Characterization of Banana and Sisal Fiber Fabrics Reinforced Epoxy Hybrid Biocomposites with Cashew Nut Shell Filler for Structural Applications

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Mechanical, thermal, and water absorption properties of banana fiber and sisal fiber-reinforced epoxy biocomposites were evaluated with and without cashew nut shell (CNS) filler, either separately, or as hybrid biocomposites. Bidirectional woven mats were used to make composites by compression molding. The CNS filler content was 5% to 10%. Adding CNS filler of up to 5% improved the mechanical and thermal properties. Further increases in filler content above the threshold value diminished their mechanical properties due to poor dispersion and increased porosity. The maximum tensile and flexural strength were found as 43 and 92 MPa. The highest impact strength was obtained with the hybrid biocomposites with 5% filler. This was attributed to the toughening effect of phenolic compounds in the CNS. In addition, the thermal stability of the biocomposites was influenced by filler content. The biocomposites exhibited varying water absorption capacities as the filler content increased with the water uptake. Scanning electron microscopy (SEM) images showed the microsurface of the fractured samples and their interfacial bonding, fiber pull-out, and fracture. However, increasing filler content in the biocomposite reduced the filler pull-out and led to fiber breakage.

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INTRODUCTION

Increasing studies underscore the growing utilization of natural fibers such as banana and sisal in polymer composites. This trend is driven by the pursuit of sustainability in production processes and the shift towards a circular economy. While natural fiber-reinforced biocomposites offer environmental benefits, challenges such as moisture absorption and durability need to be addressed for wider outdoor applications (Alias *et al*. 2023; Arivendan *et al*. 2023a). Standardized fiber extraction methods and improved interfacial properties between fibers and matrices are essential to enhance the performance of biocomposites. Multidisciplinary collaboration and research into biodegradability, life cycle assessment, and nanocomposites can further propel advancements in natural fiber-reinforced polymer (FRP) composite technology, paving the way for a smarter and eco-conscious future (Arivendan *et al.* 2023b; Makinde-Isola *et al.* 2023). Outstanding physical, chemical, and electrical qualities set nanomaterials apart from traditional materials (Zhang *et al.* 2023b).

A review on banana and jute fiber revealed the potential of jute and banana fiber composites, highlighting their mechanical, physical, and chemical attributes. The composites offer cost-effectiveness and versatility, with other advantages, such as low density, biodegradability, and fire resistance. Jute-substituted wood is found in diverse applications, while banana fibers exhibited strength that was comparable with glass fibers and enhanced by alkali treatments. Together, they offer promising eco-friendly alternatives for various engineering applications (Pujari *et al.* 2010). The compression and water absorption behavior of hybrid fiber polymer composites composed of banana and sisal fibers indicated that water absorption was influenced by the composition of the hybrid fibers and the polymer matrix. Hybrid composites showed varying degrees of water absorption when compared with pure banana or sisal fiber composites, suggesting synergistic effects (Badyankal *et al.* 2021). A review provided a comprehensive analysis of the mechanical performance of epoxy composites reinforced with banana fibers, showing that the tensile and impact strengths of the banana fiber epoxy composite improved with higher fiber length (Nehete 2020). The comparative analysis of the mechanical properties of polymer-based composites reinforced with banana and sisal fiber showed that the amount of ordinary water absorbed around 20% higher than seawater absorption and around 10% higher than distilled water absorption (Badrinath and Senthilvelan 2014).

Investigation of mechanical properties and water absorption behavior of woven jute/banana hybrid composites has indicated that failure of the composites occurred due to the presence of voids, resulting in fiber pull-out. The presence of these voids alongside those between fibers and matrix suggested inadequate fiber-matrix adhesion, leading to decreased mechanical properties (Venkateshwaran and Elayaperumal 2012). The water absorption process in flax fiber-reinforced bio-epoxy composites established that both initial and maximum absorption capacities increased as fiber volume fraction increased. This phenomenon was due to the hydrophilic nature of vegetable fibers, potentially leading to micro-crack formation in the brittle epoxy matrix. It also facilitated an increased water transport through the fiber-matrix interface, leading to an increase in tensile and flexural strengths of the fiber epoxy composites than drier fiber epoxy composites (Błędzki and Gasasan 1999). Fourier-transform infrared spectroscopy (FTIR) analysis confirmed the functional groups in banana and sisal fibers, indicating OH, CH, C=C, C=O, and C-O-H groups. Thermogravimetric analysis (TGA) revealed that hybrid composites had a lower mass loss at higher temperatures when compared with single-fiber counterparts, showing the best high-temperature stability with sisal and a banana fiber ratio of 30:70%. Natural fiber composites typically degrade at 300 to 520 °C, with minimal impact of hybridization on stability (Okafor *et al.* 2021a). This impact of total fiber volume percentage and banana-sisal fractional distribution on the mechanical properties of polyester hybrid composites indicated that tensile and flexural strength increased with higher total fiber volume percentage and increased banana fraction in the composite. This was attributed to banana fiber's superior tensile strength (Gupta *et al.* 2021).

A developed banana/sisal fiber-reinforced fully biodegradable hybrid biocomposite rod with fiber reinforcement of 40% has been studied. Its tensile, compression, and flexural strengths increased approximately 2.5 times when compared with neat polylactic acid (PLA). Impact strength similarly improved nearly 2.0 times (Pannu and Singh 2023). The banana and sisal fiber-reinforced composites produced optimal compressive, tensile, and flexural strengths when 1.0% volume of fiber was added. Sisal fiber reinforcement exhibited superior tensile, compressive, and flexural strengths when compared with banana fiber. Increasing fiber content beyond 1.5% decreased strength while adding 1.0 to 1.5% enhanced tensile and flexural strengths (Bharathi *et al.* 2021). The sisal/epoxy composite demonstrated the highest tensile, flexural, and impact strengths, suggesting its suitability for lightweight commercial and consumer applications. However, increasing the number of mat layers raised the risk of delamination and inter-laminar cracks, leading to a reduction in mechanical strength (Siva *et al.* 2021). Previous research has shown that when T increases, epoxy polymer composites' mechanical characteristics will drastically decline (Jiang *et al.* 2024). Composites were investigated to reveal characteristic peaks in their FTIR spectra. A strong and broad peak indicated O-H stretching with intermolecular hydrogen bonding, while a weak band suggested the presence of hydrogen bond-free O-H groups from the epoxy resin. The presence of saturated and unsaturated C-C stretching frequencies indicated C-O stretching frequency and C-O-C ether linkage in all the polymer composites. These confirm the presence of phenolic groups rather than acidic groups in the composites (Balaji *et al.* 2019). The pure sisal and banana composites with hybrid types, which consisted of different fiber percentages, have been studied. The hybrid composites with 15% sisal and 30% banana fibers showed optimal tensile and flexural strengths, while those with 30% sisal and 15% banana fibers exhibited improved impact energy (Sathish *et al.* 2015). The sisal fiber-reinforced polymer composites for aviation applications exhibited better compression, tensile, yield strengths, and minimal elongation (Sridhar *et al.* 2019). The natural fiber-epoxy resin hybrid composite samples with 40% hibiscus and gongura fiber and 20% Madura showed minimal water absorption, and high tensile, flexural, and impact strengths (Marichelvam *et al.* 2023). Pang *et al.* 2022 suggested that the fiber coating layer, which was combined with water borne epoxy polymer and embedded cement particles (inlay), enhanced interfacial bonding while also protecting the fibers.

The thermal properties of hybrid banana/sisal fiber-reinforced composites demonstrated improved thermal stability with a combination of 70% sisal and 30% banana, exhibiting the best stability (Okafor *et al.* 2021b). The impact testing methods for natural fiber composites highlighted the limitations of Izod and Charpy tests in capturing their impact behavior due to their anisotropic nature. Drop weight impact testing offered detailed insights, particularly on delamination influenced by some factors, including fiber-matrix interface and sample characteristics, with energy absorption mainly during elastic deformation (Rong and Sun 2012). The mechanical properties of sisal/banana fiber hybrid sandwich composites showed that their exposure to water led to a decline in mechanical properties of the hybrid sandwich composites, with significant reductions in tensile, impact, and flexural strengths up to 18.3, 20.3, and 23.1%, respectively (Chithra Devi *et al.* 2022). The function and role of curing agents in epoxy resin systems established their impact on mechanical properties and cure kinetics of composites. The effects of various types of curing agents, including amine-type, alkali, anhydrides, and catalytic agents, were examined on resin characteristics and industrial applications, with a focus on enhancing their mechanical functionality and eco-friendliness (Aziz *et al.* 2023). Temperature changes will always have an impact on adhesively bonded structures over the course of their useful lives (Zhang *et al.*2024) .

Banana fiber-based hybrid composites have been studied. For example, Prashanth *et al.* (2021) found that the addition of nano-clay improved their mechanical strength and thermal stability. Moreover, hybrid composites of banana and jute fibers with a 50% weight percentage of jute showed better thermal and mechanical properties and moisture resistance (Prashanth *et al.* 2021). Reinforcement of fillers played a vital role against buckling in structural components (Wang *et al.* 2023). Investigations of the tensile and impact properties of banana FRP composites found that alkali treatment (10% NaOH) of banana fibers improved their fiber-matrix bonding, increasing tensile and impact strengths due to better fiber-matrix adhesion and interfacial bonding (Sivaranjana and Arumugaprabu 2021). The jute/sisal fiber reinforced epoxy composite laminate plates fabricated with hand lay-up technique showed that sequenced sisal/jute/jute/sisal FRP hybrid composite had better static mechanical properties (Dhinesh Kumar *et al.* 2021). The epoxy-based composites for mechanical stability revealed optimal combinations for superior mechanical qualities with 10% sisal, 15% banana, 8% NaOH, 10MPa pressure, and 100 °C temperature as well as 20% sisal, 10% banana, 5% NaOH, 10MPa pressure, and 120 °C temperature (Sumesh and Kanthavel 2020). (Su *et al.* 2024) studied the importance and impact of particle and matrix surface collisions. The epoxy composites with intra-ply flax/sisal and jute/sisal composite laminates were created for mechanical characteristics, using hand lay-up with intra-ply woven techniques following American Society for Testing and Materials (ASTM) standards for assessing tensile and flexural strengths. The results obtained from their flexural and tensile behaviors revealed the mechanical responses of intra-ply flax/sisal and jute/sisal epoxy composites, emphasizing higher stress absorption through interlocking fiber threads (Zuo *et al.* 2021). The flexural strength of hybrid composites was varied by altering the ramie/flax fiber length. The hybridization of fibers has shown better results in polymer composites (Sumesh *et al.* 2023). Egg shell filler was used to prepare the composites and study mechanical behaviours in hyacinth (WH) plant ash composites (Ajithram *et al.* 2023). According to the findings (Zhang *et al.* 2023a), the composite beam made of natural fillers increases the beam's ultimate load capacity when subjected to a unidirectional load.

Considering the relevant literature, it is evident that the effects of carbonated CNS filler on the properties of banana and sisal fiber-reinforced hybrid biocomposites have not been investigated. The development of medium weight fibreboards for light weight applications are needed to add available CNS filler in the hybrid composites. Therefore, this study characterized the mechanical, thermal, and water absorption properties of banana and sisal fiber-reinforced epoxy hybrid biocomposites with the addition of CNS filler. The investigation mainly analysed the impact of filler content on the performance of the biocomposites, including tensile and flexural strengths, impact resistance, and thermal stability.

EXPERIMENTAL

Materials

Fiber materials

Figure 1(a) shows bi-directional plain sisal fiber woven fabric obtained from GoGreen products located in Chennai, Tamil Nadu, India. The tensile strength of the woven fabric was approximately 897 MPa. Its density and thickness were1.5 g/cm^3 and 0.21 mm, respectively. The sisal fiber exhibited a thermal stability of 38.5 °C. Similarly, Fig. 1(b) depicts a bi-directional plain banana fiber woven fabric sourced from the same place but with a different tensile strength of approximately 529 MPa, with a density and thickness of 1.28 g/cm^{3}and 3 mm, respectively. The thermal stability of banana fiber was 250 °C. The CNS filler was obtained from CNS plate. The dried CNS was powdered by using flour mill. The small steel mesh was used to separate the filler size by manually. The surface texture of CNS filler was rougher (Sathishkumar *et al.* 2018) and it increased the fiber matrix bonding to increase the mechanical properties of the composites.

Epoxy resin and hardener

The materials acquisition involved obtaining LY556 epoxy of laboratory quality and HY951 hardener from Covai Seenu industry, a resin supplier based in Coimbatore, Tamil Nadu, India. The viscosity of the resin and hardener were approximately 12000 CPs and 250 Cps, respectively. The epoxy resin and hardener had densities of 1.20 and 0.98 g/cm³, respectively. The thermal tolerance of the epoxy resin was 315 °C.

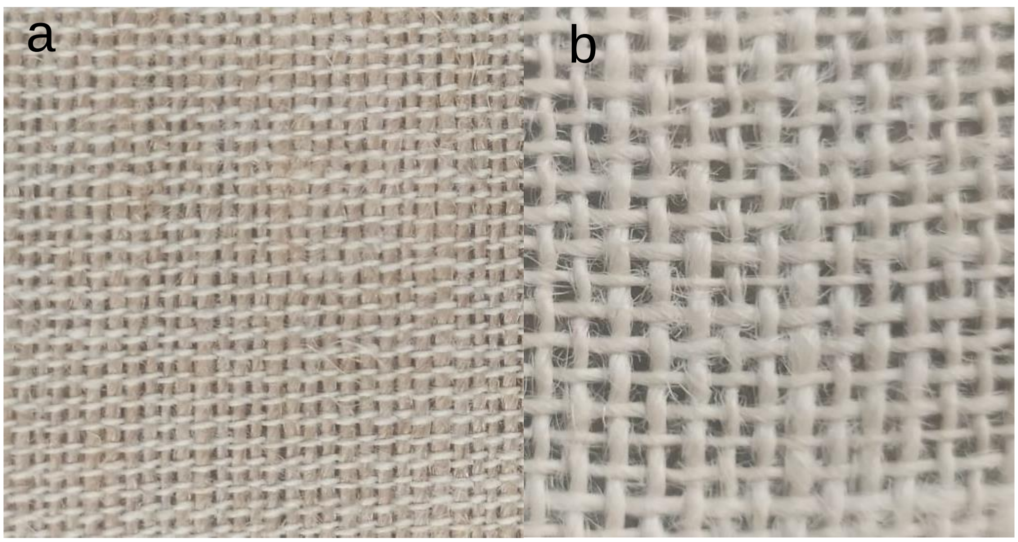

Fig. 1. (a)Sisal and (b) banana fiber woven fabrics

Methods

Fabrication of composites

The process began with the compression molding technique to create composite plates, using sisal and banana fibers. Fibers were tailored to match the 240 mm × 210 mm mold size. For blending, a cup housed the resin and hardener and it was stirred thoroughly. Layering commenced by alternating banana and sisal fibers with resin and hardener filling the interspaces. The single fiber composites were maintained at 40% fiber weight fraction. The banana and sisal fiber woven mat composites contained the fiber ratio of 1:1 with 50:50% fibers weight fraction from 40% total weight fraction of fiber. The resin content was 60% for specimens without filler addition. The filler addition composites contained 55% and 50% of resin in 5% and 10% CNS filler composites, respectively. Fabrication steps included the assembly of a mold box with an affixed overhead projector sheet, epoxy resin, and hardener preparation, considering filler weight fraction of 5% and 10% in the mixture. The banana fiber was placed in the mold base, spreading the mixture over the banana fiber evenly. The sisal fiber was on top of the banana fiber, pouring and spreading the mixture over the sisal fiber, iterating steps 4 to 7 for additional layers. The mold box was sealed, using a C-clamp for compression (applied 5-bar hydraulic pressure) and the composition was left for 24 h for the biocomposite to cure at atmospheric temperature. The mold was opened using a chisel to carefully extract the undamaged biocomposite plate. A biocomposite plate was fabricated by incorporating five layers of banana and sisal fibers, resulting in a thickness of approximately 3 mm. To ensure consistent thickness across the biocomposite plates, four steel plates measuring 10×10×2 mm were strategically positioned at the four corners of the mold. The molded composite plates had dimensions of 240 × 210 × 3 mm, respectively. For easy removal of composite, the mold surface was coated with a thin layer of polyvinylchloride.

Tensile properties

Tensile samples were prepared using a laser-cutting machine by ASTM D638 standards. The samples were dog-bone-shaped, featuring dimensions of 160 × 20 × 3 mm, respectively. The universal testing machine, made by Deepak Poly Plastic Pvt ltd, India, model of DTRX - 30 kN equipped with a 5 kN load cell, was employed to conduct the tensile test. Tensile stress, strain, and modulus were derived from the recorded load *versus* elongation curve. The load cell measured the load, while an encoder gauged the extension of the sample. The test was conducted at a crosshead speed of 1.0 mm/min at room temperature. Five identical samples for each of the five composites were tested, and the average values were used for plotting stress-strain curves as used for further discussion.

Flexural properties

Flexural test samples were obtained using a laser-cutting machine in adherence to ASTM D790 standards. The rectangular sample had dimensions of 120 × 13 × 3 mm, respectively. Maintaining a span-to-depth ratio of 16:1, the universal testing machine, made by Deepak Poly Plastic Pvt ltd, India, model of DTRX - 30 kN equipped with a 5 kN load cell, was used to conduct the flexural test. The test utilized a crosshead speed of 1.5 mm/min to calculate the flexural stress. For each of the five composites, five identical flexural samples were tested. The average values were plotted based on flexural stress in MPa to flexural strain in percentage and were utilized for subsequent discussion.

Impact properties

Impact test samples were obtained using a laser-cutting machine by ASTM D256 standards. Each testing sample had dimensions of 60 × 13 × 3 mm. The impact testing machine, made by Deepak Poly Plastic Pvt ltd, India outfitted with a pendulum, produced a potential energy of 2.57 J, and it was equipped with a load cell for the drop weight hammer. These specifications supported a machining accuracy of 25 J and 0.001 J. Before testing, a manually operated notch cutter was employed to create a V-notch on each sample. For each composite, five identical samples were tested, and the average values were plotted based on impact energy obtained in $kJ/m^2$from various biocomposite samples and were used for further analysis.

Scanning electron microscope

Scanning electron microscopy (SEM) imaging on the tensile fractured samples was carried out to investigate the microstructure and surface morphology of epoxy composites. The SEM machine employed for image scanning had the following specifications: an image resolution of 3.0 nm, achieved under operating conditions of an acceleration voltage of 15 kV and a working distance ranging between 8 to 9 mm. The magnification capability ranged from 50 to 500 times, offering detailed imaging across various scales. Additionally, the electron gun utilized an accelerating voltage spanning from 0.5 to 30.0 kV.

Thermogravimetric analysis

Thermogravimetric analysis was used to investigate the thermal degradation behavior of the various epoxy composites. The experimental setup utilized the Jupiter Simultaneous Thermal Analyzer (JSTA) to gradually raise the temperature of a powdered biocomposite sample from ambient conditions to 1000 °C at a heating rate of 10 °C/min. To mitigate potential oxidation effects, the combustion process occurred within a nitrogen atmosphere. High-grade nitrogen gas was consistently introduced into the furnace at a flow rate of 20 mL/min.

Water absorption

Samples for the water absorption test were obtained using a laser-cutting machine. The rectangular samples with dimensions of 50× 13 × 3 mm were dropped in water, soaked, and weighed daily for 32 days. Before the samples were put in water, they were weighed and marked, and two samples for each biocomposite were soaked. The average values were used to plot the curves obtained, based on water gained in percentage to the time taken in square root of minutes.

RESULTS AND DISCUSSION

Water Absorption

Figure 2 shows the water absorption capacities of the various biocomposites. It was observed that the time for stabilization of hybrid biocomposites with 5 and 10% CNS filler was approximately 29 days. The results showed that the hybrid biocomposite with a 10% addition of CNS filler recorded the highest water absorption and the banana FRP composite had the lowest water absorption capacity. The curves indicate that an increase in the addition of the CNS filler increased the water absorption of the hybrid biocomposites. Cashew nut shell contains natural hygroscopic compounds that tend to absorb moisture from the environment. When CNS filler was incorporated into the biocomposite, the compounds could have contributed to the overall water absorption of the samples. The CNS filler may have interfered with the interaction between the epoxy matrix and the reinforcing banana and sisal fibers. This reduced interaction and bond or adhesion led to increased water absorption and potentially degraded the material properties over time.

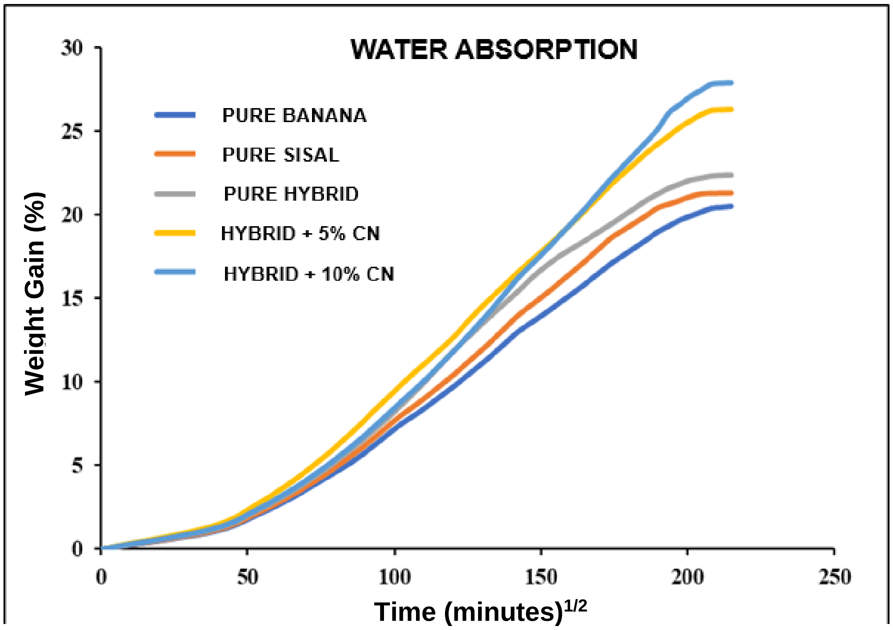

Fig. 2. Water absorption of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

Tensile Properties

Figure 3 depicts the tensile stress *versus* strain curves of the various biocomposites. The stresses for all the biocomposites were gradually increased with their strains. The maximum stress with strain was observed for hybrid biocomposites containing 5% filler content. Figure 4 shows the comparison between tensile stresses, strains, and moduli of all the biocomposite samples. It was observed that the addition of CNS filler up to 5% increased the tensile strength as the particle filler provided additional support to the banana and sisal fibers, resulting in a more efficient load transfer. Moreover, the presence of CNS filler supported more stress distribution evenly throughout the biocomposites during tensile loading. This uniform stress distribution minimized localized areas of high-stress concentration, which promoted a more gradual and controlled failure mechanism. Additionally, it promoted better adhesion between the natural fibers and the polymer matrix. This improved interfacial bonding reduced the possibility of fiber pull-out or de-bonding effect during tensile testing, ensuring higher tensile strength values. However, a further increase in the addition of CNS filler led to a decrease in tensile strength, due to an increase in CNS filler beyond a certain threshold. It resulted in poor dispersion within the composite matrix, forming agglomeration of filler particles. It also created regions of weakness and stress concentration within the materials, leading to failure under load. As the filler loading increased, the available surface area for the fiber-matrix interaction reduced, causing weaker interfacial bonding and decreased tensile strength. The result showed that the tensile stress of sisal FRP biocomposite was 25.9% higher than that of banana FRP biocomposite, while hybrid biocomposite was 29.3% higher than that of sisal FRP biocomposite. The hybrid biocomposite with 5% filler recorded the highest tensile stress of 43.0 MPa and was 9.3% higher than other hybrid biocomposite samples. This implied that a further increase in hybrid biocomposite by 10% filler decreased the tensile stress by 9.7% when compared with the hybrid biocomposite with 5% filler.

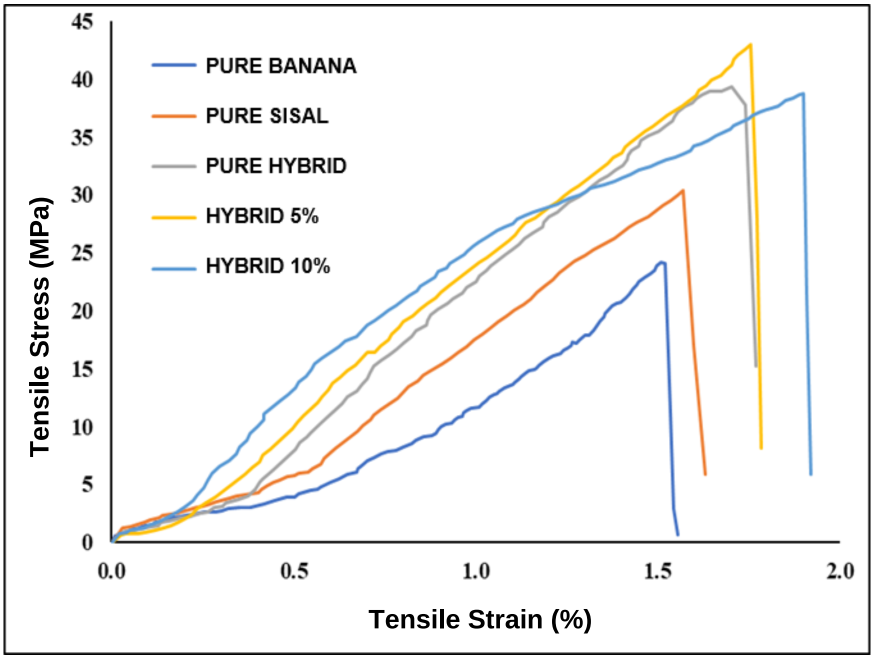

Fig. 3. Tensile stress *versus* strain curve of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

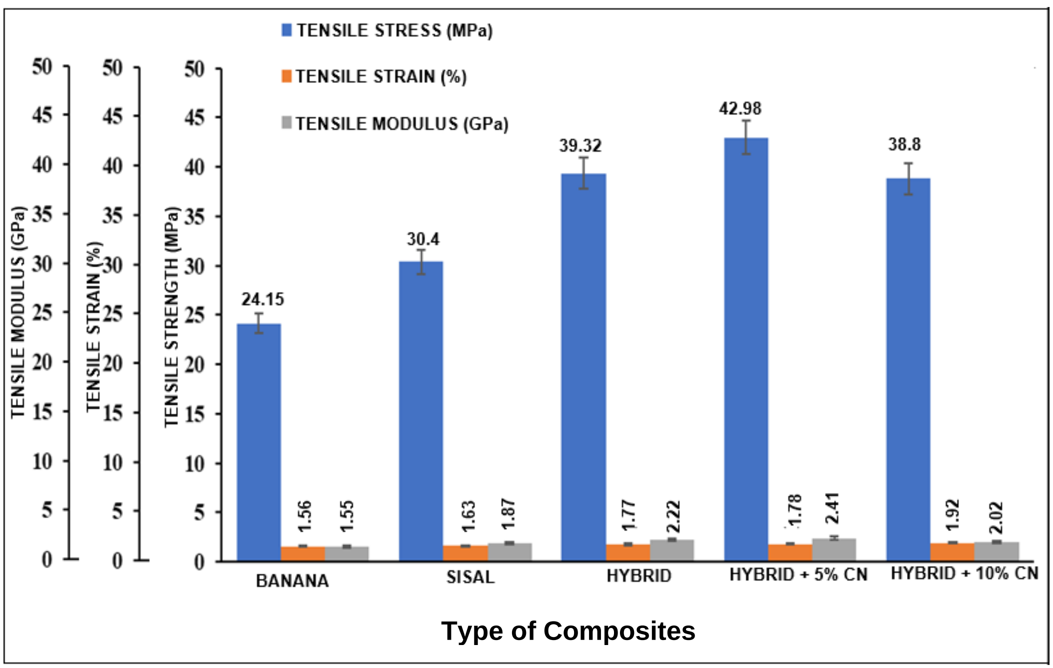

Fig. 4. Tensile properties of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

Flexural Properties

Figure 5 shows the flexural stress against the strain curve of all the biocomposites. Figure 6 shows the comparison between flexural stresses, strains, and moduli of the various composites. It was observed that up to the addition of 5% CNS filler, a better adhesion between the natural fibers and the epoxy was obtained, leading to improved interfacial bonding. This ensured effective load transfer between the constituents and CNS filler particles with high stiffness properties, resulting in increased stiffness of the biocomposites coupled with higher resistance to bending deformation and higher flexural stress values. Moreover, a combination of CNS filler with banana and sisal fibers led to synergistic effects in which the properties of the individual components were enhanced when combined, resulting in a biocomposite material with superior flexural stress when compared with the individual constituents, individually. Further addition of CNS filler reduced their flexural strengths due to the addition of it beyond a certain threshold. This resulted in an overloading effect and weak fiber-matrix interfacial bonding. Consequently, there was an increased porosity within the biocomposite samples where voids acted as stress concentration points and initiation sites for cracks under flexural loading. Hence, the flexural strength was reduced. In addition, it was evident that the flexural stress of sisal FRP biocomposite was higher than that of banana biocomposite by 4.5%. The flexural strength of the hybrid biocomposite was higher than that of sisal biocomposite by 14.3%, but the hybrid biocomposite with 5% filler exhibited highest flexural stress of 92.8 MPa and was higher than that of hybrid biocomposite with 10% filler by 15.9%. A further increase in the filler decreased flexural stress by 9.2% when compared with the hybrid biocomposite with 5% filler. During the flexural test, the composites were delaminated and the loading surface was subjected to compressive stress and bottom surface was subjected to tensile stress.

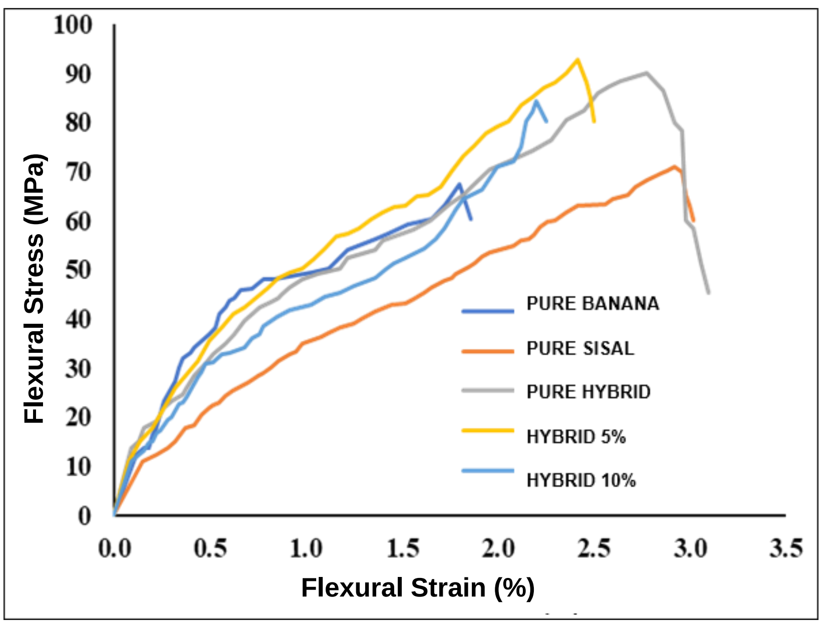

Fig. 5. Flexural stress *versus* strain curves of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content.

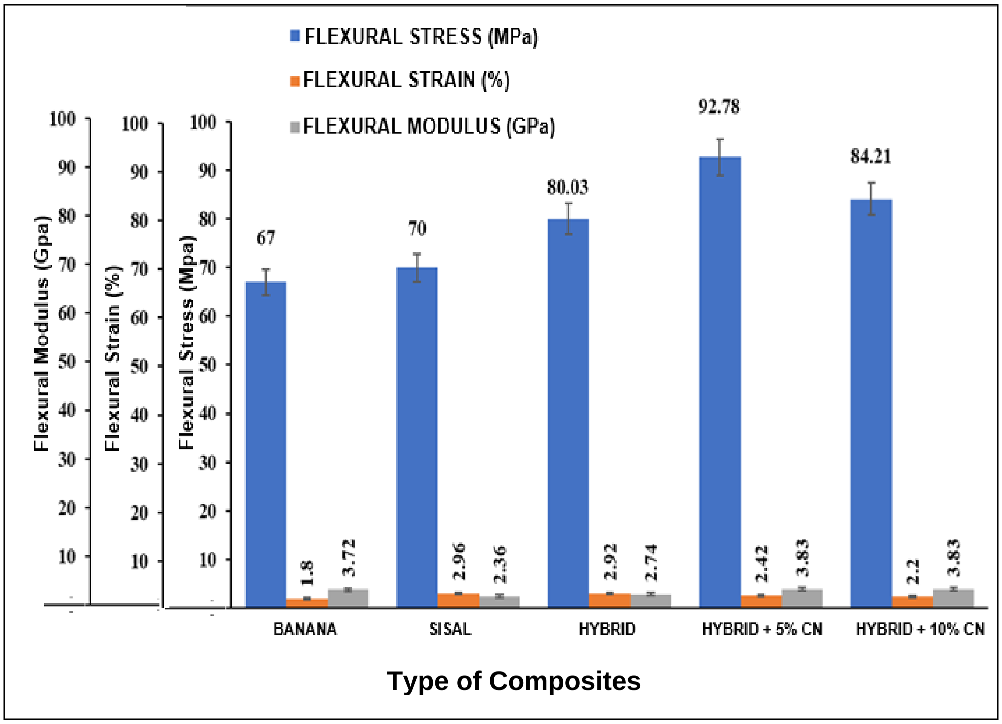

Fig. 6. Flexural properties of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

Impact Strengths

Figure 7 depicts the impact strengths of the various biocomposite samples considered within this study. It was observed that the addition of CNS filler similarly increased the impact strengths of the hybrid biocomposites because the filler contained phenolic compounds that improved the toughness and energy absorption capabilities of the biocomposite material. The compounds acted as toughening agents, effectively dissipating energy and reducing the possibility of crack propagation under impact loading. The addition of CNS filler promoted better adhesion between the natural banana/sisal fibers and the epoxy resin. The enhanced interfacial bonding minimized delamination and fiber pull-out during impact loading, leading to improved impact strengths. Further increase in the addition of the filler led to a decrease in impact strengths because higher filler loading could increase the overall porosity of the biocomposite material and consequently lead to the presence of voids between the filler particles and the epoxy. This could also act as stress concentration points, making the biocomposites more susceptible to crack initiation and propagation under impact loading. Furthermore, the hybrid biocomposite with 5% CNS filler recorded the highest impact strength of 5.61 kJ/m^2. The impact strength of the sisal FRP biocomposite was higher than that of its banana counterpart by 16.5%. The hybrid biocomposite was higher than that of sisal biocomposite by 5.1%. In addition, the hybrid biocomposite with 5% filler recorded higher impact strength than 10% filler by 30.4%. Summarily, further increase in filler addition above a threshold value of 5% decreased their impact strengths by 4.6% when compared with hybrid biocomposite with 5% filler addition.

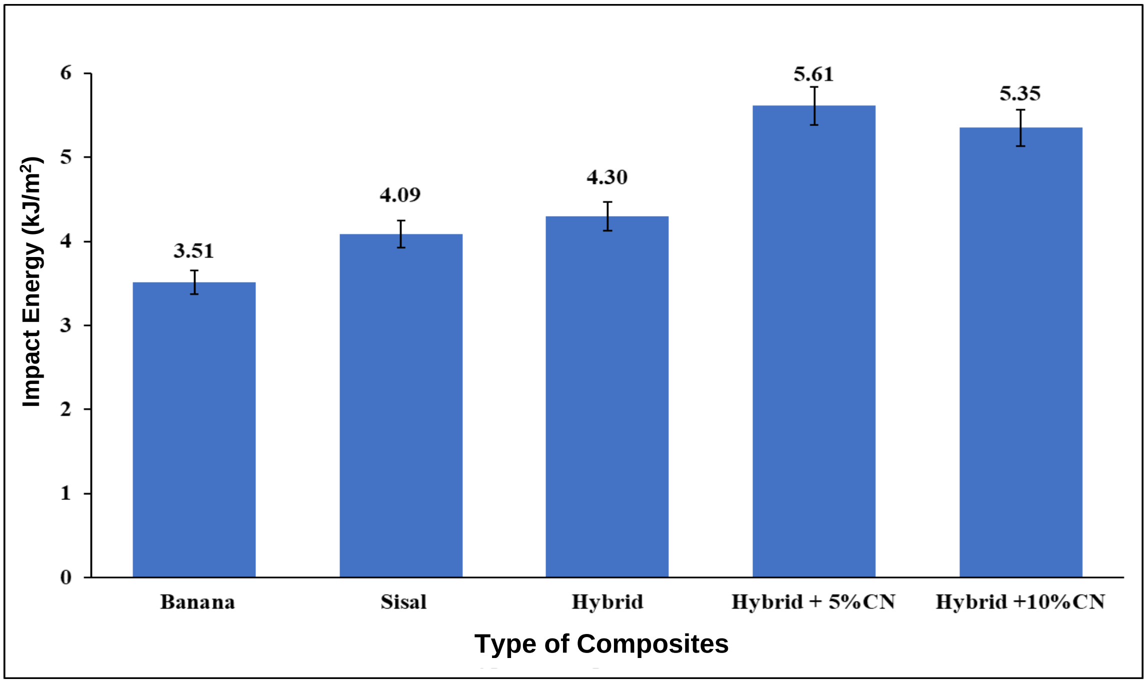

Fig. 7. Impact strengths of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

Thermogravimetric Analysis

Figure 8 shows the TGA weight loss profiles of the natural fibers and their hybrid biocomposites with CNS filler addition, as conducted to assess their various thermal stabilities. It was evident that the hybrid biocomposites with CNS filler exhibited lesser mass loss at higher temperatures than the pure natural fiber biocomposites. The hybrid biocomposite with 5% CNS filler produced the highest thermal stability. It was observed that until 270 °C, initial mass loss of the natural fiber and its hybrid biocomposites with filler occurred, due to the evaporation of moisture. From 270 to 420 °C, as the temperature increased, the main decomposition stage occurred, characterized by a significant weight loss, which resulted from the decomposition of cellulosic fibers and fillers by the pyrolysis process after the main decomposition stage. Significantly, from 420 °C upward, a considerably flat region appeared where the rate of weight loss stabilized. This indicated the completion of the decomposition process and the presence of more stable materials in the biocomposite samples.

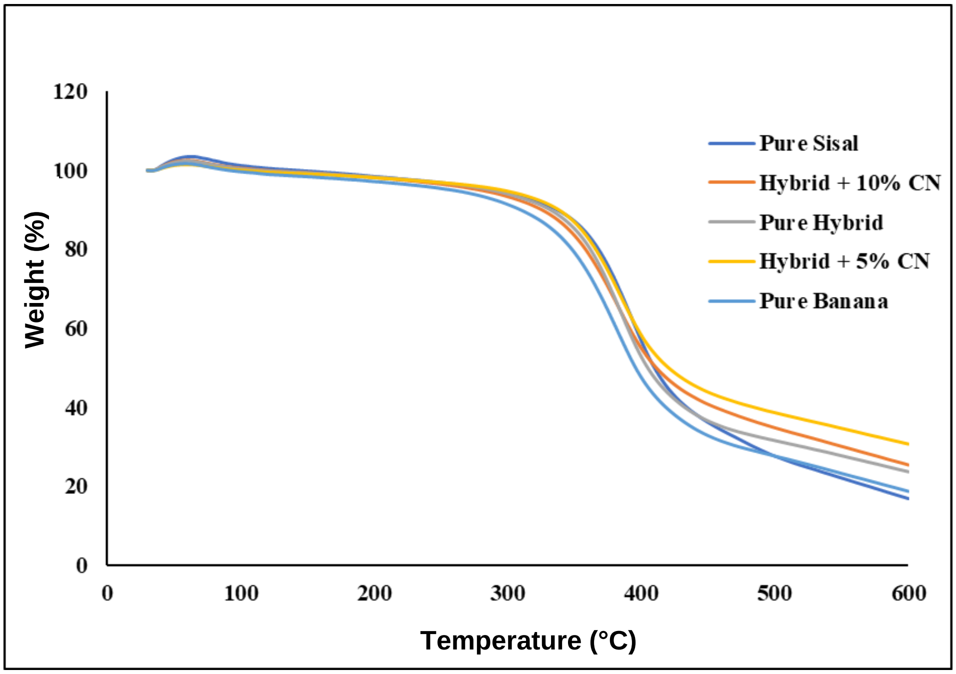

Fig. 8. Thermogravimetric analysis of the pure banana (40% weight content), sisal (40% weight content), hybrid (40% weight content with 1:1 ratio), and hybrid with 5 and 10% CNS content

Fracture Morphology of Tested Samples

The SEM images of fractured surfaces of banana and sisal FRP hybrid biocomposite samples provided valuable insights into their bonding behavior and fracture mechanisms, influenced by the addition of CNS filler.

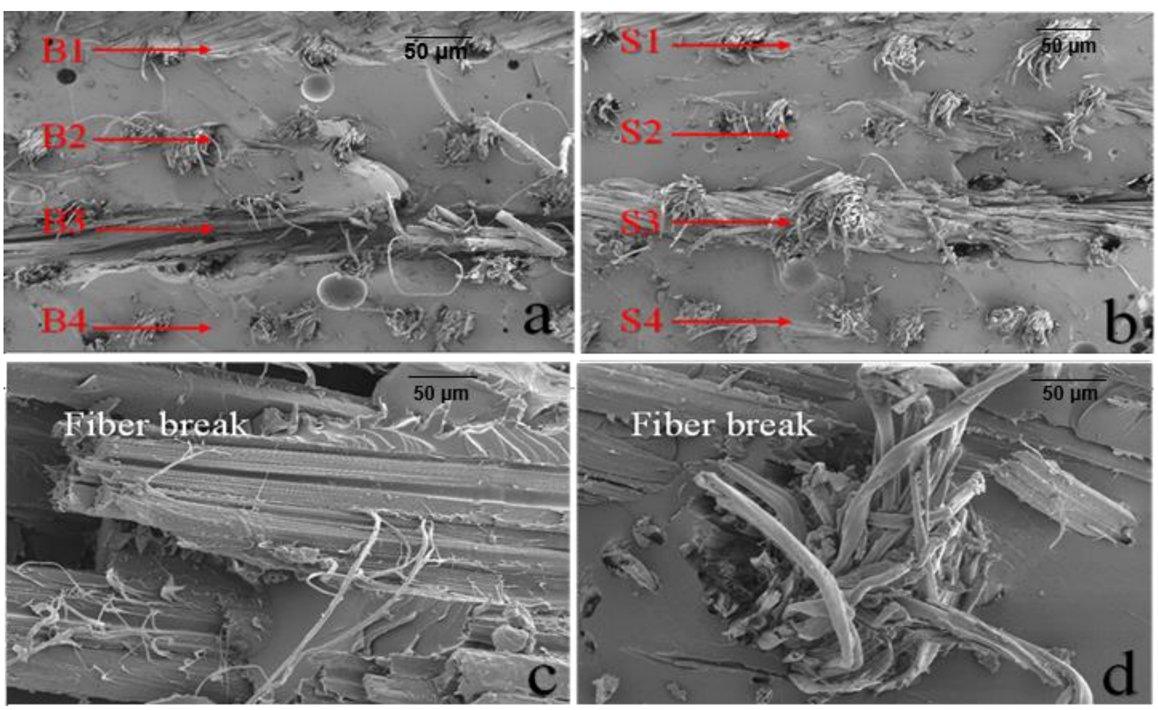

Fig. 9. Tensile fractured sample images, showing: (a, c) banana and(b, d) sisal fiber epoxy biocomposite samples (Bidirectional orientation)

Figures 9(a) and (b) show the images of fractured tensile samples of banana and sisal fiber-reinforced epoxy biocomposites, respectively, presenting the layers of banana fiber as B1, B2, B3, and B4 and layers of sisal fiber as S1, S2, S3, and S4.

The fractured surfaces exhibited a lack of strong interfacial bonding between the fibers and the epoxy, as shown in Figs. 9(c) and (d). This can be attributed to the inherent hydrophilic nature of the natural fibers and their limited compatibility with the hydrophobic epoxy matrix. Consequently, their surfaces fractured layer-by-layer, and fiber pull-out occurred when the load was applied. Hybrid biocomposite (Fig. 10a) depicts banana/sisal/banana/sisal as layers.

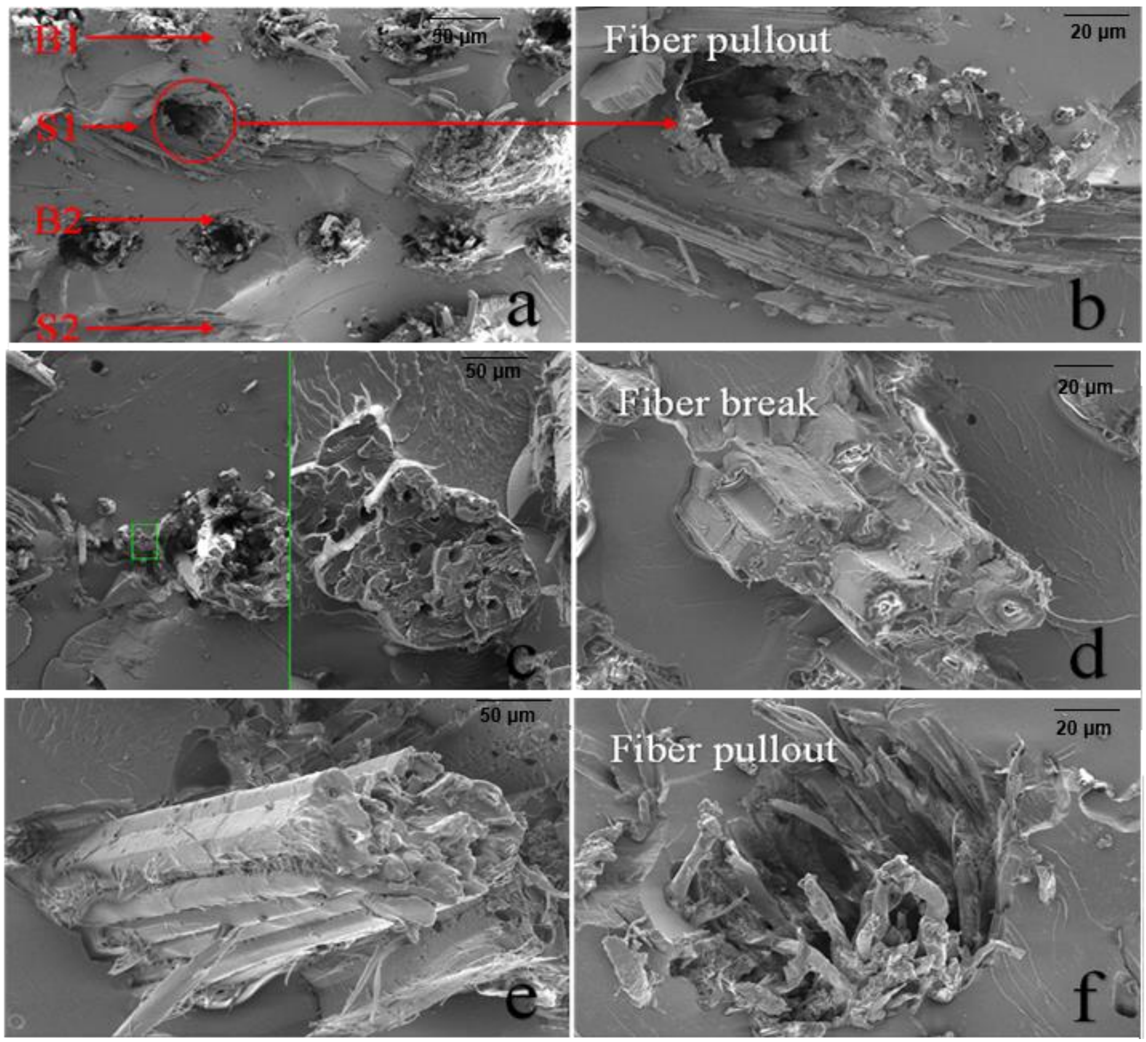

Fig. 10. Tensile fractured sample images, depicting:(a, b) banana/sisal fiber-reinforced epoxy hybridbiocomposites as well as hybrid biocomposites with (c, d) 5% and (e, f) 10% filler additions. (Note: B and S represent the layer of banana and sisal woven mats, respectively)

The applied tensile load on the hybrid biocomposite caused the fibers to de-bond from the matrix, with some fibers partially or completely pulled out of the matrix material, as shown in Fig. 10(b). This phenomenon was commonly observed in hybrid biocomposites, due to the variations in fiber morphology, diameter, and the fiber surface roughness. These factors contributed to uneven stress distribution and differential bonding with the epoxy matrix. The bonding strength between the fibers and the matrix could result in the de-bonding of the weaker or less compatible fibers, leading to fiber pull-out during fracture. However, the presence of CNS filler in the hybrid biocomposites improved their mechanical properties, because the filler covered and penetrated the outer surface of fibers to support the interfacial adhesion of the biocomposites through mechanical interlocking. The even dispersion of CNS filler within the hybrid composite matrix promoted better adhesion between the fibers and the matrix, resulting in an increased contact area, as shown in Fig. 10(c). In addition, the irregular surface morphology of the filler particles provided attaching sites for the fibers, which promoted their interfacial bonding and prevented fiber pull-out during rupture and consequently increased the mechanical properties. Afterward, it caused multilayer fiber breakage (Fig. 10d) during the inevitably delayed fracture of the samples. The SEM images in Figs 10(e) and (f) depict higher filler loading, which led to an increase in the fiber pull-out. This can be traced to a lack of resin content, causing weak adhesion and interfacial de-bonding. This was due to the clumping of the CNS filler particles, not spreading out evenly, creating more areas where stress built up within the biocomposites. This occurrence established the importance of accurate filler content in a biocomposite system to maintain effective bonding and enhance mechanical performance.

CONCLUSIONS

1. The characterization of banana and sisal fiber-reinforced epoxy hybrid biocomposites with cashew nut shell (CNS) filler revealed their mechanical (tensile, flexural, and impact), water absorption, and thermal properties. The water absorption response indicated that the addition of CNS filler increased the water absorption of the hybrid biocomposites. This phenomenon can be attributed to the hygroscopic and hydrophilic natures of the CNS and biofibers, respectively, as the CNS absorbs moisture from the environment.
2. Excessive filler loading led to a compromised interfacial bonding between the fibers and the epoxy matrix, resulting in increased water absorption. The tensile and flexural tests showed that the hybrid biocomposites exhibited improved mechanical properties when compared with the banana FRP and sisal FRP biocomposites separately. The addition of up to 5% CNS filler enhanced their interfacial bonding, resulting in increased tensile and flexural strengths. However, further increases in filler content beyond this threshold led to decreased mechanical properties due to poor filler dispersion and increased stress concentration.
3. In addition, the banana and sisal hybrid biocomposites with 5% CNS filler exhibited the highest impact strength, which can be attributed to the toughening effect of phenolic compounds present in the CNS filler. Thermogravimetric analysis (TGA) established that hybrid biocomposites with 5% CNS filler exhibited the highest thermal stability.
4. Scanning electron microscopy analysis of fractured surfaces provided insights into the bonding behavior and fiber fracture influenced by the addition of CNS filler. Filler improved interfacial bonding and prevented fiber pull-out, but higher filler content led to increased fiber pull-out due to inadequate resin content and filler agglomeration.

5. Up to 5% CNS filler in the hybrid biocomposite samples provided better valuable insights for their optimization in various applications.
6. The present study is used to fabricate the fiberboard sheet for various light weight applications and for the study of life cycle assessment.

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