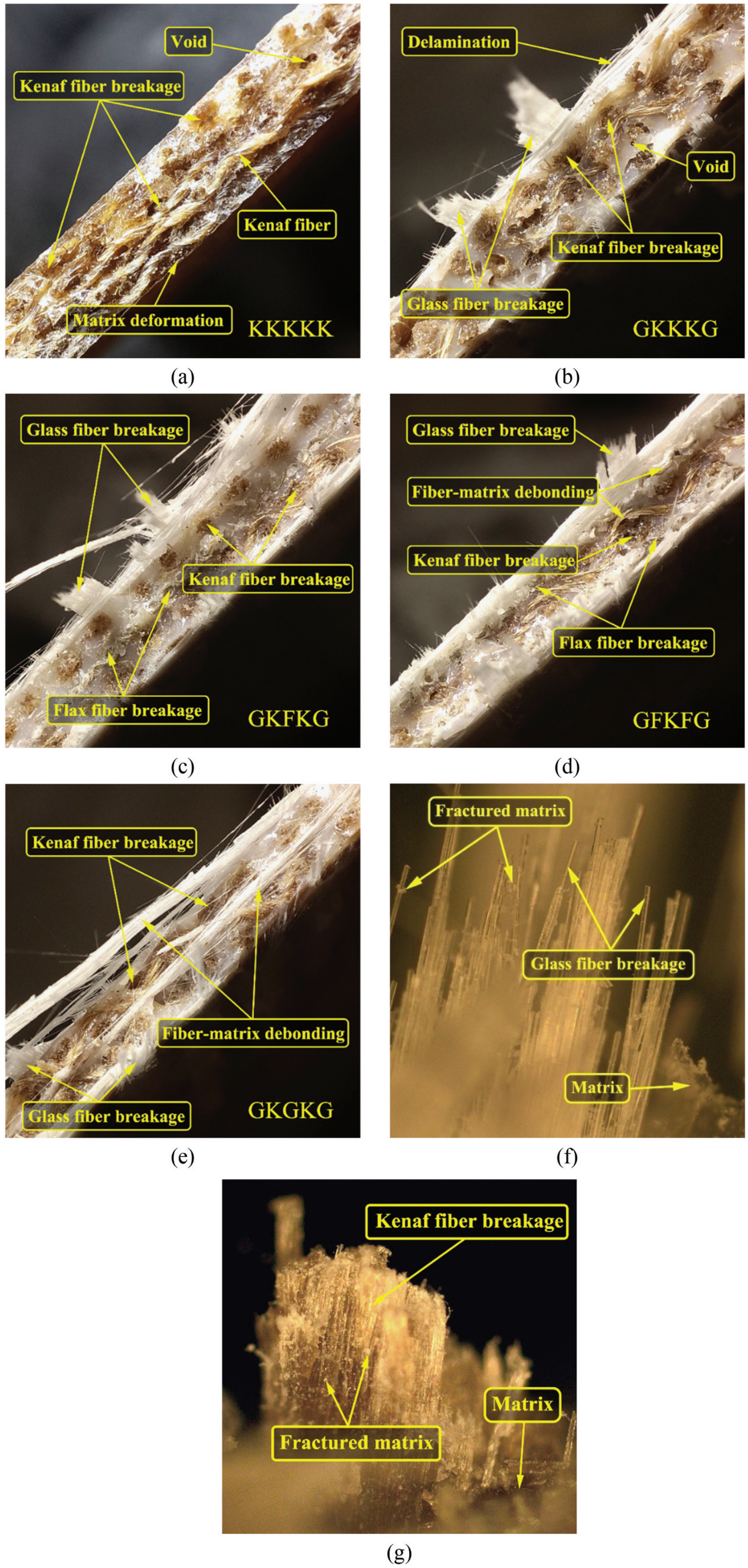


Figure 6. Cross-section OM images of failed kenaf fiber-based laminates after tensile testing: (a) KKKKK; (b) GKKKG; (c) GKFKG; (d) GFKFG; (e) GKGKG; (f) failure morphology of glass fibers; (g) failure morphology of kenaf fibers.

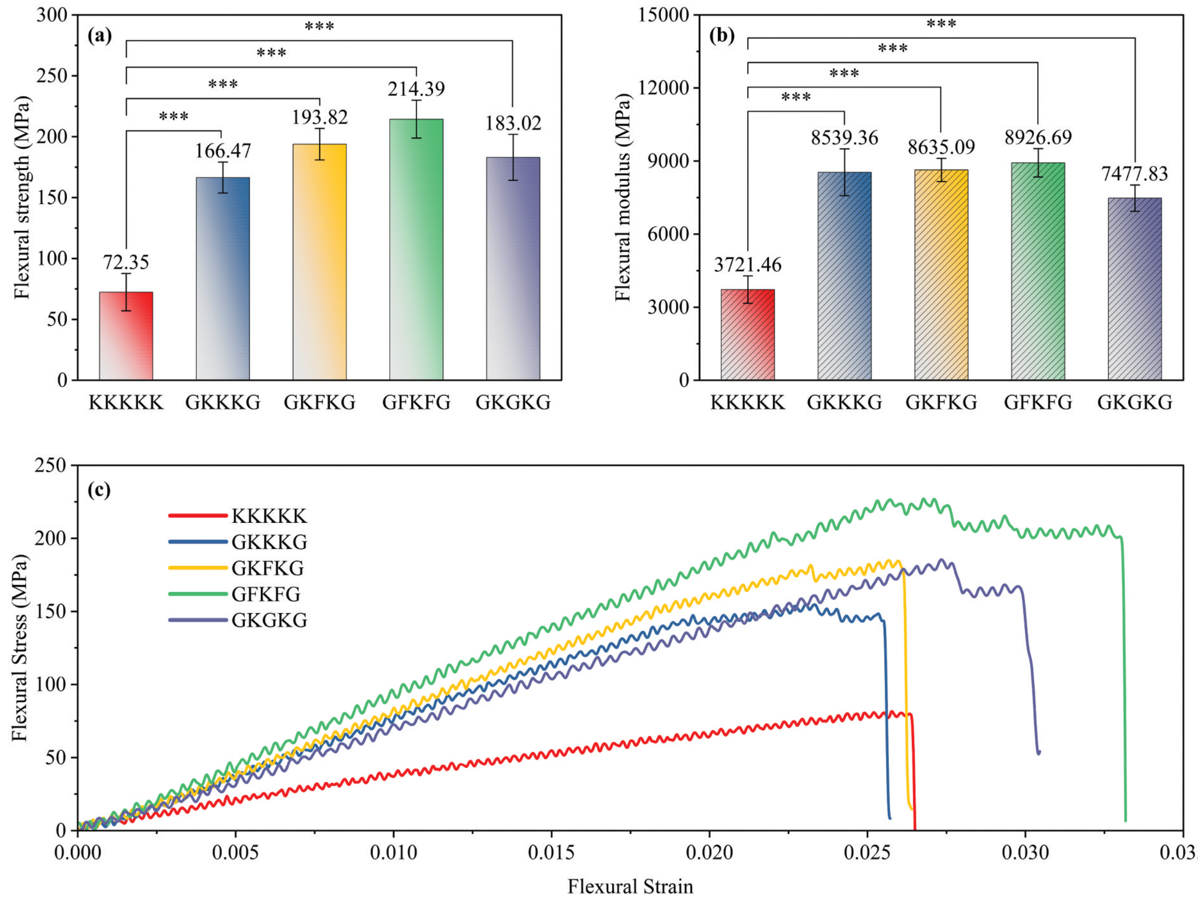


Figure 7. Three-point bending properties of kenaf fiber-based composites: (a) flexural strength; (b) flexural modulus; (c) typical flexural stress–strain curves. Data are presented as mean±SD (n=5). Statistical significance was evaluated using one-way ANOVA and Tukey test (*$p \leq .05$, **$p \leq .01$, ***$p \leq .001$).

Flexural properties

Three-point bending tests were used to determine the flexural properties of laminates. After the test, the average values of flexural strength and modulus of kanaf fiber-based laminates were presented in Figure 7(a, b), and the typical flexural stress–strain curves were presented in Figure 7(c). It is observed that the pure kenaf fiber composite KKKKK exhibits a minimum flexural strength of 72.35 MPa and a flexural modulus of 3721.46 MPa. In contrast, the hybrid composites display excellent flexural strength and flexural modulus, greater than the pure natural fiber reinforced one. The flexural strength and modulus of GKKKG increase by 130.09% and 129.46% compared to KKKKK, reaching 166.47 MPa and 8539.36 MPa. The main reason is that the outer layer of the hybrid laminate employed woven glass fabrics, which have superior mechanical properties and can absorb more energy. Additionally, glass fibers as the outer layers can bear higher stresses than plant fiber under bending load and prevent the direct exposure of weaker natural fiber in high-stress areas, thus improving the bending resistance of hybrid ones in this study. The flexural strength of GKGKG, which contains three layers of glass fiber and the highest proportion of glass fiber, only reaches 183.02 MPa; its flexural modulus is 74,477.83 MPa, which is 100.9% higher than that of KKKKK but 12.4% lower than that of GKKKG. Compared with employing glass fabric as the core layer, placing flax fabric in the core position can result in a similar enhancement in flexural behavior. The flexural strength and modulus of GKFKG are 5.9% and 15.5% higher than that of GKGKG, respectively, reaching 193.82 MPa and 8635.09 MPa. In addition, the maximum flexural strength and modulus in this study appeared in the hybrid laminate, GFKFG, reaching 213.91 MPa and 8906.65 MPa. This result indicated that the hybrid inner part with kenaf and flax fiber significantly increases the flexural properties of hybrid composites.

According to Figure 7(c), the stress–strain curves exhibit a gradual upward trend during the initial loading phase. However, near the peak load, they show distinct variations in behavior. The pure kenaf fiber-reinforced

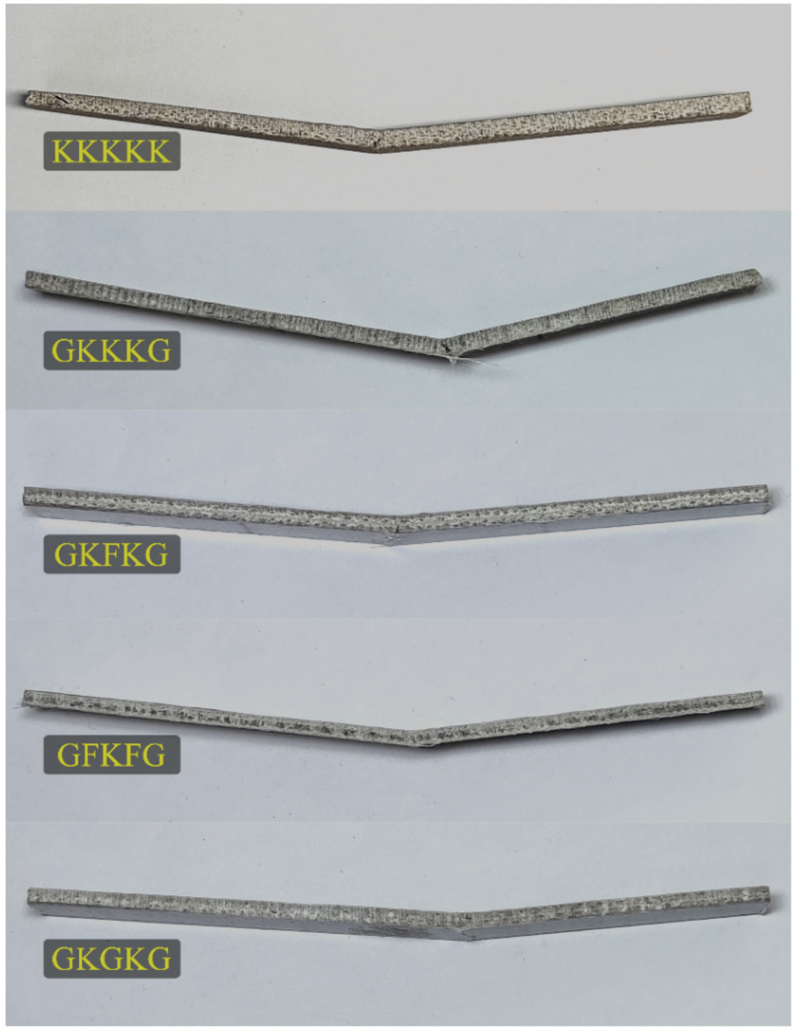


Figure 8. The appearance of kenaf fiber-based composites after flexural testing.

laminate (KKKKK) exhibits a sharp and abrupt decline in the curve upon reaching its peak, demonstrating its brittle nature. However, the hybrid composites exhibit a distinct plateau phase near the peak load, highlighting their strong ductility properties. The phase predicts the imminent sharp decline in the curve and the imminent failure of the specimen. The main reason is that multilayers and multiple fabrics can allow the bending damage of hybrid laminates to occur in stages. Furthermore, using glass fibers as the outer layer significantly increases the tensile properties of the hybrid composite edge material, thus improving the bending load capacity.

After the bending experiments, the composite specimen exhibits an irrecoverable bending damage pattern, as shown in Figure 8. Fractures and cracks result from fiber and matrix breakage, debonding, and delamination, as displayed in Figure 9(a-j). These images illustrate the failure morphology of kenaf fiber-based composites, highlighting crack locations and propagation direction within the structure. After the bending load, failure occurred at the outer tensile surface of the KKKKK laminate. The fibers and matrix are pulled off and cracked at the outermost side of the loading point. The crack develops from the outer tensile surface to the inner compressive surface. From Figure 9(a), the crack crosses the entire outer tensile surface of the specimen, causing overall failure of the outer fibers and matrix at this area. The propagating crack extends from the tensile surface toward the compression surface, as shown in Figure 9(b), indicating the failure of the specimen. This failure mode appears across all flexural test samples. However, the cracking of the outer surface of the hybrid composite at failure is unlike that of KKKKK. The superior mechanical properties of the outer glass fibers result in only partial fiber pull-off. Consequently, the bending failure fracture does not extend through the entire bottom of the sample. The result explains why hybrid laminates with glass fabrics as the outer layer exhibit superior ductility compared to the laminate made solely from kenaf fiber. In addition, debonding and delamination of the glass

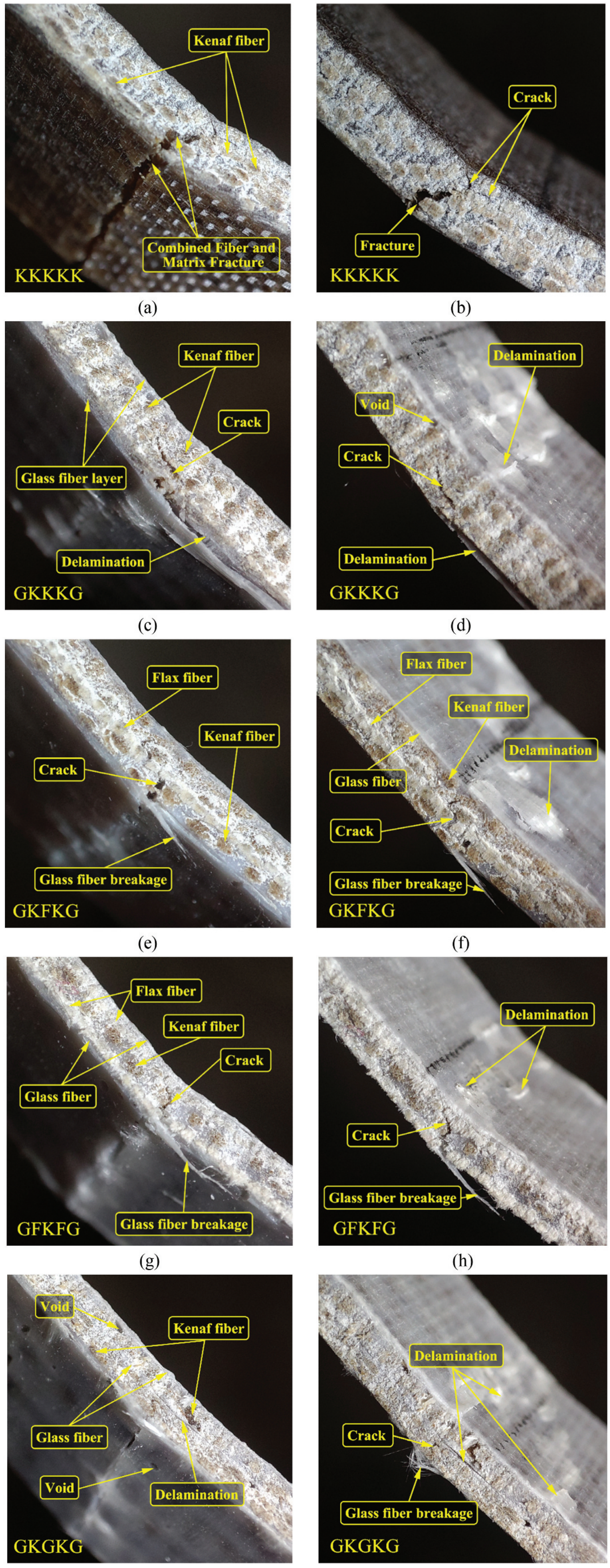


Figure 9. Middle loading point OM images of failed kenaf fiber-based laminates after the three-point bending testing: (a, b) KKKKK; (c, d) GKKKG; (e, f) GKFKG; (g, h) GFKFG; (i, j) GKGKG.

layer can be found in small regions of the outside surface, regardless of the compression or tension side, as shown in Figure 9(c-j). The exceptional adhesion capability of the composite matrix plays a crucial role. In Figure 9(i,j), a noticeable delamination crack appears at the central region of the laminate, occurring between the glass fabric and kenaf fabric layers. This phenomenon is not distinctly observed in the other laminates, indicating that debonding is more likely to occur between glass and plant fabrics than between plant fabrics alone under high loading conditions. This finding also implies that the epoxy resin matrix containing 3% nano-SiO_2 exhibits superior adhesion between adjacent plant fabric layers compared to the adhesion between plant and glass fabric layers under flexural load. For this reason, GKFKG and GFKFG exhibit superior bending properties among all the laminates.

Moisture absorption behavior in distilled and artificial seawater

The moisture absorption of all composite samples was calculated according to Equation (4). Figure 10 reports the percentage of distilled and artificial seawater absorption (in days) as the aging time increases. All samples showed a gradual increase in weight with increasing aging time. At the initial stage, the composite's water absorption efficiency is remarkable, reaching a saturated water absorption rate of 60% in less than 2 weeks. Subsequently, the rate slowed down and gradually stabilized to saturation. This result is compatible with the findings of Baigh et al. (2023). The absorption rate at the saturated condition of KKKKK, GKKKG, GKFKG, GFKFG, and GKGKG is 7.37%, 4.97%, 4.01%, 4.26%, and 4.13%, respectively, in the distilled water. However, the rates are 6.76%, 4.28%, 3.48%, 3.82%, and 3.68%, respectively, in the artificial seawater. KKKKK has the maximum water absorption rate, much higher than other hybrid fiber-reinforced composites in this research, both in distilled water and artificial seawater. With KKKKK having maximum plant fiber content, more plant fiber content has a positive effect on the increase in water absorption of fiber composites.

Compared to KKKKK laminate, the moisture absorption of GKKKG, GKFKG, GFKFG, and GKGKG was reduced by 32.5%, 45.6%, 42.2%, and 43.9% in distilled water and decreased by 36.6%, 48.6%, 43.4%, and 45.5% in seawater. This result shows that the composites consisting of glass fibers as the outer layer and plant fibers as the inner layer have a significant effect on reducing water absorption because the glass fiber has a low moisture uptake rate compared with plant fibers. In addition, the difference in moisture absorption between the different composites also indicates that the lay-up sequence has a certain effect on moisture uptake. Moreover, the same laminate displayed different capabilities in distilled water and seawater. The moisture uptake of laminate immersed in seawater exists less than in distilled water, and the value decreased by 8.28%, 13.88%, 13.22%, 10.33%, and 10.90% in KKKKK, GKKKG, GKFKG, GFKFG, and GKGKG laminates, respectively. This is due to the accumulation of ions (such as K^+, Ca^{2+}, Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, and F^-) from seawater on the surface of the material hindering the diffusion of water molecules in the composite (Singh and Zafar 2021; Singh et al. 2022; Yi et al. 2020).

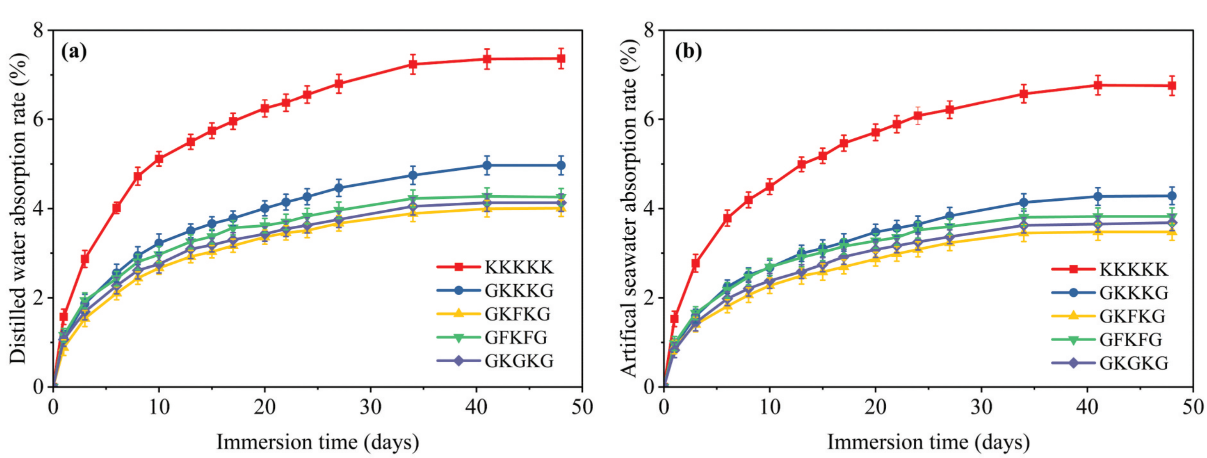


Figure 10. The moisture absorption rates in distilled water and artificial seawater.

Table 3. Time taken for moisture absorption rate to increase in distilled water and sea water (day).

	KKKKK		GKKKG		GKFKG		GFKFG		GKGKG	
Growth range	DW	SW	DW	SW	DW	SW	DW	SW	DW	SW
0–60%	7	8	8	9	8	9	7	7	8	9
60–90%	20	19	26	25	19	18	17	17	19	18
0–100%	48	48	48	48	48	41	48	41	48	41

Note: 100% represents saturated moisture absorption. DW means distilled water solution immersion condition, SW means sea water solution immersion condition.

The standard deviation of the water absorption test of laminates can be observed in the two figures, and it can be attributed to two aspects. The first influence is due to measurement operation errors. After the specimens were removed from the immersion solution, some of the surface moisture would evaporate in addition to being wiped dry, and although the samples were weighed as soon as possible after they left the solution, there would inevitably be a sequential ordering, leading to measurement errors. The second reason is attributable to changes in the properties of natural fibers. Cellulosic fiber reinforcements can vary in their mechanical properties because of several factors, such as chemical composition, fiber size, and density, all of which can be affected by local agricultural growing conditions or manufacturing processes (Calabrese et al. 2019).

The time taken for the water absorption to reach the different stages is recorded in Table 3. It is clear from this table that the first 0–60% of the water absorption is much faster than the duration of 60–90%. All the samples can finish the stage in 9 days. As the progress goes from 60% to 90%, the moisture absorption value is reduced by half. However, the time required for this stage is approximately two to three times longer than that of the 0–60% stage. Moreover, the duration (0–60%) in distilled water is slightly less than that in seawater, while the duration (60–90%) in seawater is shorter than that in distilled water.

The composites were not coated with a water barrier. At the initial stage, the fibers at the cut breaks around the perimeter of the sample are in direct contact with the soaking solution, and water molecules diffuse rapidly in these regions to the interior of the dried composite laminate, causing the weight increase phenomenon to show a rapid upward trend during the initial soaking stage. Kanaf and flax fibers belong to lignocellulosic fibers, which are mainly composed of polysaccharides (such as cellulose, hemicellulose, and lignin). The inherent hydrophilicity of these components leads to strong water affinity in the plant fibers in a wet environment (Z. Calabrese et al. 2019; Z. Liu and Tisserat 2018). Water molecules diffuse in the privileged paths of these hydrophilic regions. In addition, during water aging, water molecules also enter the interior of the composite from defects at the fiber/matrix interface and surface microcracks due to hydraulic pressure and capillary action. As the water molecules penetrate deeper into the composite, their diffusion paths are blocked by hydrophobic materials (resins and nanofillers), which gradually reduce the diffusion rate and eventually lead to saturation by water absorption. In addition, the porosity of materials has a significant impact on their water absorption capacity. Generally, materials with a higher porosity can absorb more moisture (Sari, Zaidan Fadhlurrohman Rivlan, and Muthu Kumar Thiagamani 2025).

Plant fibers have larger diameters and more unstable cross-sectional patterns compared to glass fibers, resulting in a greater number of tiny voids and microcracks at the contact surface of the plant fiber and matrix, causing adverse effects. Moreover, heterogeneity at the weft-warp intersection of the fabric also adversely affects the resin wetting of the fibers, triggering defects in the composite (Calabrese et al. 2019). As the aging time increases, the massive water molecules will cause the plant fibers to swell, generating negative stresses within the composite material, which will lead to the detachment of the fibers from the matrix, causing more microcracks to develop in composites. The mechanical properties of natural fiber-reinforced biocomposites deteriorate under water aging, primarily due to hydrolytic degradation at the fiber–polymer interface Parameswaranpillai et al. (2022). This also implies that natural fiber-reinforced composites with high water absorption increase the risk of degradation in mechanical properties. Controlling the water absorption behavior of composites is particularly critical for ensuring their reliability in aqueous environments.

Constant temperature and concentration of the immersion solution were ensured during the experiment; therefore, the change in water content in a laminate can be predicted and described by Fick’s law, which is denoted by the following equation:

$$\frac{M_t}{M_m} = 1 - \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{exp\left(\frac{-(2i+1)^2\pi^2 Dt}{h^2}\right)}{(2i+1)^2} \tag{6}$$

Where:
M_t = the moisture content at time t, %,
M_m = the maximum moisture content at the time of moisture saturation, %
D = the diffusion coefficient, mm^2/s,
h = the thickness of the laminate, mm.

When, $M_t/M_m > 0.6$, the Equation (6) can be described as follows (X. Xiao, Cheng, and Zhong 2022):

$$\frac{M_t}{M_m} = 1 - exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{\frac{3}{4}}\right] \tag{7}$$

When $M_t/M_m < 0.6$, the relation between $\sqrt{t}$ and M_t can be approximated linearly, Equation (6) can be simplified to (X. Xiao, Cheng, and Zhong 2022):

$$\frac{M_t}{M_m} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}} \tag{8}$$

In the study, the D can be expressed as follows:

$$D = \pi\left(\frac{h}{4M_m}\right)^2\left(\frac{M_t}{\sqrt{t}}\right)^2 \tag{9}$$

When k is defined as the slope of $M_t/\sqrt{t}$. Finally, D can be expressed as:

$$D = \pi\left(\frac{kh}{4M_m}\right)^2 \tag{10}$$

The diffusion coefficient is corrected to consider the positive effect of the edges of the sample on the water absorption effect. Assuming the same rate of diffusion in all directions, the corrected diffusion coefficient D_c for a rectangular specimen is expressed as (Calabrese et al. 2019; Karad, Jones, and Attwood 2002; Orue et al. 2016):

$$D_c = D\left(1 + \frac{h}{l} + \frac{h}{w}\right)^{-2} \tag{11}$$

Where:
L = the length of the sample, mm,

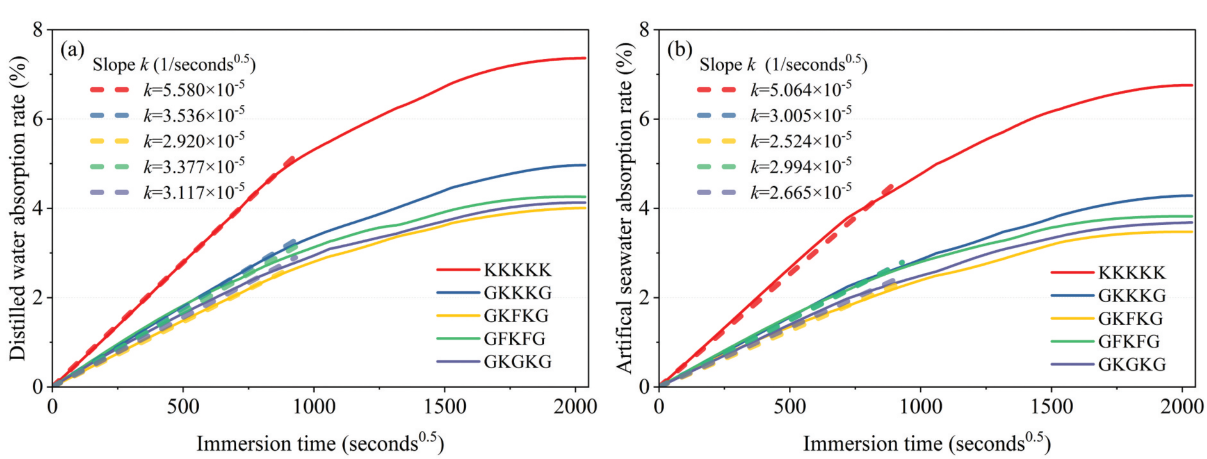


Figure 11. The value of slope k in distilled water and seawater immersion process.

Table 4. Diffusion coefficients of composite in distilled water and seawater immersion.

Laminate	Distilled water condition			Sea water condition		
	M_m^{DW} (%)	D^{DW} (mm^2/s)	D_c^{DW} (mm^2/s)	M_m^{SW} (%)	D^{SW} (mm^2/s)	D_c^{SW} (mm^2/s)
KKKKK	7.37	1.580×10^{-6}	1.106×10^{-6}	6.76	1.548×10^{-6}	1.083×10^{-6}
GKKKG	4.97	1.189×10^{-6}	0.853×10^{-6}	4.28	1.158×10^{-6}	0.831×10^{-6}
GKFKF	4.01	1.119×10^{-6}	0.816×10^{-6}	3.48	1.111×10^{-6}	0.810×10^{-6}
GFKFG	4.26	0.834×10^{-6}	0.646×10^{-6}	3.82	0.815×10^{-6}	0.632×10^{-6}
GKGKG	4.13	0.914×10^{-6}	0.692×10^{-6}	3.68	0.842×10^{-6}	0.638×10^{-6}

w = the width of the sample, mm.

In this research, when values of $M_t/M_m < 0.6$, the value of slope k in distilled water and seawater immersion process is shown in Figure 11, and the diffusion coefficients of laminate in distilled water and seawater immersion are shown in Table 4. In the tables, it is observed that all samples demonstrated lower water absorption and permeability coefficients in seawater than in distilled water. Material rankings for water absorption were KKKKK > GKKKG > GFKFG > GKGKG > GKFKF, while permeability rankings were KKKKK > GKKKG > GKFKF > GKGKG > GFKFG. In both distilled water and seawater conditions, the maximum value of D_c occurred in the KKKKK composite, are 1.106×10^{-6} and 1.083×10^{-6}, respectively; the minimum value of D_c occurred in the GFKFG composite, are 0.646×10^{-6} and 0.632×10^{-6}, respectively. Compared to the KKKKK, the diffusion coefficient of GFKFG decreased by 41.59% and 41.64% in distilled and seawater environments. Replacing layers of kenaf fabric with glass or flax fabric effectively reduced water absorption and permeability coefficients. The water absorption of fiber-reinforced composites alters with the change in the stacking form of the hybrid composites (Saw et al. 2014).

Specific strength analysis

The specific strengths of kenaf fiber-based laminates are compared in Figure 12. The specific strength values of materials vary with the stacking order of the fabric layers. In the study, the hybrid composite materials have a high level of specific strength values due to the use of glass fiber. The hybrid laminate, GFKFG, exhibits the highest specific strength value of 8.05×10^4 Pa m^3/kg, which is 90.3% greater than that of KKKKK (4.23×10^4 Pa m^3/kg). Additionally, the laminates, GKKKG, GKFKG, and GFKFG, exhibited specific strength values of 6.61×10^4 Pa m^3/kg, 7.02×10^4 Pa m^3/kg, and 7.43×10^4 Pa m^3/kg, respectively, which are 56.3%, 66.0%, and 75.7% higher than that of KKKKK. A robust positive correlation can be observed between specific strength values and tensile strengths, due to the

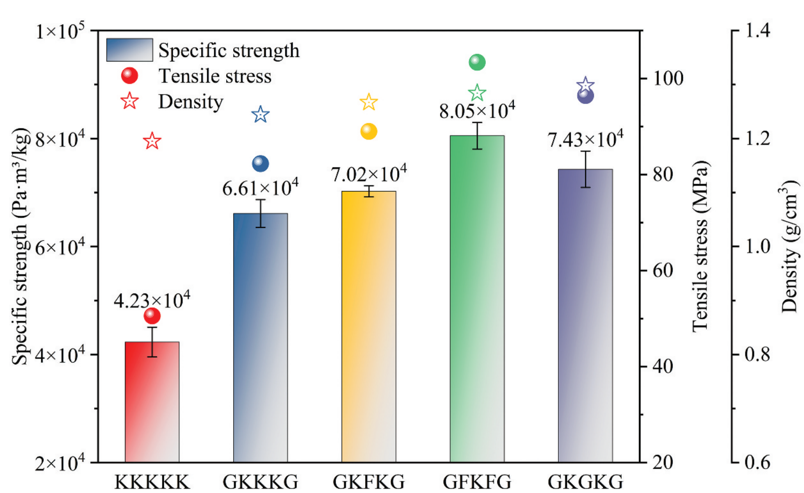


Figure 12. Comparison of specific strength, tensile strength, and density in kenaf fiber-based laminates.

densities of the five laminates exhibiting minimal variation within a narrow range of 1.195 g/cm^3 to 1.298 g/cm^3. Moreover, reducing the density value of the material is essential to increase the value of the specific strength. For example, the density of GKGKG and GFKFG is 1.298 g/cm^3 and 1.284 g/cm^3, respectively, with a slight variation. Despite their tensile strength exhibiting a 7.17% difference, their specific strength differs by 8.3%.

Compared to natural fibers, glass fibers have much superior mechanical properties than either kenaf or flax fibers. However, employing plant fibers has a more significant positive impact on reducing the density of the material. Incorporating plant fibers benefits the advancement of lightweight structural components, reducing overall weight while significantly enhancing mechanical strength by modifying the stacking sequence, as shown in Figure 12. In this study, the GFKFG combination shows the best specific strength value, with the percentage of plant fibers in the material reaching 21.6%, showing excellent environmental properties. The prior study found that well-processed hybrid plant fiber composites can be an environmentally friendly alternative to replace traditional glass fiber-reinforced materials (Balakrishnan, Thariq Hameed Sultan, Syazwani Shahar, Azriff Basri, et al. 2024). Then, these composites with high specific strength and low weight can be widely employed in aerospace, marine, automotive, and other engineering fields to minimize overall structural weight, optimize load-bearing performance, and enhance fuel efficiency.

Conclusions

In the present study, five kenaf fiber-based biocomposites were fabricated with different stacking sequences using the hand lay-up method. The study investigated the physical, tensile, flexural, water uptake, and specific strength properties of these biocomposites. Based on the results, the following conclusions can be drawn.

(i) Hybrid bio-laminates with glass fibers as the outer layers exhibit lower thickness and reduce areal density than the single kenaf fiber-reinforced composites (KKKKK) with the same number of stacked layers. The areal density of GFKFG is only 0.333 g/cm^2, reflecting a 25.67% reduction compared to KKKKK, while the natural fiber content in the composite reaches 21.6 wt.%.
(ii) In tensile tests, the hybrid biocomposites exhibit significantly enhanced performance. The tensile strength and tensile modulus of GFKFG are 104.47% and 65.57% higher than those of KKKKK, respectively. Similarly, the specific strength value of GFKFG is 90.31% higher than that of KKKKK. The results show that the incorporation of glass fiber and flax fiber fabrics effectively improves the tensile properties of the composite.
(iii) The nanocomposite matrix significantly strengthens fiber-matrix adhesion, thereby enhancing mechanical performance. In the three-point bending test, GFKFG exhibits superior properties, achieving a bending strength of 214.39 MPa and a flexural modulus of 8926.69 MPa, far exceeding those of other bio-laminates.
(iv) All samples absorb slightly less moisture in artificial seawater than in distilled water. Additionally, hybrid fiber-reinforced laminates exhibit lower moisture absorption under-saturated conditions. GKFKG displays the lowest absorption in all the test samples, with 4.01% in distilled water and 3.48% in artificial seawater, significantly lower than KKKKK. This suggests adjusting fiber textile stacking and incorporating nano-silica can effectively hinder water penetration.

These results emphasize the promising future of plant fiber-reinforced materials as a viable solution to produce lightweight and economical structural components. In addition, hybrid fiber-reinforced biocomposites have superior properties to pure natural fiber-reinforced composites, combining better environmental friendliness. Furthermore, by optimizing the hybridization design, the biocomposites fabricated using hand lay-up and vacuum bag molding techniques possessed lower water absorption. These findings provide the necessary experimental support for applying hybridized plant fiber-reinforced biocomposites in the marine environment as structural and non-structural components. Moreover, the production of fiber-reinforced composites with plant fiber resources is a true practice of Sustainable Development Goals. The research promotes the application of environmentally friendly material alternatives in industries.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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