Journal of Materials Research and Technology 41 (2026) 29–38

Contents lists available at ScienceDirect

Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

# Performance enhancement of hybrid kenaf/bamboo fibre-reinforced bio-epoxy composites for sustainable structural applications

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ARTICLE INFO

*Keywords:*
Hybrid biocomposites
Thermal stability
DMA analysis
Mechanical properties
CTE tests

ABSTRACT

In this study, bamboo (B) and kenaf (K) fibres were employed as reinforcements in bio-epoxy matrices to develop biocomposites, aiming to evaluate their mechanical, thermal, and morphological properties. Biocomposites fabricated by Hand lay-up techniques by using different formulations. TGA results indicated that the biocomposites maintained thermal stability up to 230 °C before decomposition, with complete degradation occurring at 600 °C. The findings demonstrated that hybrid biocomposites exhibited superior mechanical performance; however, the sample (K50) exhibited the greatest tensile strength among all the biocomposites, which was approximately 43 MPa. On the other hand, the 5K/5B biocomposite exhibits the maximum elongation at break, approximately 2 %. The K50 biocomposite showed the highest flexural strength among all samples. DMA analysis revealed an increase in the storage modulus (É) for hybrid biocomposites, indicating improved stiffness and reduced damping. According to the DMA results, the storage modulus values were enhanced compared to those of the single biocomposites, while the loss modulus exhibited lower values with the hybrid biocomposites. Following, the storage modulus increased from 3566.92 MPa (K50) to 3764.14 MPa for the optimised hybrid composite (5K/5B), indicating improved stiffness under load. Likewise, the loss modulus increased from 300.48 MPa (K50) to 360.65 MPa (3K/7B), which confirms improved energy dissipation capability and stronger fibre–matrix interlocking. SEM analysis provided insights into fibre-matrix adhesion and bonding, confirming that the integration of hybrid natural fibres enhances the overall properties of bio-epoxy composites. In contrast, the WA and TS percentages exhibited higher values. Thus, incorporating the kenaf fibres with bamboo as hybrid biocomposites in this study would meet the demand for sustainable packaging, serving as a viable alternative to conventional plastics and enhancing environmental sustainability. From the TMA findings, the results indicate that the 3K/7B biocomposite has the highest CTE value, indicating the most significant thermal expansion among the samples. These combined improvements demonstrate strong potential for use in lightweight automotive structures, building panels, and eco-friendly consumer products where greater strength and thermal resistance are needed.

## 1. Introduction

Hybrid biocomposites are materials made by combining natural fibres or bio-based components with synthetic or other natural reinforcements to create a composite material. The goal of hybridising biocomposites is to enhance their mechanical, thermal, and other functional properties while maintaining or improving their sustainability and environmental benefits [1,2]. These materials leverage the renewable nature of natural fibres such as flax, hemp, jute, or bamboo, alongside synthetic matrices like biodegradable polymers, traditional

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https://doi.org/10.1016/j.jmrt.2025.12.017
Received 22 October 2025; Received in revised form 27 November 2025; Accepted 1 December 2025
Available online 3 December 2025

thermosets, or even other bio-based materials [3,4]. The hybridisation process allows for the tailoring of biocomposites to suit specific applications, providing a balance between strength, weight, cost, and performance. For instance, the combination of natural fibres with recycled plastics can offer enhanced durability and resistance to environmental factors, while still being eco-friendly [5–7]. Hybrid biocomposites have found applications in various industries, including automotive, construction, packaging, and consumer goods, as they offer a promising alternative to traditional petroleum-based composites [8–10]. Natural fibres such as kenaf have been given more importance recently by researchers and industries owing to the demand for sustainable manufacturing practices and eco-friendly products [11]. Generally, kenaf fibre, an essential raw material across a wide range of industries, is a bast fibre derived from the phloem of the kenaf plant. The stem of the kenaf plant has a thick base layer. Therefore, the kenaf fibre yield is very high, contributing to the proportion of the base layer weight of 35 % of the total dry weight of the stem [12]. Additionally, the height of the mature kenaf plant is considerable, facilitating the extraction of longer kenaf fibre with excellent features. Furthermore, cultivating kenaf crops has a positive effect on the environment due to kenaf being a highly efficient photosynthetic plant. During the growth process, it can absorb large amounts of carbon dioxide from the air and contribute positively to the carbon sink [13–15]. Kenaf fibres can replace the conventional synthetic fibres used in polymer composites due to their comparable specific properties [16]. Bamboo fibre is gaining significant attention in various industries due to its outstanding mechanical characteristics, biodegradability, and sustainability [17]. It exhibits high tensile strength, flexibility, and natural antimicrobial properties, making it suitable for applications in textiles, composite materials, and eco-friendly products. Bamboo fibre composites are widely used in the automotive, construction, and packaging industries due to their lightweight nature and impressive durability. Moreover, bamboo's rapid growth and renewability make it an attractive alternative to synthetic fibres, aligning with green manufacturing initiatives [18,19]. Hybrid kenaf/bamboo fibre biocomposites exhibit remarkable mechanical properties due to the synergistic effect of both natural fibres. The combination of kenaf's high tensile strength and bamboo's flexibility results in biocomposites with enhanced impact resistance, tensile strength, and thermal stability. These composites also demonstrate improved moisture resistance compared to pure kenaf or bamboo biocomposites, owing to the balanced fibre-matrix interaction. The hybridisation not only enhances the structural integrity but also contributes to sustainable material development, making them suitable for automotive, construction, and packaging applications [20,21]. Despite the promising attributes of single-fibre composites, most existing studies have focused on either kenaf or bamboo fibres individually, which often results in composites with unstable mechanical and moisture resistance properties. Kenaf-based biocomposites exhibit high stiffness but tend to suffer from moisture absorption, while bamboo-based ones offer better flexibility and water resistance but relatively lower tensile strength. The need to develop hybrid biocomposites that combine different natural fibres to synergistically balance mechanical performance, durability, and sustainability. The present study introduces an innovative hybrid biocomposite system by combining kenaf and bamboo fibres within a bio-epoxy matrix. The novelty of this work lies in exploring the synergistic interactions between the two natural fibres to achieve enhanced thermo-mechanical and moisture-resistance characteristics. By leveraging kenaf's high tensile strength and bamboo's flexibility and hydrophobic nature, the developed hybrid aims to deliver a lightweight, high-performance, and eco-friendly composite suitable for demanding applications such as automotive interiors, construction panels, and sustainable consumer products. This approach helps develop advanced biocomposites that meet sustainability goals and deliver better engineering performance.

## 2. Materials and methods

### 2.1. Materials and composite fabrication

The Kenaf (K) and Bamboo fibres (B), performed in this study, Kenaf (K) and bamboo fibres (B) were provided by Sri Achu Fibres, Erode, Tamil Nadu, India. Table 1 shows various properties of the investigated fibres in this work.

The resin employed in this study consists of SR Greenpoxy 56® and SD Surf Clear® from Sicomin Epoxy Systems, a company located in France. It was blended using a weight ratio of 10 parts of SR Greenpoxy 56® to 3.7 parts of SD Surf Clear®. SR Greenpoxy 56® is derived from renewable carbon sources (≥56 % bio-based carbon content) and is designed for high-performance composite manufacturing. It possesses a viscosity of 600–900 mPa s at 25 °C and a density of 1.15 g/cm$^3$. SD Surf Clear® curing agent is characterised by a viscosity of 100–300 mPa s at 25 °C and a density of 1.00 g/cm$^3$. The resin and hardener were blended at a weight ratio of 10:3.7 as recommended by the manufacturer. The system was cured at room temperature for 24 h followed by a post-cure at 60 °C for 4 h, ensuring complete cross-linking and enhanced mechanical performance.

### 2.2. Biocomposite fabrication

Two kinds of natural fibres were used in this study: bamboo (B) and kenaf (K). Prior to composite fabrication, the raw fibres were oven-dried for seven days at 70–80 °C to remove moisture and improve interfacial adhesion during blending. The dried fibres were then ground to a fine powder using a mechanical grinder, resulting in an average particle size of approximately 2 μm. To ensure complete dryness, the powdered fibres were further conditioned in an oven at 60 °C for 24 h before use.

Subsequently, the bio-epoxy resin was reinforced with the B and K powders at a total filler content of 50 wt%, resulting in a composite density of about 1.2 g/cm$^3$. This relatively low density indicates the lightweight nature of the developed material, which is advantageous for applications requiring reduced weight, such as in automotive interiors and packaging structures. The resin–fibre blend was mechanically stirred to ensure uniform dispersion and then poured into a silicone-coated mould of 150 mm × 150 mm × 5 mm. The filled mould was cured in a hot press at 110 °C for 10 min, followed by cold pressing for 5 min to consolidate the structure. After demoulding, the fabricated kenaf/bamboo hybrid biocomposite samples were cut to the required dimensions and subjected to mechanical and thermal characterisation tests. Fig. 1 illustrates the prepared biocomposite samples, while Table 2 illustrates the formation of the prepared biocomposites.

## 3. Characterisations

### 3.1. Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability of B fibres, including both single and hybrid biocomposites, using a Hitachi STA7000 thermogravimetric analyser, which measures weight changes as the temperature rises at a constant

**Table 1**
Physical and chemical properties of kenaf and bamboo fibres used in this study.

| Property | Kenaf Fiber | Bamboo Fiber | References |
|---|---|---|---|
| Moisture content (%) | 8–12 | 6–10 | [22–24] |
| Cellulose content (%) | 55–65 | 40–50 | [23–25] |
| Hemicellulose content (%) | 18–23 | 15–25 | [21,23,25] |
| Lignin content (%) | 12–19 | 20–30 | [23,25,26] |
| Fibre density (g/cm$^3$) | 1.20–1.45 | 0.90–1.20 | [24,27] |
| Tensile strength (MPa) | 350–930 | 140–800 | [21,22,27] |
| Young's modulus (GPa) | 14–53 | 11–32 | [21,27] |
| Fibre diameter (μm) | 80–150 | 150–250 | [22,26] |

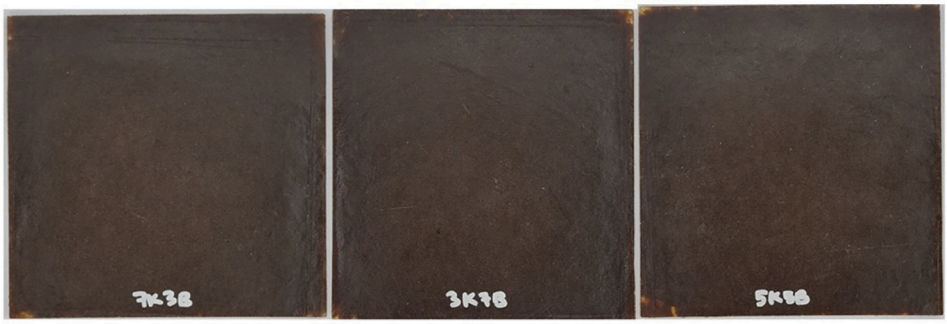


**Fig. 1.** The prepared various hybrid fibre biocomposites.

**Table 2**
Formulations of the prepared bio-composite.

| Samples of biocomposites | The formation | | |
|---|---|---|---|
| | Epoxy resin (wt.%) | K (wt. %) | B (wt. %) |
| K50 | 50 | 50 | 0 |
| B50 | 50 | 0 | 50 |
| 7K/3B | 50 | 35 | 15 |
| 5K/5B | 50 | 25 | 25 |
| 3K/7B | 50 | 15 | 35 |

rate. Bamboo fibre samples, placed in TGA-appropriate pans, were subjected to heating from 20 °C to 700 °C at a heating rate of 20 °C/min under nitrogen. The data obtained, presented as percentage mass loss, offered valuable insights into the fibres' thermal decomposition behaviour and stability, facilitating comparisons between treated and untreated fibres in terms of onset temperatures, peak decomposition temperatures, and residual masses, thereby highlighting the effects of treatment on their thermal characteristics and decomposition patterns.

### 3.2. Tensile test

The tensile test, conducted according to ASTM-D 3039, utilised a Universal Testing Machine (Bluehill INSTRON 5567, Shakopee, USA) with a 30 kN grip force, performed at an ambient temperature of 23 ± 3 °C with a relative humidity of 50 ± 5 %, using specimens with dimensions of 120 × 20 × 3 mm [28]. Tensile testing was performed following ASTM D3039 recommendations. A crosshead speed of 2 mm/min was selected, corresponding to a nominal strain rate of approximately 0.017 $s^{-1}$, which ensures uniform stress distribution and avoids premature failure in continuous fibre-reinforced polymer composites. The strain rate was chosen based on both the standard guidelines and relevant literature reports on natural fibre/epoxy composites, where similar loading rates provide a reliable measurement of elastic and failure behaviour.

### 3.3. Impact test

To ensure accuracy and repeatability, five samples of each preparation were subjected to impact testing using a Rayran impact tester equipped with a 2.75 J hammer, adhering to ASTM standard D256 to evaluate material resilience and brittleness.

### 3.4. Flexural test

The flexural properties of the biocomposites were examined according to ASTM D790-17 (2017) standards, employing specimens measuring 127 × 12.7 × 6 mm in a three-point bending setup, with a Universal Testing Machine (UTM) providing a 50 kN load capacity, maintaining a span-to-depth ratio of 16:1, and a crosshead speed of approximately 2 mm/min to ensure consistent testing conditions.

### 3.5. Dynamic mechanical analysis (DMA)

To study the viscoelastic properties of biocomposite materials under temperature variations, dynamic mechanical analysis (DMA) was carried out using a TA Instruments Q800 DMA machine, following ASTM D 4065–01 guidelines, at an oscillation frequency of 1 Hz within a temperature range of 30–200 °C and a heating rate of 5 °C/min.

### 3.6. Thermomechanical analysis (TMA)

Thermomechanical analysis (TMA) was conducted using a TA Instrument model Q.400 to determine the coefficient of thermal expansion (CTE), utilising the penetration method with a heating rate of 5 °C/min from 30 °C to 180 °C under a nitrogen atmosphere.

### 3.7. Water absorption and thickness swelling (TS)

The water absorption (WA) and thickness swelling (TS) tests for all specimens, sized 20 × 20 × 3 mm, were performed according to ASTM D 570–988, recording the initial weight and thickness before and after immersion in distilled water for periods ranging from 24 h to 7 days. The WA and TS values were calculated using equations (1) and (2) [29], respectively given as:

$$\textit{Water Absorption}\ (WA) = \frac{W_1 - W_0}{W_0} \times 100 \quad (1)$$

Where $W_1$ is due to the weight of specimens after the immersion, while $W_0$ is the sample's weight before the immersion

$$\textit{Thickness Swelling}\ (TS) = \frac{T_1 - T_0}{T_0} \times 100 \quad (2)$$

$T_1$ represents the thickness after the soaking, while the $T_o$ represents the thickness before soaking.

### 3.8. Scanning electron microscope (SEM)

The fracture surface morphology of tensile and flexural biocomposite samples was examined using a scanning electron microscope (SEM) (EM-30AX-COXEM, Daejon, Korea) at an acceleration voltage of 20 kV and a magnification of 100–200. Samples were gold-coated to enhance image clarity.

## 4. Results and discussion

### 4.1. TGA results

At the initial mass loss region (0 °C–200 °C), the thermal decomposition peaks of biocomposites (3K/7B, 5K/5B, 7K/3B, B50, K50)

exhibited a slight mass loss in all samples, as shown in Fig. 2A. This early-stage mass loss is typically due to the loss of moisture and/or the removal of volatile components. At the major decomposition range, all samples show a sharp mass loss in this temperature range. This sharp decline is indicative of the thermal decomposition of the main organic components or the structural breakdown of the material. The onset temperature and the rate of mass loss reflect the thermal stability of the samples. Therefore, 3K/7B and 5K/5B begin to degrade at slightly higher temperatures compared to the other samples, indicating better thermal stability. The rate of decomposition seems to alter on the relative comparison of "K" and "B" components, proposing that the "K" component may enhance thermal resistance. At the final decomposition between (500 °C–700 °C), it seems that after the sharp mass loss, the samples reached a stable residual mass. Differences in the residual mass provide insights into the composition and thermal stability: Higher residual mass indicates the presence of more thermally stable inorganic components or char. Samples like B50 and K50 have slightly higher final residuals, indicating a higher content of thermally stable material. The yield char varies depending on the composition, with K50 showing the highest char residue of 26 %, indicating a higher thermal stability and carbon content of kenaf fibres. In contrast, B50 has the lowest yield char of 18 %, reflecting the relatively lower thermal stability and higher degradation of bamboo fibres. The hybrid composites (3K/7B, 5K/5B, 7K/3B) display intermediate char yields, with higher kenaf content generally resulting in higher char residues. This observation aligns with previous studies, where kenaf-based composites typically produce more char due to their higher cellulose and lignin content, whereas bamboo based composites tend to leave less residue [30–32].

On the other hand, from Table 3, it is obvious that the K50 biocomposite has the highest maximum decomposition temperature at approximately 380 °C, indicating the highest thermal stability during rapid degradation. The 7K/3B composite follows closely, suggesting that higher kenaf content contributes to increased thermal resistance. Nevertheless, the B50 composite, with predominantly bamboo fibres, exhibits the lowest maximum decomposition temperature ($T_{max}$) of around 360 °C (Table 3 and Fig. 2B), indicating that bamboo fibres degrade more rapidly compared to kenaf. The hybrid composites (3K/7B and 5K/5B) show

intermediate values, reflecting a balanced decomposition behaviour between kenaf and bamboo components. These results are consistent with a previous study [33], where kenaf fibres generally offer better thermal stability compared to bamboo fibres, likely due to their higher cellulose content and structural integrity. TGA displayed that the hybrid date palm fibres/Kenaf fibres (3DP/7 KF) biocomposites had a greater glass transition temperature ($T_g$) and better thermal degradation resistance [33].

**Table 3**
Thermal analysis properties of fibre biocomposites.

| The code of samples | The onset temperature ($T_{onst.,}$ °C) | The maximum temperature ($T_{max,}$ °C) from the DTG curves | Yield char (Yc) (%). |
|---|---|---|---|
| K50 | 320.22 | 380.25 | 26.32 |
| B50 | 280.54 | 360.23 | 18.65 |
| 7K/3B | 318.67 | 375.78 | 24.17 |
| 5K/5B | 310.35 | 370.65 | 22.25 |
| 3K/7B | 290.44 | 365.43 | 20.69 |

The hybrid composites exhibit a decreasing trend in thermal stability and char yield percentage in the following order:

**Thermal Stability:** 7K/3B (318.67 °C) > 5K/5B (310.35 °C) > 3K/7B (290.44 °C)

**Char yield(%age):** 7K/3B (24.17 %) > 5K/5B = (22.25 %) > 3K/7B = (20.69 %)

### 4.2. Mechanical properties

Fig. 3A illustrates the tensile strength and tensile modulus of various biocomposites, which are marked as K50, 7K3B, 5K5B, 3K7B, and B50. From Fig. 3A, it is evident that the K50 biocomposite exhibits the highest tensile strength among all the biocomposites, reaching approximately 43 MPa. This indicates that the K biocomposite, which contains a high percentage of kenaf fibres, demonstrates superior tensile properties compared to other biocomposites. In contrast, the B biocomposite, which represents a high bamboo content, shows the lowest tensile strength, around 32 MPa. The other hybrid biocomposites, namely 7K3B, 5K5B, and 3K7B, show intermediate tensile strength values, suggesting that blending fibres in specific ratios affects the overall strength characteristics. The pattern suggests that the incorporation of kenaf fibres significantly enhances tensile strength, while the addition of bamboo tends to reduce it. This trend aligns with the known mechanical properties of kenaf, which generally exhibit better tensile strength due to the high cellulose content and effective fibre-matrix bonding. In previous related work, the findings of mechanical tests showed that the hybrid bamboo (B)/oil palm fibre (O) biocomposites (5B5O) had the highest tensile strength and modulus, which were 35.66 MPa and 4.95 GPa, respectively [4]. On the other hand, Fig. 3B shows the elongation at break (%) of various biocomposites marked as K50, 7K3B, 5K5B, 3K7B, and B50. As shown in Fig. 3B, it is evident that the elongation at break varies significantly among the biocomposite types. The 5K/5B biocomposite exhibits the highest elongation at break, approximately 2 %, indicating that this combination of fibres provides the greatest flexibility and ductility before fracture. This is closely followed by the 3K/7B

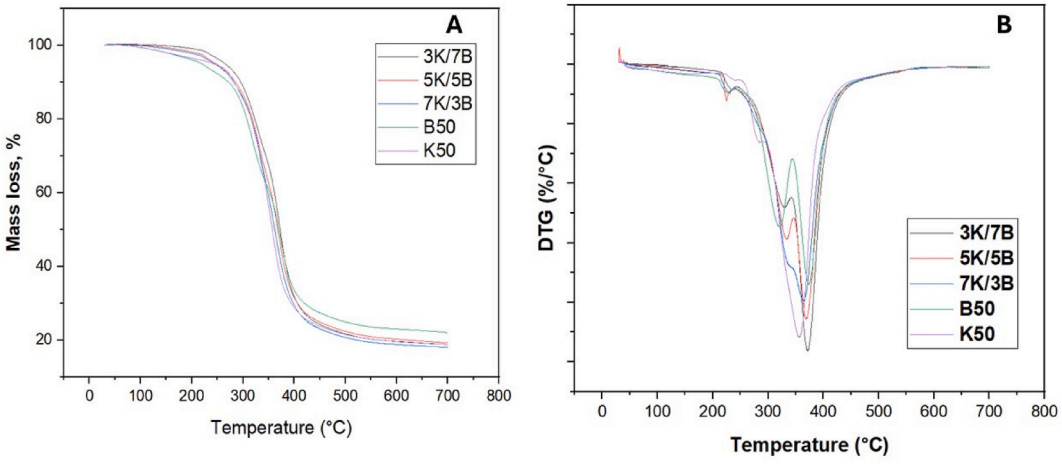


**Fig. 2.** Thermogram curves (A) TGA and (B) DTG of various biocomposites.

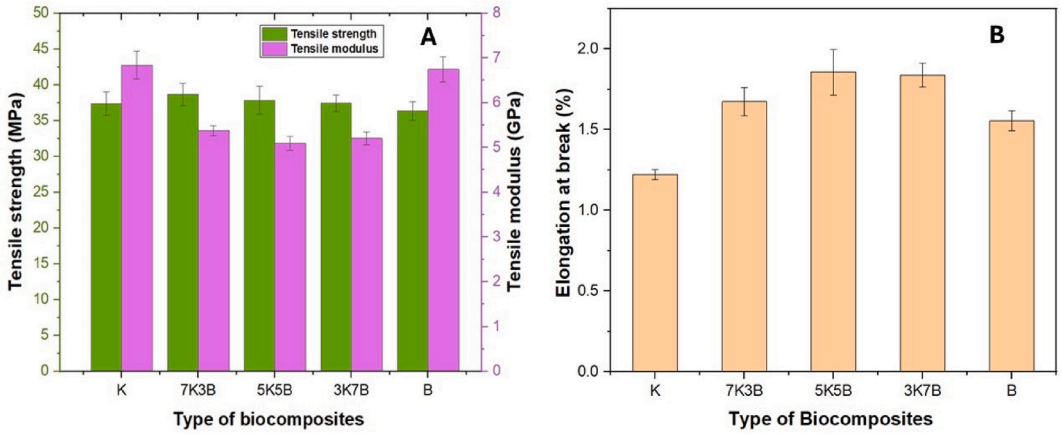


**Fig. 3.** The tensile strength and modulus (A) and the elongation at break (%) (B) of fibre biocomposites.

biocomposite, which also demonstrates relatively high elongation, suggesting that a balanced ratio of kenaf and bamboo fibres enhances the material's ability to stretch under stress. In contrast, the B50 biocomposite, predominantly composed of bamboo fibres, shows the lowest elongation at break, slightly above 1 %. This indicates that bamboo fibres contribute to a more rigid and less ductile composite. Similarly, the K50 biocomposite, containing a higher ratio of kenaf fibres, also displays a lower elongation compared to the hybrid biocomposites, though it is marginally higher than the B50 biocomposite. The hybrid biocomposites, particularly 7K3B and 5K5B, exhibit intermediate elongation values, suggesting that combining bamboo and kenaf in specific ratios results in improved flexibility compared to pure fibre biocomposites. This trend aligns with the typical behaviour of natural fibre biocomposites, where a combination of fibres with different mechanical properties can enhance the overall flexibility. The results indicate that optimising the fibre blend ratio can significantly influence the ductility of the biocomposite, making hybrid combinations particularly valuable for applications requiring both strength and flexibility. Although the 5K/5B composite exhibited higher elongation at break, its tensile strength was comparatively lower. This can be attributed to insufficient fibre–matrix adhesion at higher total fibre loading, leading to ineffective stress transfer and early fibre pull-out. The simultaneous presence of both kenaf and bamboo fibres at equal proportions may also cause heterogeneous dispersion and microvoid formation, acting as stress concentrators that promote premature failure. The higher elongation, however, arises from the matrix's greater ability to deform plastically once fibre debonding occurs, allowing fibre sliding and crack bridging before complete fracture.

Fig. 4 explains the impact strength (J/m$^2$) and impact resistance (J/m) of various biocomposites marked as K50, 7K3B, 5K5B, 3K7B, and B50. From Fig. 4, it is obvious that the K50 biocomposite exhibits the highest impact strength, approximately 7000 J/m$^2$. This suggests that the K50 biocomposite sample, likely composed predominantly of kenaf fibres, demonstrates superior energy absorption upon impact, indicating a high resistance to fracture. The impact resistance for the K50 biocomposite is also high, close to 70 J/m. The combination of high strength and resistance indicates that kenaf fibres significantly contribute to the material's toughness and ability to resist unexpected forces. In contrast, the B50 biocomposite exhibits the lowest impact strength among the samples, approximately 5000 J/m$^2$. However, it demonstrates the highest impact resistance, exceeding 80 J/m. This combination of lower strength but higher resistance indicates that bamboo fibres, while not as strong under impact, are more resilient and able to resist damage propagation. This suggests that bamboo's structural characteristics make it more resistant to crack initiation despite its lower overall strength. The hybrid biocomposites, namely 7K/3B, 5K/5B, and 3K/7B, exhibit intermediate values for both impact strength and

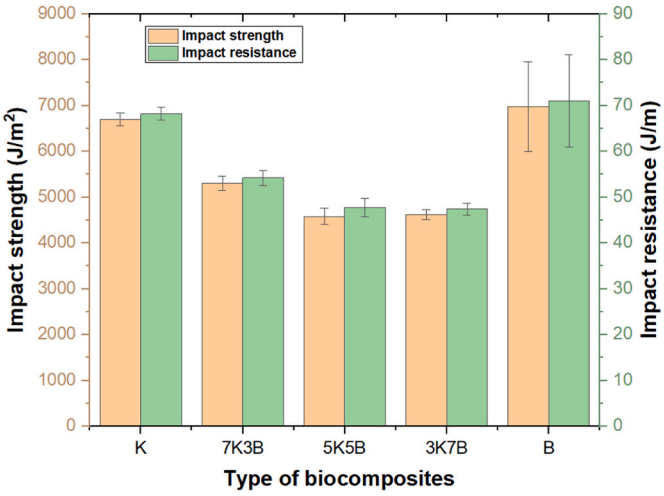


**Fig. 4.** The impact strength and impact resistance of biocomposite samples at different loading of fibres.

impact resistance. Among them, the 7K/3B biocomposite shows relatively higher values compared to the other hybrid biocomposites, with an impact strength of around 6000 J/m$^2$ and an impact resistance of approximately 60 J/m. The 5K/5B and 3K/7B biocomposites display comparable values, with slightly lower impact strength and resistance than 7K3B. This trend suggests that incorporating a higher proportion of kenaf fibres within the hybrid structure enhances the composite's impact performance. it is known that kenaf fibres, as natural fibres, generally enhance the impact strength due to their high cellulose content and fibrous structure, which allows for better energy dissipation. In contrast, bamboo fibres, while exhibiting good resistance due to their lignin-rich matrix, do not absorb impact energy as efficiently, resulting in lower impact strength. Hybrid biocomposites exhibit a balance between these characteristics, with the ratio of kenaf to bamboo significantly affecting the final properties. The combination of impact strength and impact resistance observed in the graph indicates that kenaf fibres are more suitable for applications requiring high energy absorption during impact, while bamboo fibres are advantageous when resistance to crack propagation is crucial. The hybrid biocomposites offer a balanced performance, making them suitable for applications where moderate toughness and resilience are required. The results align with the fundamental mechanical behaviour of the individual fibre types and highlight the potential of hybridisation to achieve tailored impact properties.

Fig. 5 presents the flexural strength (MPa) and flexural modulus

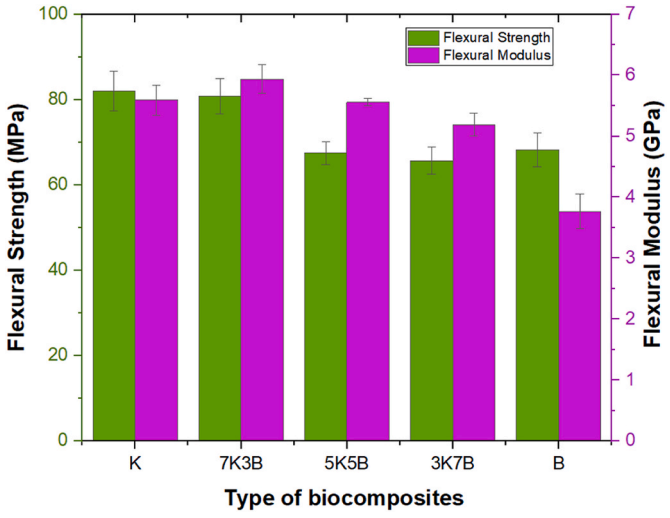


**Fig. 5.** The flexural strength and modulus of biocomposite samples at different loading of fibres.

(GPa) of various biocomposites (K50, 7K3B, 5K5B, 3K7B, and B50). The K50 biocomposite exhibits the highest flexural strength, approximately 85 MPa, indicating its superior ability to withstand bending forces without fracturing. Additionally, the flexural modulus of the K50 biocomposite is around 6 GPa, demonstrating significant stiffness. These results suggest that kenaf fibres contribute significantly to both the strength and rigidity of the biocomposite, making it highly resistant to deformation under flexural stress.

The strong interfacial bonding between the kenaf fibres and the matrix material likely enhances the overall flexural properties. The B50 biocomposite shows the lowest flexural strength, roughly 70 MPa, and the lowest flexural modulus of about 4 GPa. This indicates that bamboo fibres, while inherently strong in tensile applications, may not perform as well under bending stress compared to kenaf fibres. The lower modulus also reflects reduced stiffness, which can be attributed to the natural structure of bamboo fibres that may not integrate as effectively within the matrix compared to kenaf. The hybrid biocomposites (7K/3B, 5K/5B, 3K/7B) exhibit average flexural properties, demonstrating that combining kenaf and bamboo fibres influences the balance between strength and stiffness. Among the hybrids, the 5K/5B biocomposite shows relatively higher flexural strength (around 80 MPa) and modulus (approximately 5.5 GPa), implying that an equal ratio of kenaf and bamboo yields a balanced flexural performance. The 7K/3B biocomposite follows closely, while the 3K/7B biocomposite shows a slight reduction in both strength and modulus compared to the 5K/5B. This trend aligns with the typical mechanical behaviour of natural fibre biocomposites, where the fibre type, composition, and interfacial adhesion significantly influence the final properties. Kenaf fibres, known for their high cellulose content and promising mechanical characteristics, contribute to higher flexural strength and stiffness. In contrast, bamboo fibres, although providing a degree of rigidity, may reduce the overall performance when used as the primary reinforcement.

### 4.3. DMA analysis

The comparative analysis of the storage modulus versus temperature for the five material compositions (3K/7B, 5K/5B, 7K/3B, B50, and K50) reveals distinct variations in stiffness and thermal response (Fig. 6). At lower temperatures (20–60 °C), the 5K/5B composition exhibits the highest storage modulus, indicating the greatest rigidity, followed closely by 3K/7B and 7K/3B. In contrast, the sample (B50) shows the lowest modulus, indicating increased flexibility. As the temperature approaches the glass transition range (70–100 °C), all biocomposites

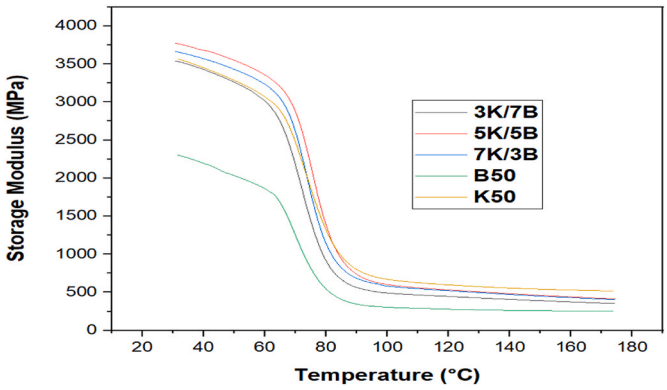


**Fig. 6.** Storage modulus curves of biocomposite samples.

exhibit a significant drop in storage modulus, marking the transition from the glassy to the rubbery state. The rate of decline is sharper for 5K/5B and 3K/7B, while B50 and K50 exhibit a more gradual reduction. Beyond this transition, at higher temperatures (100–180 °C), the storage modulus values for 3K/7B, 5K/5B, and 7K/3B converge and stabilise around 100–300 MPa, reflecting similar mechanical behaviour in the rubbery state. On the other hand, B50 and K50 maintain lower modulus values (around 100–200 MPa), suggesting these compositions are more prone to softening and deformation at elevated temperatures. In summary, 5K/5B demonstrates the highest initial stiffness, while B50 remains the most flexible throughout the temperature range, with all compositions converging to similar values as they reach the rubbery state. Generally, the biocomposite sample (5K/5B) has the highest storage modulus (3764.14 MPa) among the given data points (Fig. 6), indicating that it has the greatest stiffness and resistance to deformation, while the sample (7K/3B) showed slightly lower storage modulus (3654.71 MPa). This blend also exhibits high stiffness, though marginally reduced compared to the first. On the other hand, the sample (3K/7B) observed the lowest storage modulus (3529.64 MPa) among all hybrid biocomposites, which maintains considerable stiffness. The single biocomposite (B50) showed the lowest storage modulus (2313.81 MPa) among all samples, which means that this composition is significantly more flexible or less stiff compared to the others, as shown in Fig. 6.

Fig. 7 illustrates the viscoelastic behaviour of the biocomposites, where 3K/7B shows the highest loss modulus, indicating greater energy

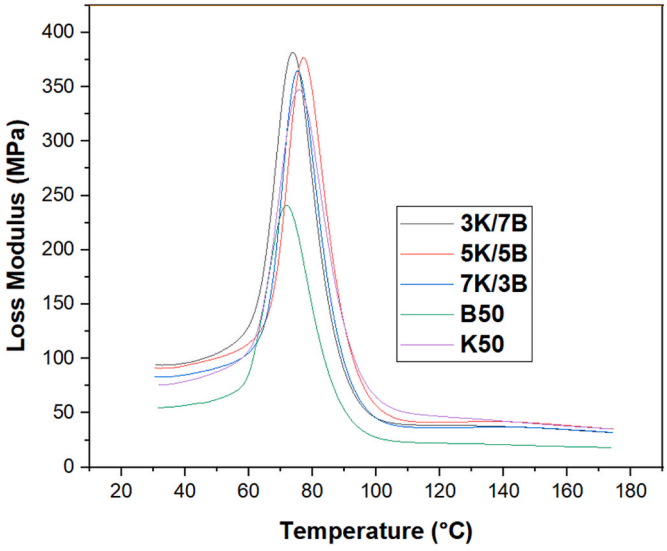


**Fig. 7.** The loss modulus of various biocomposite samples.

dissipation and damping capacity near $T_g$, while B50 shows the lowest. The small differences in the $T_g$ temperatures suggest that the composition ratio influences the temperature range of viscoelastic performance, with 5K/5B and 7K/3B exhibiting slightly higher transition temperatures compared to B50. This indicates that compositions with a higher "K" content may offer better performance in applications requiring energy absorption at slightly higher temperatures.

The damping factor or loss factor (tan δ) for a method relates to the elastic relation to viscous characterisations [34–36], thus, an excellent degree for energy absorption with an elevated degree for non-elastic deformation [37]. As seen in Fig. 8, the tan δ increased with increasing temperature, therefore reached its maximum in the transition region, in addition to regularly decreasing in the rubbery region [38,39]. It was remarked that the tan δ value was greatest at the $T_g$ temperature of all biocomposites owing to the ability of chain portions to easily shift in this region. The single biocomposite sample (B50) displayed a minor rise in tan δ value (0.30) among all biocomposite samples. The argument may be owing to that the hybrid biocomposite with a higher amount of B fibre had a higher degree of molecular mobility [40]. With the incorporation of hybrid fibres at a higher loading of single K50 fibres, the sample (7K3B) exhibited the lowest tan δ value (0.26) among all the biocomposites. This indicates a reduction in molecular mobility due to the enhanced interlocking between the hybrid fibres and the matrix.

Hence, the peak of the tan δ was dropped, as demonstrated in Table 4 and Fig. 8. On the other hand, the $T_g$ from the greatest peaks for tan δ showed slight differences. Furthermore, the $T_g$ value of a single B50 biocomposite exhibited a lower value (77.70 °C) compared to other biocomposite samples. On the other hand, other hybrid biocomposites exhibited closer values of $T_g$ compared to the single biocomposites. Idicula et al. [41] found that the hybridisation of fibres enhanced in lowering the damping value associated with $T_g$ has revealed improved load characterisations owing to enhanced interfacial interactions.

### 4.4. TMA analysis of biocomposites

The TMA is an appropriate factor to evaluate the thermal properties of materials, specifically polymers. It observes, in addition, the variations in the specimen's dimensions when subjected to heat, displaying information on the composition of the material [42]. The results indicate that the 3K/7B biocomposite has the highest CTE value, indicating the most significant thermal expansion among the samples. This is consistent with the observed Fig. 9, where the dimension change for 3K/7B was the highest. The K50 biocomposite, composed mainly of kenaf fibres, shows the lowest CTE, indicating that kenaf-based biocomposites are more dimensionally stable under temperature changes. The hybrid biocomposites exhibit intermediate CTE values, with the 5K/5B biocomposite showing a balanced thermal expansion compared to the others. The trend suggests that composites with a higher proportion of bamboo tend to expand more under heat, while those with a higher kenaf content exhibit better dimensional stability. This difference can be attributed to the distinct thermal and hygroscopic properties of bamboo and kenaf fibres. Bamboo's higher moisture absorption and structural composition may contribute to its greater thermal expansion, while kenaf's fibrous structure and lower moisture absorption offer better thermal stability. The dimensional change of all composites increased gradually with temperature, reflecting the typical thermal expansion behaviour of polymer-based materials. However, the extent of expansion strongly depended on the kenaf-to-bamboo ratio. Among the samples, the 3K/7B composite exhibited the highest dimensional change, reaching nearly 100 μm at 180 °C, indicating the lowest thermal stability. This behaviour can be attributed to the higher bamboo fibre content, which, due to its relatively lower stiffness and higher moisture affinity, promotes microvoid expansion and softening of the surrounding matrix during heating. In contrast, the 7K/3B and B50 composites showed the lowest dimensional expansion, suggesting superior dimensional stability and stronger interfacial integrity between the fibre and matrix. The results in Fig. 9 show the dimensional change (μm) as a function of temperature (°C) for the various biocomposites: 3K/7B, 5K/5B, 7K/3B, B50, and K50. From Fig. 9, it is evident that the 3K/7B biocomposite exhibits the highest dimension change, reaching approximately 90 μm at 180 °C. This suggests that the biocomposite with a higher proportion of bamboo (7B) has a greater tendency to expand when exposed to increased temperatures. The 5K/5B biocomposite follows closely, with a dimension change of around 80 μm, while the 7K/3B

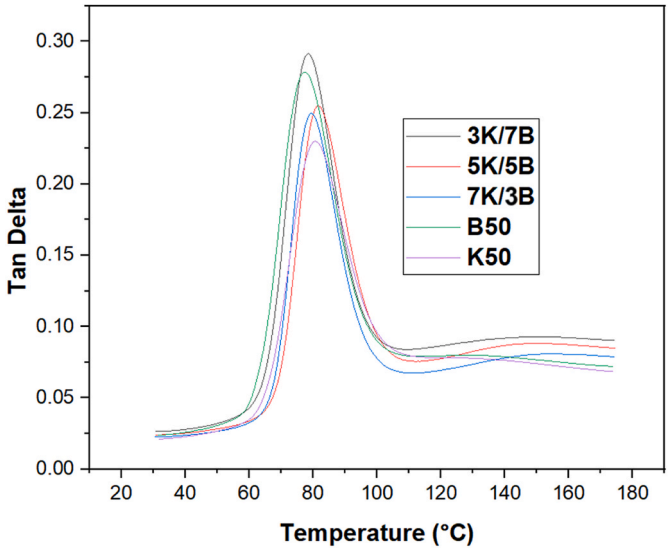


**Fig. 8.** The Damping factor (tan δ) of biocomposite samples.

**Table 4**
The DMA tests the data of the epoxy biocomposite.

| Sample code | Storage modulus (E′) peak (MPa) | Loss modulus (E″) peak (MPa) | Tan δ | $T_g$ (°C) From Tan δ peak |
|---|---|---|---|---|
| K50 | 3566.92 | 300.48 | 0.25 | 80.55 |
| B50 | 2313.81 | 250.25 | 0.30 | 85.22 |
| 7K/3B | 3654.71 | 340.87 | 0.26 | 75.20 |
| 5K/5B | 3764.14 | 350.42 | 0.27 | 90.42 |
| 3K/7B | 3529.64 | 360.65 | 0.28 | 95.22 |

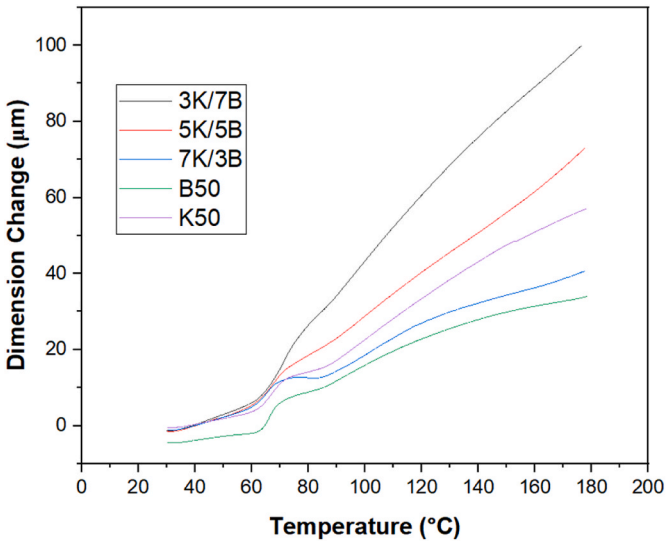


**Fig. 9.** TMA results explain the dimensional changes as a temperature function of biocomposites.

composite exhibits a slightly lower change of approximately 70 μm. The B50 biocomposite, which is predominantly bamboo-based, shows a more moderate change of around 60 μm, while the K50 biocomposite (kenaf-based) displays the lowest dimension change, approximately 50 μm, indicating the lowest thermal expansion among the samples. The presence of more kenaf fibres in 7K/3B enhanced stiffness and restricted the molecular motion of the polymer chains, thus limiting thermal expansion. The 5K/5B hybrid exhibited an intermediate dimensional change, which reflects a balanced interaction between kenaf's rigidity and bamboo's flexibility. Although this ratio led to moderate thermal expansion, it also indicates good fibre dispersion and interfacial adhesion, providing a compromise between stiffness and ductility.

Overall, the TMA findings demonstrate that increasing kenaf fibre content improves the dimensional stability of the hybrid biocomposites by restricting polymer chain mobility and reducing thermal strain accumulation [36]. Conversely, higher bamboo fibre content increases dimensional changes due to weaker thermal constraints and higher hygroscopicity. This trend confirms that fibre composition plays a dominant role in governing the thermo-mechanical dimensional behaviour of bio-epoxy hybrid composites.

### 4.5. Physical properties

#### 4.5.1. Water absorption

Fig. 10 shows the percentage of water absorption (WA, %) for days for different biocomposite samples (K50, 7K/3B, 5K/5B, 3K/7B, B50). The 7K/3B sample exhibits the highest water absorption, reaching 16–17 % after 7 days, indicating that a higher proportion of Kenaf fibres leads to greater water uptake due to Kenaf's hydrophilic nature. The B50 sample exhibits comparatively elevated water absorption, approximately 15 %, which is indicative of the moisture-retentive properties inherent to bamboo fibres [43]. In contrast, the K50 sample shows the lowest water absorption (around 12 %), suggesting that pure kenaf fibre exhibits lower moisture uptake than the blends. The 5K/5B and 3K/7B samples show intermediate water absorption levels, approximately 13–14 %, indicating that balanced or higher bamboo fibre ratios reduce water absorption compared to predominantly kenaf fibre composites. Overall, the results indicate that increasing the Kenaf fibre ratio increases water absorption, while higher bamboo content tends to reduce it slightly, but not as effectively as pure Kenaf.

#### 4.5.2. Thickness swelling (TS)

Fig. 11 shows the thickness swelling (%) over time for different biocomposite samples (K50, 7K/3B, 5K/5B, 3K/7B, B50). The 7K/3B sample exhibits the highest thickness swelling, reaching around 20 % after 7 days, indicating that the higher proportion of kenaf fibre leads to greater moisture absorption and subsequent swelling. Similarly, the B50 sample, which is composed entirely of bamboo fibres, also shows significant swelling (around 18 %) but slightly lower than the 7K/3B. In contrast, the K50 sample shows the lowest thickness swelling at approximately 10 %, suggesting that pure kenaf fibres have better dimensional stability compared to bamboo and its blend. The 5K/5B and 3K/7B samples demonstrate average swelling percentages, around 14–16 %, indicating that increasing the bamboo fibre loading reduces swelling compared to a high kenaf ratio, as shown in Fig. 11. Overall, the results suggest that the additional bamboo content in the biocomposite results in lower swelling, with pure Kenaf fibres showing the best dimensional stability in moisture conditions.

### 4.6. SEM analysis

Fig. 12(a–e) demonstrates the SEM micrographs for fractured surfaces of all samples. Numerous types of failure jointly functioned and then enhanced the fracture toughness of all biocomposites. The surface of a single biocomposite (B50) exhibits significant roughness and irregularity, suggesting brittle fracture behaviour. This could be attributed to a poor interfacial bonding between the fibres and the polymer matrix. In addition, several fibres appear to be pulled out from the matrix, indicating insufficient bonding. This is a common characteristic when the matrix fails to effectively compress the fibres. The voids remaining by the pulled-out fibres suggest that interfacial adhesion was not strong enough to hold the fibres steadily. On the other hand, the surface micrograph of a single biocomposite sample (K50) showed lower pull-out and voids (Fig. 12e) compared to the sample (B50), as shown in Fig. 12d.

## 5. Conclusions

This study successfully developed kenaf/bamboo hybrid bio-epoxy biocomposites and demonstrated that fibre hybridisation enhances the overall structural, mechanical, and thermal characteristics compared to single-fibre composites. Tensile testing revealed that the hybrid formulations achieved higher strength and stiffness, with 3K/7B exhibiting the

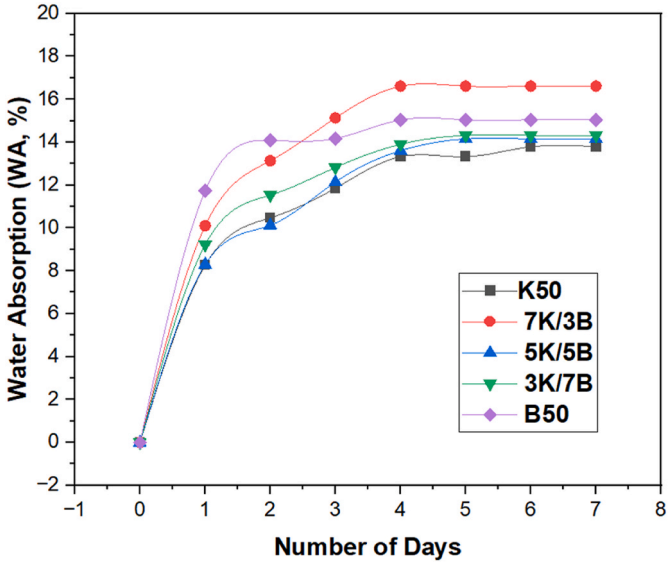


**Fig. 10.** Water absorption, WA (%) of biocomposites against the immersion time.

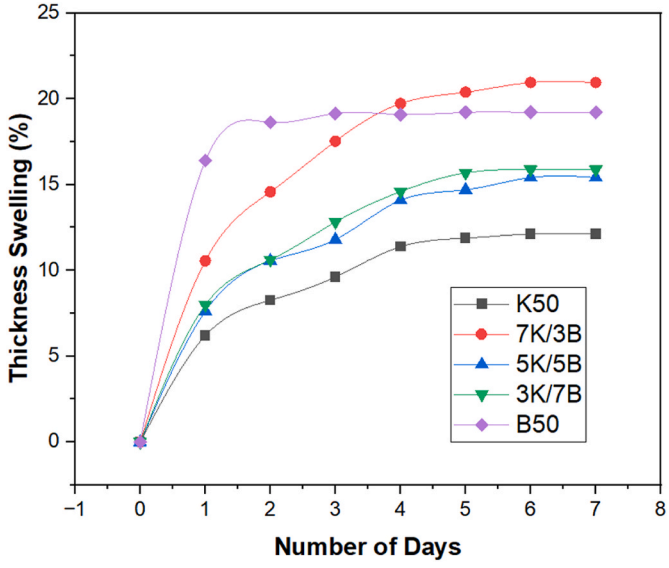


**Fig. 11.** Thickness swelling, TS (%) of biocomposites against the immersion time.

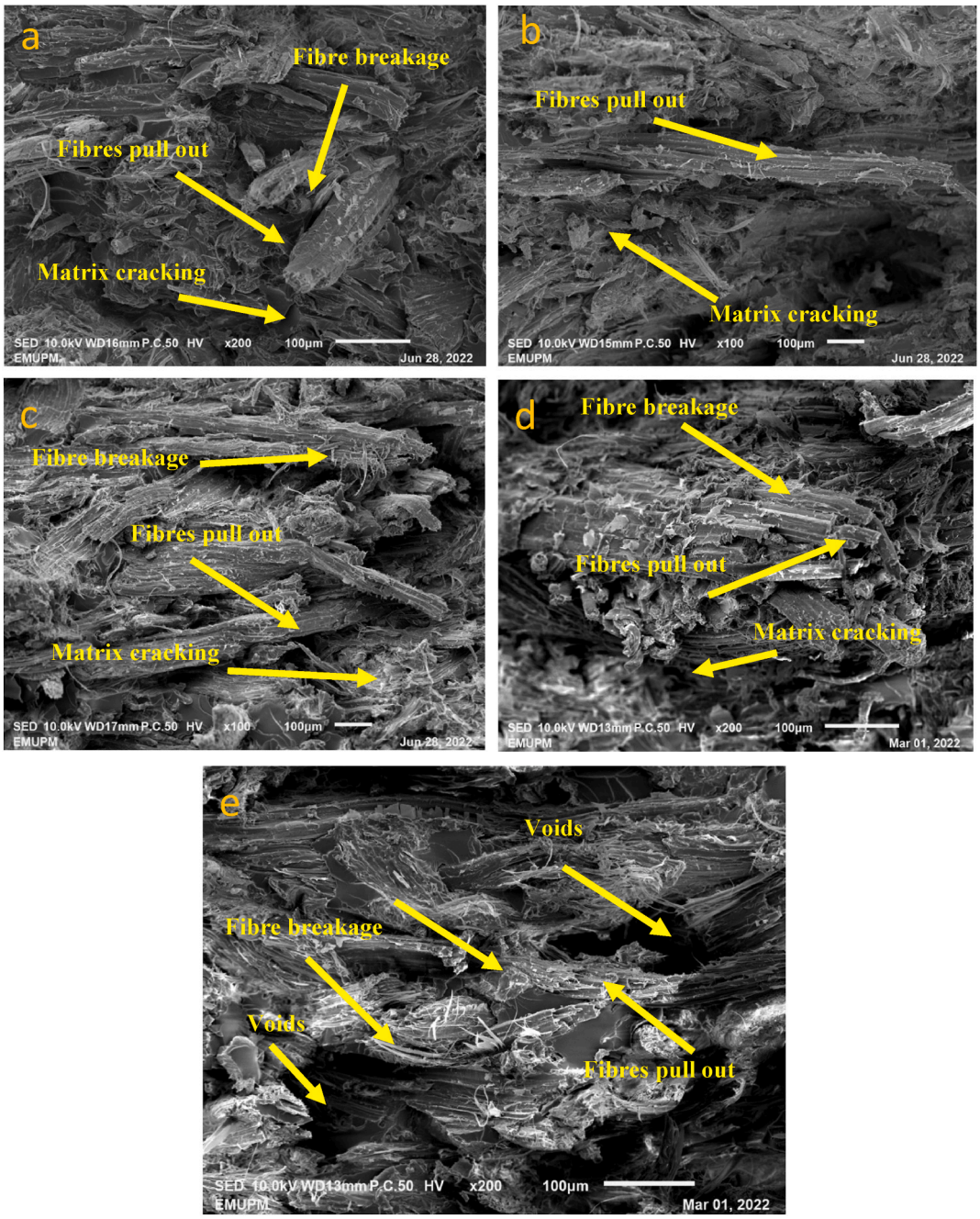


**Fig. 12.** SEM micrographs from the flexural fracture surface at 100× magnifications of pure a (3K/7B) and b(5K/5B) and hybrid c (7K/3B), d (B50) and e(K50) biocomposites.

highest tensile strength (41.7 MPa) and a notable improvement in modulus (~6.9 GPa) relative to the single-fibre composites. DMA results further confirmed this enhancement, where both the storage modulus and loss modulus increased, demonstrating better stiffness and energy dissipation behaviour. The glass transition temperature ($T_g$) increased from 80.55 °C (K50) to 95.22 °C (3K/7B), indicating restricted molecular mobility and improved interfacial adhesion. Thermal characterisation showed that hybrid composites exhibited improved thermal stability relative to the B50 composite, while K50 remained the most thermally stable overall. Importantly, the dimensional change under thermal exposure followed the trend K50 (~50 µm) < B50 (~60 µm) < 7K/3B (~70 µm) < 5K/5B (~80 µm), confirming the role of kenaf in reducing thermal expansion and providing better dimensional integrity at elevated temperatures.Physical characterisation revealed an increase in water absorption with hybridisation content, while thickness swelling decreased, emphasising contrasting effects of fibre composition on moisture interaction and dimensional stability. SEM analysis supported these improvements by confirming stronger fibre–matrix interfacial adhesion and reduced fibre pull-out in hybrid samples. Overall, a kenaf-dominant hybrid ratio delivered the best balance of performance, making K/B biocomposites suitable for automotive interior parts, sustainable construction panels, lightweight structural components, and consumer products requiring improved thermal and mechanical reliability.

## Funding

The authors extend their gratitude to the United Arab Emirates

University for providing the funds through Fund CODE 12R287. This work is also funded by the ongoing Research Funding Program (ORF-2025-117), King Saud University, Riyadh, Saudi Arabia.

## 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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