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# Kenaf Fiber and Hemp Fiber Multi-Walled Carbon Nanotube Filler-Reinforced Epoxy-Based Hybrid Composites for Biomedical Applications: Morphological and Mechanical Characterization

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**Abstract:** This study used a hybrid combination of kenaf and hemp fibers and the multi-walled carbon nanotube (MWCNT) reinforcements in the matrix phase to synthesize the composites. A kenaf/hemp fiber blend with MWCNTs in epoxy was used for the specific concentration. The procedure used three composite materials chosen from pilot trials. The ratio of MWCNT filler particles was altered up to the agglomeration limit based on initial trials. Two specimens (2 and 3) were supplemented with MWCNTs in a concentration range of 0.5 wt. % to 1 wt. %, with the fiber concentration being maintained in equilibrium with the epoxy resin, all of the materials were tested under the same conditions. The hybrid nanocomposite was characterized for its morphological and mechanical properties; the tensile properties were higher for 1% MWCNTs concentration (specimen 2), while the flexural properties were higher for 0.5% MWCNTs, with values of 43.24 MPa and 55.63 MPa, correspondingly. Once the MWCNT concentration was increased to 1 wt. %, the maximum impact strength was achieved (specimen 3). In the limits of the Shore-D scale, the kenaf fiber and hemp fiber matrix composite (specimen 1) gained a hardness index of 84. Scanning electron microscopy was carried out to analyze the morphological features of the fractured samples and to assess the adhesion between the fiber, matrix, and surface. Among the various fillers tested, the kenaf fiber/hemp/MWCNT composite (specimen 3) demonstrated superior binding and reduced the incidence of fiber pull-out, breakage, and voids. In addition to the comparative analysis, the addition of 0.5 wt. % MWCNTs resulted in better mechanical properties compared to the other two combinations.

**Keywords:** hemp fiber; kenaf fiber; epoxy resin; hybrid composites; mechanical characterization

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## 1. Introduction

Newer, natural-fiber-based polymeric composite materials are being introduced into biomedical components exponentially. Natural-fiber-reinforced polymer can provide a cost-effective solution to dispel market misconceptions. Hybrid composites' specific applications can protect against high costs and excessive weight [1–3]. This replacement can lead to cascading benefits throughout the manufacturing process. The use of composites is typically growing daily, and the application base is expanding, such as enhanced strength, for lower-weight composite structures [4,5]. In addition, the inherent corrosion and chemical resistance properties of hemp/kenaf hybrid composites contribute to an extended service life [6–8].

Several researchers have worked on fabrication models, particularly for aircraft and military cars, which were among the components revealed to have a low-specific bodyweight with higher strength and load-bearing capacities. Researchers have examined a natural composite framework made of numerous materials and organic fibers like flax, hemp, and sisal reinforced with epoxy resin [9–12]. Researchers have also experimented with ways to enhance thermal (thermogravimetric analysis and derivative thermogravimetric) characteristics and mechanical (flexural strength, tensile strength, and impact strength) properties [13–15].

It is noted that hybrid composites have superior characteristics. These hybrid composites include combining hemp and kenaf fibers with various matrix materials. They primarily attain the maximum yield strength due to the reinforced fiber mat. For integrated MWCNTs to efficiently absorb energy, the extra impact resistance has to reach over 81% of the base value. In studies on epoxy composites [16–19], several newer varieties of reinforcements were proposed to be included in the matrix. On technical grounds, researchers have discussed how cellulose, hemicellulose, and lignin improve the mechanical characteristics of the composites. To ensure thermal stability, the material's cellulose content was regulated by modifying the epoxy matrix's structure, considering the hemicellulose crystalline form and amorphous region [20–22]. The degradation of lignin's aromatic rings poses a significant challenge in developing high-quality materials to enhance the mechanical and physical properties of the natural hybrid composites. The morphological structure was used to investigate a heterogeneous kenaf and bamboo fiber matrix to enhance the flexural characteristics and impact resistance [23,24]. Also, from the comparison of various natural fibers, it was noted that, compared to kenaf fiber, bamboo fiber combination's maximum flexural strength was 116.4 MPa. Also, the distinctions might be better understood using coir, leading to the identical bamboo and coir fibers outperforming the kenaf fibers in terms of mechanical characteristics.

Research has been conducted to develop hybrid composites with superior properties that can enhance the material's performance [25,26]. Incorporating bamboo and date palm fiber into a composite significantly improved the impact strength and tensile strength, with 12.7 J/m and 61 MPa values, respectively. The fracture surfaces exhibited a favorable morphological structure and demonstrated adequate interfacial adhesion between the materials, resulting in fewer voids and better integration with date palm fiber [27]. Date palm fiber was removed from a tree trunk for mechanical and morphological characterization. When PDF trunk tree fiber was stretched to 22.5% of its remaining material in the composite, it showed the highest strength. Additionally, the fiber's morphological structure facilitated its adhesion to the filler matrix, and the diameter of the bamboo fiber led to an improvement in the composite's strength and modulus of elasticity. The bamboo/jute and kenaf/jute epoxy composites were two different concentrations of the composites produced. Extreme tensile and flexural strength was attained by jute/bamboo, which was 39.4% stronger than jute/kenaf fiber-reinforced epoxy composites [28].

Researchers have extensively worked on thermoplastic matrix composites of bamboo and unidirectional coconut fiber. Only a small portion of the bamboo/coir fiber experienced failure under strain and stress, while the SEM analysis indicated that the exterior was notably stronger and tougher. They assessed the fracture morphology. The hybrid composite's coir content increased the elasticity compared to other variations (mono-composites), but the bamboo fibers' tensile strength was lower [29]. To increase the mechanical properties of the bamboo fibers, nano-reinforcements were added to the matrix material, and a novel phase was extracted from fibrous materials generated through steam explosion methods. The mechanical properties of natural fibers depended on their diverse chemical compositions, with this arrangement containing over 50% holocellulose [30].

Some studies comparing treated and untreated material found that the untreated material exhibited higher longitudinal bending strength, indicating better performance [31]. Additionally, extended unidirectional sisal fiber reinforcement in the composite enhanced flexural and tensile strength [32]. The researchers researched the fabrication of the composites using fibers and powder made using the compression molding technique. They also experimented with 70% fiber loading. Flexural strength decreased by keeping the mold temperature at 180 °C. The material was then given a flexural strength of 272 MPa after the mold temperature was lowered to 160 °C, ensuring it was biodegradable [33]. The Young's modulus and tensile strength values in a natural-hemp-fiber-material-reinforced matrix hybrid composite increased by 75% with the inclusion of the natural fibers in the epoxy matrix. However, the deterioration of the material is a major issue with the use of natural fibers, and the volume % of fibrous/filler material used has several implications for the mechanical properties [34–38]. Mija et al. worked on bio-based epoxy resins and examined their impact on physical and chemical characteristics [39].

Furthermore, Mija et al. worked on sustainable epoxy resins with better glass transition temperatures to make biopolymers suitable for potential applications in aerospace components [40]. Furthermore, Thomas et al. studied the effect of cationic co-polymers of norbornylized seed oils for improving the adhesion and enhancing the mechanical characteristics of fiber-reinforced composites [41]. Similarly, Manas-Zloczower et al. studied the synergizing effects of carbon nanotubes and graphene nanoplatelets on the characteristics of epoxy composites and reported that the combination of graphene nanoplatelets and carbon nanotubes improves the mechanical and electrical properties of composites [42].

Due to its distinct morphological and mechanical properties, a hybrid composite made of kenaf Fiber and hemp Fiber, reinforced with MWCNT filler in an epoxy matrix has a lot of promise for use in biomedical applications. It may create tissue engineering scaffolds that offer a biocompatible cell growth and regeneration environment. It can be a strong and lightweight material to strengthen or replace broken or damaged bones. The composite can be molded into intricate shapes and has adaptable qualities that make it appropriate for creating lightweight, patient-specific prostheses. Due to their low density and excellent stiffness and strength, hybrid composites are a great option for lightweight components in biomedical applications. The overall weight may be decreased while the structural integrity is preserved. A composite's lightweight design and vibration-dampening capabilities may reduce vibrations in engineering structures like equipment, bridges, and buildings. The corrosion resistance of the composite may be improved by adding natural fibres and MWCNTs, making it ideal for usage in humid and marine settings.

The rapid introduction of natural-fiber-based polymeric composite materials into biomedical components presents opportunities for cost-effective solutions and dispelling market misconceptions. However, there is a need to further investigate the mechanical characteristics and performance of hybrid composites, particularly those combining hemp and kenaf fibers with various matrix materials. Many research questions need to be answered, such as how different hybrid composite variations, specifically combining hemp and kenaf fibers with multiple matrix materials, affect mechanical characteristics such as tensile, flexural, hardness, and impact strength.

In this regard, the current work addresses a research gap that involves three distinct hybrid composite variations and the use of high-quality materials to ensure greater mechanical characteristics, including tensile, flexural, hardness, and impact strength. Additionally, premium filler materials are included and discussed in the present work for their use in real-time applications [43–46].

## 2. Materials and Methods

The natural fibers, viz., the hemp and kenaf fibers, were sourced from Go Green Products, Chennai, India. The fibers were manually cut into pieces in size ranges between 0.5 cm and 1 cm. KS Marketing Ltd., Bangalore, India, provided the L-12 epoxy resin, K-6 hardener, and hand lay-up equipment setup. The multi-walled carbon nanotubes were obtained from Adnano Technologies, Bangalore, Karnataka Province, India. These nanotubes have a diameter ranging from 10 to 20 nm and a length of 10 microns.

The epoxy resin and hardener were mixed thoroughly in a ratio of 10:1. The matrix chosen in the present work is a type of thermosetting polymer comprising two main components: the L-12 epoxy resin and the K-6 hardener, also known as the curing agent. The L-12 epoxy resin is a low-viscosity liquid with reactive sites called epoxide groups that can undergo polymerization through an epoxy curing reaction. When the K-6 hardener, a chemical compound containing active hydrogen atoms, is mixed with the L-12 epoxy resin, it reacts with the epoxide groups during curing. This chemical reaction creates a three-dimensional network of covalent bonds, transforming the liquid epoxy resin into a rigid, solid material with desirable mechanical and chemical properties.

The mixing ratio between the L-12 epoxy resin and the K-6 hardener is crucial to ensure complete curing and optimal performance. The manufacturer has provided specific mixing ratios, and deviations from these ratios can result in issues such as reduced mechanical strength, chemical resistance, or adhesion in the cured material.

L-12 epoxy curing is an exothermic process, generating heat during the chemical reaction. The curing temperature and time significantly impact the properties of the cured epoxy. Some epoxy systems require elevated temperatures to achieve high-performance properties, while others cure at room temperature for convenience in certain applications.

The cured epoxy's performance properties depend on its basic chemistry. These properties include mechanical strength, hardness, and toughness, all influenced by the degree of crosslinking achieved during proper curing. The chemical composition affects the epoxy's resistance to chemicals, solvents, and environmental conditions. Epoxy resins often exhibit excellent adhesion to various substrates, making them suitable for bonding applications. Thermal stability is crucial for applications exposed to high temperatures, while good electrical insulating properties make epoxies useful in electronics.

Figure 1 shows (a) the hemp fiber and (b) the kenaf fiber used in the present work. Table 1 gives the material compositions and properties of the kenaf fiber, hemp fiber, and MWCNTs, as provided by the supplier in the supplier datasheet.

**Figure 1.** (**a**) Hemp fiber and (**b**) kenaf fiber.

**Table 1.** Material compositions and properties of the kenaf fiber, hemp fiber, and MWCNTs.

| Materials | Density ($g/cm^3$) | Specific Gravity ($g/cm^3$) | Cellulose (%) | Elongation (%) | Lignin (%) | Hemicellulose (%) |
|---|---|---|---|---|---|---|
| Kenaf fiber | 1.45 | - | 53–57 | 1.6 | 5–11 | 15–19 |
| Hemp fiber | 0.86 | - | 67–75 | 71.5 | 3–5 | 16–18 |
| MWCNTs | 3.1 | 3.4 | - | 10.3 | - | - |

## 3. Experimental Procedure

The composite was produced using epoxy resin, kenaf fiber, hemp fiber, MWCNT filler, and the appropriate wt. % hardener. The lengths of the hemp fiber were limited to the 100-micron range and tested using the ASTM process. The kenaf fiber mat was applied as a uniform layer over the hemp fiber–resin matrix bed and covered with woven material and a resin–hardener combination. The covering plate surface of the die set was cleaned using a moist cloth to remove any small debris, and wax and release film were evenly distributed throughout the plate to facilitate the easy removal of the laminate prepared as per the different compositions fixed. Table 2 gives the compositions of the composite specimens in wt. %.

**Table 2.** Compositions of the composite specimens in wt. %.

| Specimens | Hemp Fiber (Wt. %) | Kenaf Fiber (Wt. %) | Epoxy Resin (Wt. %) | MWCNTs (Wt. %) |
|---|---|---|---|---|
| Specimen 1 | 6 | 9 | 85 | 0 |
| Specimen 2 | 9 | 11 | 79 | 1 |
| Specimen 3 | 11 | 14 | 74.5 | 0.5 |

The mat was stacked together, and subsequently, the epoxy was applied in several steps. The entire process was carried out in a clean room environment, from measuring the epoxy and hardener according to the ASTM specifications using weighing equipment to mixing and applying the epoxy and hardener. Once the multi-walled carbon nanotube (MWCNT) filler and epoxy resin had been blended, the hand lay-up process was accomplished to disperse the small-scale flakes with the coarse particles.

## 4. Results and Discussion

### *4.1. Tensile Test*

Figure 2 illustrates the setup used for the tensile testing of the samples in accordance with the ASTM D3039 standard. Three replicate specimens of each sample, viz., S1, S2, and S3, were cut to 250 mm length and 25 mm width with 3.2 thickness and having a gauge length of 150 mm, and the tensile test was conducted, and the averages of the tensile strength values were tabulated. The ER-1 electronic tensometer apparatus made by Kudale Instruments was used for the tensile test with a strain loading rate of 0.02 mm/s. The enhancement of tensile strength in hybrid composite materials relies on the specific objective of maintaining an optimal composition of fibers and fillers while improving the tensile strength. The incorporation of the MWCNTs into the epoxy hybrid composite reinforced with hemp and kenaf fibers was carried out to resist mechanical damage when subjected to stress, which can further increase the tensile strength. It was observed that this combination results in a composite material with excellent mechanical properties.

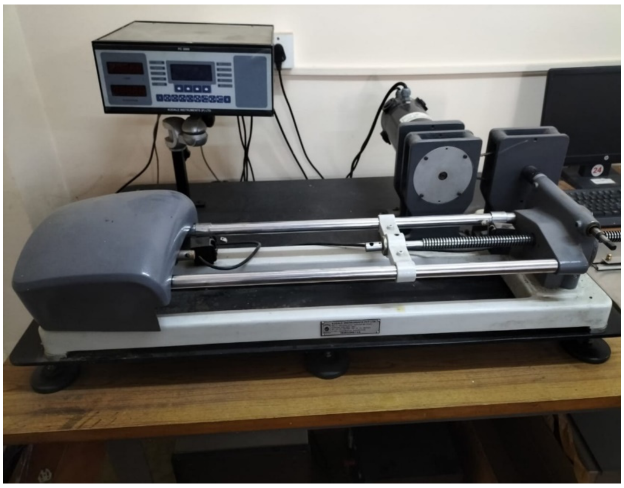

**Figure 2.** Electronic tensometer.

The Figure 3 gives the graph of the variation of tensile strength for different specimens. The tensile strength of specimen 1, which included 6 wt. % hemp fiber and 9 wt. % kenaf fiber, was found to be 34.56 MPa. During testing, the specimen's head experienced a maximum load, which caused an initial fracture to occur later than anticipated. This was because kenaf fiber takes up all the load and improves its yield point. However, after a brief period, the fiber reaches the necking point, which is the point at which the material is ready to fracture, and the crack spreads randomly because of the packing of the epoxy matrix. The fiber was then seen to withstand the maximum load in the cracked portion owing to micro-coring and bonding of the fiber with the matrix; however, a sustained increase in loading further caused the crystal to break, reducing the fiber's yield strength immediately. Subsequently, the sample then broke into brittle, uneven pieces and began to crack directly.

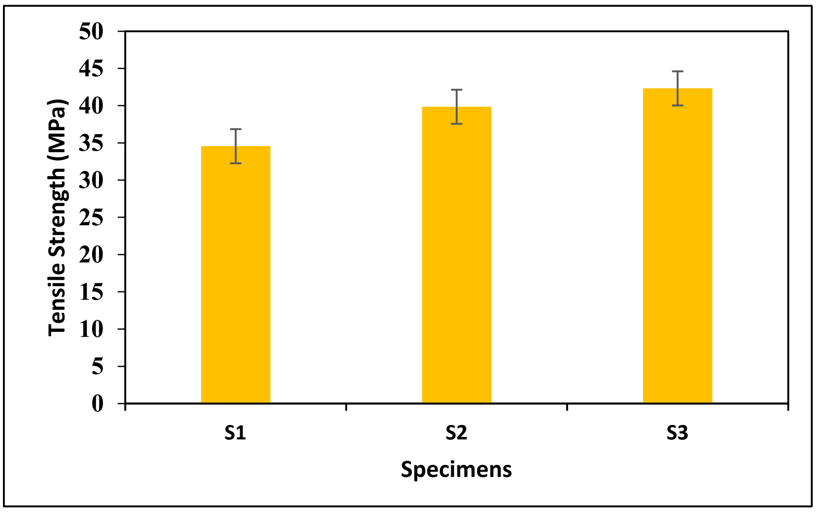

**Figure 3.** Tensile strength (MPa) for the different composite specimens.

Composite specimen 2, which contains 9 wt. % hemp fiber, 11 wt. % kenaf fiber, and 1 wt. % MWCNT, was found to have a tensile strength of 39.86 MPa. The inclusion of the MWCNT filler up to 1 wt. % increased the maximum tensile strength by 15.33%. However, the tensile strength value was lesser than 0.5 wt. % MWCNTs. MWCNTs were added to the mixture to strengthen the connections between the small particles that make up the cellular network architecture, and the inclusions enhanced the characteristics. Additionally, hemp fiber's cellulose and silica content is higher, making it a richer substance. Hemp fiber packing can significantly enhance the mechanical properties of the matrix.

Composite sample 3's material consisted of 11 wt. % hemp fiber and 14 wt. % kenaf fiber with 0.5 wt. % MWCNTs, and specimen 3 exhibited a maximum tensile strength of 42.33 MPa. However, the increase in tensile strength as compared to specimen 2 was limited to 6.2%. The ratio of fiber to filler may be saturated in this combination, and excessive natural fiber incorporation is another effect of a lesser increase in the tensile strength of the composite material. The stacking of filler material in a particular area may experience a decrease in strength when more filler substance is added to the specimen. As a result, additional time is required to stir the mixture thoroughly while creating the specimen until the solution is uniformly distributed during the curing process. The hardening of the composite laminate is also crucial in determining how much fiber or filler will fit into the plate's dimension, which will further affect the tensile characteristics of the composite.

### *4.2. Flexural Test*

The flexural characteristics of the three specimen replicates of each sample, viz., S1, S2, and S3, were tested using a three-point bending setup on an Instron-made 6800 series 25 kN nano UTM. With increased fiber loading, the bending strength rises, but once the loaded fiber goes beyond the saturation limit, the bending strength gradually declines. Test specimen 1 was composed of 6 wt. % hemp fiber and 9 wt. % kenaf fiber, and it was subjected to a three-point flexural bending test using a machine with two support points and one loading point with a knob. The specimen responded to the load application by bending downward and achieving maximum deflection. After going above, when the material reaches its limit, it cracks and spreads in the specified dimensions. The bamboo fiber mat alone can achieve its maximum yield point in this setup. However, when the epoxy initiates the crack, the top layer breaks immediately, altering the lattice structure and causing the fiber to reach its maximum yield point. Specimen S2 was fabricated with the inclusion of 1 wt. % multi-walled carbon nanotubes (MWCNTs), 9 wt. % hemp fiber, and 11 wt. % kenaf fiber. The highest flexural strength was for the specimen S2, which was 59.72 MPa (Table 3). The hand lay-up technique also successfully improved the bonding among the fiber matrices. The primary factor was addressed to evaluate the inclusion of hemp fiber, kenaf fiber, and MWCNTs by homogeneous sonication. Therefore, using the composite specimen, the flexural strength of the composite specimen was increased to 59.72 MPa. Like specimen 2, specimen 3 included more hemp fiber and 0.5 wt. % MWCNTs, which increased the expectation of higher flexural strength but somewhat decreased the combination. As a result, when the specimen is loaded, the specific area breaks immediately. The Figure 4 gives the flexural strength for the different composite specimens.

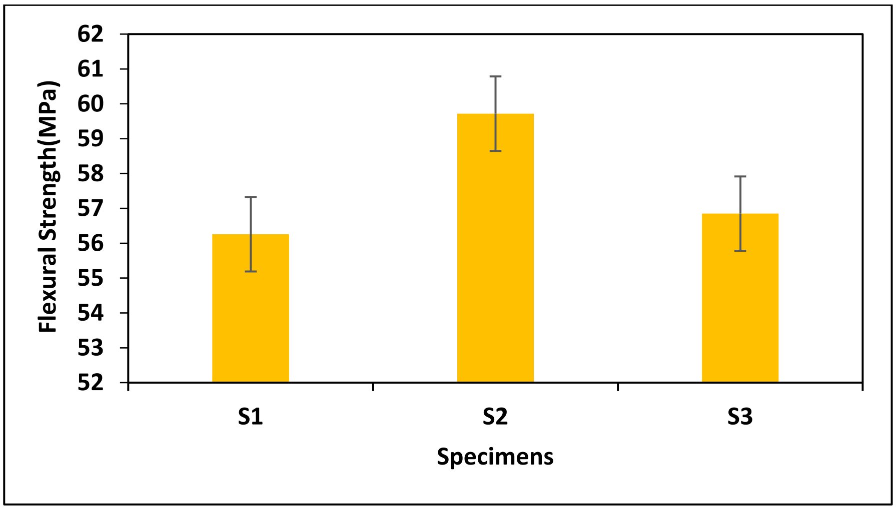

**Figure 4.** Flexural strength (MPa) for the different composite specimens.

**Table 3.** Mechanical properties of the composites.

| Specimens | Tensile Strength (MPa) | Flexural Strength (MPa) | Impact Strength (J/m) | Hardness (Shore-D) (%) |
|---|---|---|---|---|
| S1 | 34.56 | 56.26 | 44.23 | 87.45 |
| S2 | 39.86 | 59.72 | 50.48 | 86.5 |
| S3 | 42.33 | 56.85 | 56.6 | 84 |

Adding fillers can have various effects on the flexural properties of a composite material. Firstly, fillers, particularly rigid ones like carbon nano tubes (CNTs), and halloysite nano tubes (HNTs), can significantly increase the stiffness of the composite. As the filler content rises, so does the composite's flexural modulus, resulting in a stiffer material that is more resistant to bending or deformation when subjected to loads [47]. Secondly, certain fillers can enhance the flexural strength of the composite. The presence of strong fillers can effectively resist crack propagation and contribute to a higher capacity to withstand bending forces [48]. Furthermore, the flexural strength of the composite can be further improved by carefully selecting and adding appropriate fillers. These fillers act as reinforcement agents within the composite matrix, effectively distributing stress and preventing failure under bending loads [49]. Lastly, the incorporation of fillers can reduce the maximum strain experienced by the composite during bending. This decrease in flexural strain can be particularly advantageous for applications requiring dimensional stability and deformation resistance.

### *4.3. Impact Strength*

The impact strength of the three composite specimen replicates for each sample, viz., S1, S2, and S3, were characterized in accordance with the ASTM D256 standards. The composite specimens were 66 mm in length, 10 mm in width, and 3.2 mm in thickness. The results indicate that the hybrid nanocomposite, which contains kenaf fibers, hemp fibers, and MWCNT fillers, exhibits a higher energy absorption capacity. The key contributing component was an increase in impact resistance. As a result, the material acquired impact energy, which fractures, pulls out, and breaks fibers.

Interestingly, more energy is delivered to the specimen than required. Incorporating fibers and fillers into materials is closely associated with enhancing their mechanical performance, particularly regarding impact resistance. Although kenaf and hemp fibers made up most of the natural fibers in specimen 1, the impact strength of specimen 1 was lower than that of the other two combinations (specimens 2 and 3). The material instantly shattered after the load was rapidly withdrawn from the specimen. However, the increase in the fiber content and the inclusion of MWCNT filler improved the impact strength of the composites owing to stronger bonding due to micro-coring and segregation. The impact strength of the S3 composite was the highest at 56.6 J/m. The Figure 5 gives the impact strength for different composite specimens.

The addition of fillers can greatly influence the impact resistance of composite materials. Certain fillers possessing high toughness and energy-absorbing capabilities can enhance the composite's ability to withstand impact forces. These fillers absorb and disperse energy during impact events, preventing cracks from spreading within the material [50]. Additionally, fillers with high fracture toughness can act as crack-stopping agents, impeding the growth of cracks initiated during impacts. This characteristic contributes to the improved impact resistance and overall durability of the composite [51]. Furthermore, tough fillers within the composite matrix create a bridging effect that helps distribute stress around cracks or impact sites. This bridging effect hinders crack propagation and enhances the material's ability to resist damage induced by impacts [52]. Moreover, adding specific fillers, like CNTs and HNTs, can transform the composite's behavior from brittle to ductile. This alteration makes the composite more resilient, enabling it to absorb impact energy better and preventing sudden and catastrophic failure under impact [53].

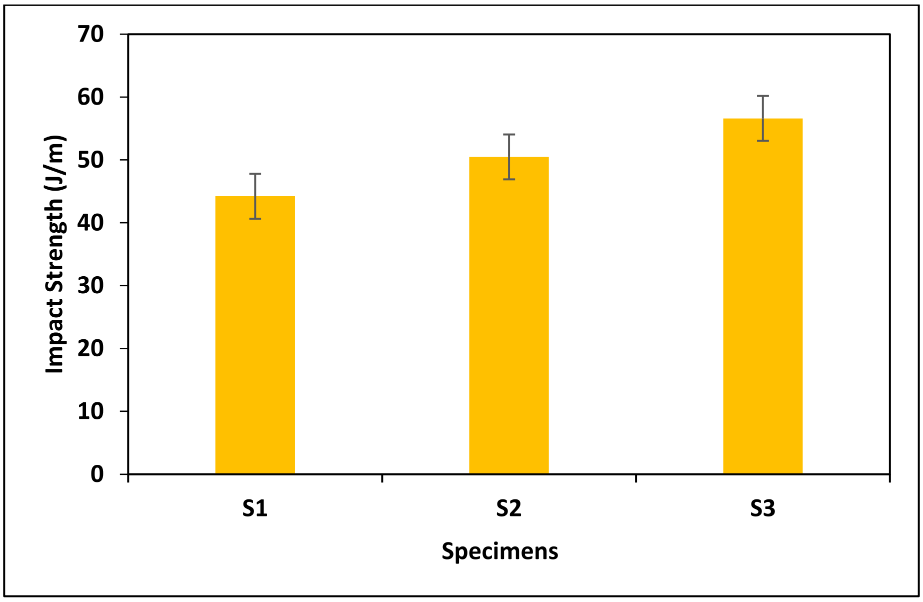

**Figure 5.** Impact strength (MPa) vs. the hemp and kenaf hybrid fiber composite.

It is crucial to consider the type, size, and distribution of fillers as they significantly impact the material's flexural properties and impact resistance. Proper selection and dispersion of fillers are key to achieving the desired improvements in these properties. Additionally, optimizing the filler concentration is essential, as excessive filler content can increase brittleness and decrease certain mechanical properties.

### *4.4. Hardness Test*

To evaluate a composite material's ability to resist indentation or penetration, hardness tests were conducted on three specimen replicates of each sample, viz., S1, S2, and S3 by applying a maximum load. These tests help to determine the composite's capacity to withstand crack initiation and propagation under stress. The Figure 6 gives the hardness (Shore D) for different composite specimens.

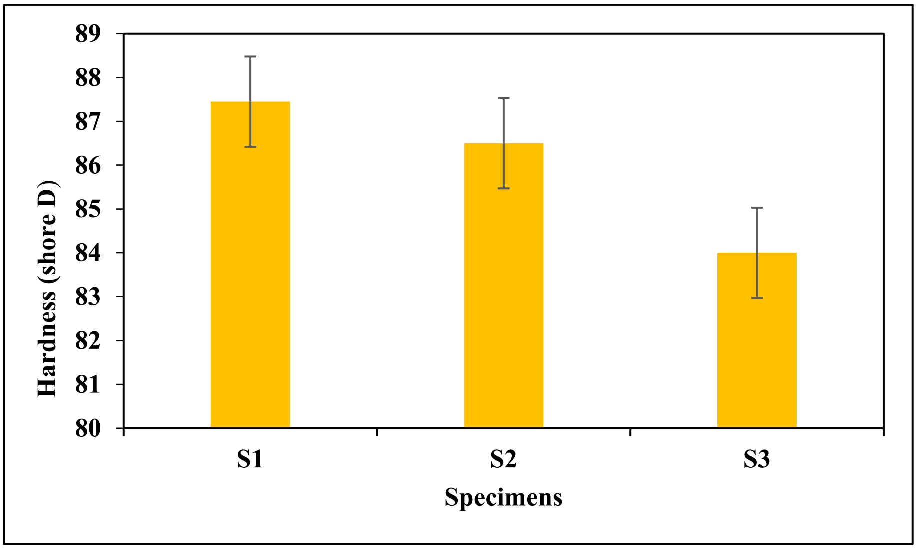

**Figure 6.** Hardness (shore-D) vs. hemp and kenaf hybrid fiber composite.

The hardness value recorded in the particular composite material comprising hemp and kenaf fiber was 87.45 Shore-D, owing to the high content of epoxy (85%), which is well known for its outstanding resistance to abrasion and indentation. Adding MWCNTs to another composite material produced a similar hardness value of 86.5 Shore-D, highlighting the efficacy of sonication in achieving optimal mechanical parameters. Conversely, the third composite material, which contained a lower proportion of filler particles, exhibited reduced mechanical performance, with a lower hardness value of 84 Shore-D. Thus, it is critical to consider appropriate material selection, agents, and fabrication techniques when aiming to enhance the hardness of composite materials.

### *4.5. Mechanical Characteristics of the Composites*

The mechanical properties of the composites synthesized in the present study align with other researchers' findings. From the works of Sapiai et al. [54], it is herewith evident that the inclusion of MWCNTs into the kenaf–epoxy composites enhances the mechanical properties of the composites owing to strong bonding between the matrix and reinforcement due to enhanced adhesion and interfacial locking. The comparative evaluation of the mechanical properties of the composites is given in Table 3.

### *4.6. Morphological Characterization*

The surface morphology of the kenaf fiber/hemp fiber/MWCNT filler interfaces in epoxy resin was analyzed using scanning electron microscopy. The cracked mechanical surfaces were evaluated using microstructural morphologies. The tensile, flexural, and impact fractured specimens and indented test specimens after the hardness test for the composite specimens with kenaf fiber, hemp fiber, and 1% MWCNT were morphologically studied, as shown in Figure 7a–d, to demonstrate the improved relationship between the epoxy resin and hydroxyl composites. Agglomeration is necessary for these nanoparticles to reach their dispersed matrix phase. The third specimen's morphological analysis revealed that the fiber fractures were distinctly observed, and the voids were prevalent due to the fractured edge of the matrix layer. The reinforced composite had enhanced adhesion and interfacial locking thanks to the inclusion of hemp fiber/MWCNTs in the matrix.

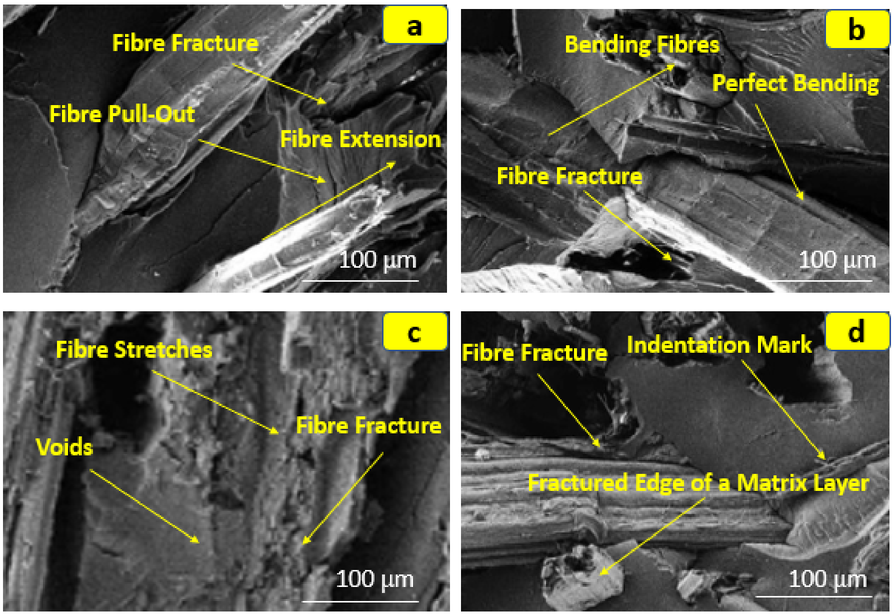

**Figure 7.** SEM fractured images for (**a**) the tensile test, (**b**) the flexural test, (**c**) the impact test, and (**d**) the hardness test.

The fiber–epoxy interaction formed an extremely stiff material with a low interface efficiency. At fractured surfaces, it was observed that the substance exhibited a noticeable behavior of fiber pull-out, which can be quantified as a weak interfacial bond between the epoxy resin and the fibers. Incorporating MWCNTs into specimens 2 and 3 of the composite materials increased their flexural strength. Furthermore, the hand layup method was employed during the fabrication process to prevent the formation of air gaps and voids, which enhanced adhesion between the fibers and the matrix. Consequently, specimen 2 demonstrated superior tensile and flexural properties due to the ability of the natural fibers to extend, as shown in Figure 7a, and due to the ability of the natural fibers to bend, as shown in Figure 7b. The lengthy fibers that were pulled out from the specimen highlighted this issue, and as shown in Figure 7b, this led to the poor mechanical performance of the specimen. However, specimen 3 had more voids and fiber pull-out in specific regions, indicating weak interfacial bonds among the matrix and fibers as in the impact fractured specimen in Figure 7c. This resulted in filler stacking in certain areas and poor matrix formation between the particles. Figure 7d gives the morphological feature of the hardness test specimen. The indentation mark is distinctly evident in Figure 7d.

The effects of voids on the composite's properties as in Figure 7c can be multifaceted. First and foremost, voids act as stress concentration points within the material. When the composite is subjected to external forces or loads, stress tends to concentrate around these voids. This localized stress concentration can lead to premature failure, reducing the composite's overall mechanical strength and toughness. Moreover, the presence of voids can compromise the composite's structural integrity. As the voids may act as sites of weakness, they can promote crack initiation and propagation under stress, further contributing to reduced mechanical performance and potentially leading to catastrophic failure. In addition to affecting mechanical properties, voids can influence other essential characteristics of composites. For instance, they can alter the material's thermal conductivity and electrical properties. The air gaps within the composite can hinder the efficient transfer of heat or electricity, limiting the material's suitability for certain applications that rely on these properties.

Furthermore, voids can lead to inconsistencies in density and homogeneity throughout the composite [55]. This non-uniform distribution can result in property variations from one composite region to another, thus affecting overall performance and reliability. Overall, understanding and addressing the issue of voids in composite materials are crucial for ensuring that the final product meets the desired performance requirements.

## 5. Implications, Conclusions, Limitations, and Future Scope

### *5.1. Implications*

The findings of this study have several implications. Firstly, the successful fabrication of hybrid composite materials with varying concentrations of kenaf fiber, hemp fiber, and MWCNT fillers demonstrates the potential for using natural fibers and nanomaterials in composite applications. Secondly, the improved thermomechanical properties observed in the hybrid composites highlight the effectiveness of combining natural fiber hybridization and MWCNT reinforcement. This opens up possibilities for developing lightweight and high-performance composite materials. The morphological features and adhesion analysis between the fibers, matrix, and surface provides valuable insights into the composites' fracture behavior and interfacial properties.

### *5.2. Conclusions*

The critical inferences of the results have yielded the following conclusions.

Hybrid composite materials were successfully fabricated with various weight concentrations of kenaf fiber, hemp fiber, and MWCNT fillers, and their mechanical characteristics were studied.

Combining natural fiber hybridization and MWCNT reinforcement in epoxy composites offers superior thermomechanical properties. In particular, the hybrid composite containing 0.5% MWCNTs (S3) exhibited maximum tensile strength of 42.33 MPa, and the hybrid composite containing 1% MWCNTs (S2) exhibited maximum flexural strength of 59.72 MPa. The S3 specimen exhibited maximum impact strength of 56.6 J/m, while the S1 specimen exhibited a maximum Shore-D hardness of 87.45.

Integrating microparticles and multi-walled carbon nanotubes (MWCNTs) through interfacial adhesion resulted in a continuous bond between the particles. As a result, a distinct crystalline structure and consistent fracture propagation of fibers were achieved. However, compared to specimens 1 and 2, specimen 3 exhibited a greater extent of fiber extension, elongation, breakage, voids, and filler matrix deposits. This is due to a reduced occurrence of agglomeration.

### *5.3. Limitations*

There are certain limitations to consider in this study. Firstly, the investigation focused on a specific concentration range of MWCNT fillers and may not cover the entire range of possible concentrations. Secondly, the study only considered kenaf and hemp fibers as reinforcing materials; other natural fibers were not explored. Thirdly, while the mechanical properties were evaluated, other properties, such as thermal or electrical conductivity, were not assessed. Finally, the study did not address the composite materials' long-term durability and aging effects.

### *5.4. Future Scope*

Based on the findings and limitations of this study, several avenues for future research can be identified. Firstly, further exploration of different concentrations of MWCNT fillers can be conducted to fully understand the impact on mechanical properties and optimize the composite performance. Secondly, investigating other natural fibers or combinations of natural and synthetic fibers can provide a broader understanding of hybrid composite materials. Additionally, exploring the effects of different processing techniques or surface modifications on the interfacial adhesion and overall properties of the composites would be valuable. Furthermore, studying the long-term durability, aging resistance and environmental sustainability of the hybrid composites can provide insights into their potential applications in real-world scenarios. Finally, expanding the characterization to include other properties, such as thermal and electrical conductivity, can enable the development of multifunctional composite materials for various biomedical applications.

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