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Eco-Friendly Tri-Layer Hybrid Composites: A Sustainable Approach to Polymer Matrix Materials

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Abstract

In the current study, we explored the use of environmentally friendly natural fibers such as sisal, banana, and kevlar. These fibers were fabricated by hand lay-up technique, and their impact on tensile and dynamic properties was evaluated according to ASTM standards. The assessment was conducted under both dry and wet conditions, considering two different chemical dosage parameters for comparison. Additionally, the tri-layer fibers underwent two separate chemical treatments using 1% NaOH solution in distilled water and 0.5% NaOH + 0.5% $KMnO_4$ solution in distilled water respectively. A solution was made, and the fibers were then dried under normal lighting for three to four hours before being taken out and immersed in the aforementioned prepared solution. The internal chemical composition and physical properties of the damaged surfaces were evaluated through the use of Scanning Electron Microscope (SEM) investigation. Additionally, the DMA showed that the chosen fibers of sisal-banana-kevlar fibers treated with 1% NaOH solution in distilled water and 0.5% NaOH + 0.5% $KMnO_4$ solution in distilled water had good viscoelastic qualities. The tri-layer fiber made of sisal, banana, and kevlar that has been chemically treated (0.5% NaOH, 0.5% $KMnO_4$ solution in distilled water) has exceptional mechanical qualities, according to the results.

Keywords: Hybrid Composite; Mechanical; Dynamic; Sisal; banana; reinforced; eco-friendly composite.

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INTRODUCTION

A variety of configurations and multifaceted uses have been devised for composite materials [1, 2]. In general, natural fibers are inexpensive, quickly biodegradable, and toxic-free. Additionally, botanically reinforced fibers are thought to be a significant and essential replacement for other commercial composites [3]. Different plant components are used to extract natural fibers, which are then categorized. Current research in bio-composites has an amazing and unique composites are continually being developed. Plant-based composites demonstrated exceptional mechanical qualities, such as strength and thermal stability. The finished materials' shapes may be in any geometrical shapes, and the composite materials are typically made of several metals, non-metals, and polymers sandwiched together [4]. Any component of a composite may initially take the form of fibers, epoxy resins, particles, whiskers, etc. The environmental properties of bio-materials nevertheless provide a significant challenge in the form of the end product's disposability in the event that it is broken or damaged [5]. Integration of plant-based natural products in the form of fibers is suggested by prior research. Composites made entirely from natural materials like plants or biodegradable trash still don't exist.

The bio-composite sector is now growing quickly to keep up with rising consumer awareness and adhere to new environmental regulations. Biomaterials for a variety of applications heavily rely on lignocelluloses bio-fibres generated from various botanicals [6]. The composition of the fibers affects the mechanical and other physical properties of the composites, as well as the potential amount of coupling agents inside the composite. [7]. Sisal fiber is regarded as one of the bio-fibres among many bio-composites, and it is readily obtained. Sisal fibers are produced annually in developing countries in excess of four million tons, with higher output in Tanzania and Brazil [8]. Bananas also belong to the Musicale family, which has about 300 species that are grown and consumed. An estimated 70 million metric tons of bananas are harvested annually in tropical and subtropical regions [9]. Banana fiber is a great material for composites utilized in a variety of industrial sectors, including construction, manufacturing, and the automotive industry. Its characteristics include a high breaking strength, low density, high tensile the modulus and a low elongation at break [10]. However, there have been some recent initiatives to include plant-based natural resources in the form of fibers. Additionally, it is yet impossible to create composite materials entirely from natural sources like plants or biodegradable trash Prior studies have examined how sandwich arrangements of natural and synthetic fibers could improve the mechanical properties and be applied to a variety of industries, such as the packaging, automotive, roofing, and household sector.

As a result, the objective of the current study is to conduct experimental research on sisal-banana-kevlar fiber reinforced polymer composites. The dynamic and mechanical characteristics of these composites, including their tensile strength, flexural strength, impact strength, loss modules, storage modules, and tan delta, were evaluated for the two above mentioned chemical treatments in dry as well as wet conditions. Additionally assessed were the fractured surfaces' interior structure, internal cracks, and interfacial characteristics. The attainment of this investigation will deliver promising eco-friendly, green derived composites [11–15].

MATERIALS AND METHODS

Materials

The matrix materials used in this experiment were Hardener 3554B and Grade 3554A of bio epoxy resin. The raw agricultural waste materials (see Table 1) that were used were sisal and bananas from Lab Chemicals in Chennai, and the kevlar fiber reinforcements came from a local market nearby.

Natural Fibre

Natural plant-based fibers are widely available and have excellent particular mechanical characteristics. Today, plant fiber resources are used to make a wide variety of textiles, ropes, canvases, and papers. It has been discovered that the many plant parts, including the fruit, stem, leaf, and flower, are crucial providers of basic materials [16]. Recent years have seen a lot of interest in polymer composites made with natural fibers. Table 1 displays the mechanical characteristics of kevlar, banana, and sisal fibers.

Table 1. Mechanical Propertiesof sisal, banana and kevlar fibres.

Fibre	Density (kg/m^3)	Flexural modulus (GPa)	Tensilestrength (MPa)	Young's modulus (GPa)
Sisal	1450	12.5-17.5	68	3.774
Banana	1350	2-5	54	3.4878
Kevlar	2.5	70-73	2500-3500	70

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Chemical Treatments of Natural Fibres

The aforementioned fibers are subjected to two distinct chemical treatments. In set one, fibers were treated with 1% NaOH solution in distilled water, and in set two, fibers were treated with 0.5% NaOH, 0.5% $KMnO_4$, in distilled water. After the fibers had dried for 3 to 4 hours under normal lighting, they were taken out and submerged in the aforementioned solution for varying lengths of time. This experiment involves submerging the fibers in the fluid for four hours. After the fibers are extracted, they are washed under running water and allowed to dry for 48 hours [17, 18]. To remove the impurities from the natural fibers, we performed a chemical treatment. After the treatment process, the fibers were dried in open sunlight for 48 hours. The fibers were then used for composite laminate fabrication.

The Preparation for the Composite the Sample

During fabrication, the various composite materials are produced by hand layup process. Two 300 mm by 300 mm rectangular sheets of mild steel that have been chrome-plated serve as the mold for creating composites. To maintain a 3 mm thickness all the way around the mold plates, four beadings were used. The specimen was made with 50 mm long banana and sisal fibers. The hybrid composite specimen will have five layers, of which L1 (top) and L5 (bottom) are fixed kevlar fiber layers. According to the Table, L2 and L4 are filled with horizontally oriented natural fibers like sisal and banana, while L3 is filled with vertically oriented natural fibres. The required amount of bio epoxy resin is used to produce each layer of fiber.

Wax was then applied to the inside sides of the molds after they had been prepared so that the composite could be easily released without adhering to the mold walls. Then epoxy and hardener were combined. Matrix was then ready. The hardener to epoxy ratio was held constant at 10:1. Before the resin hardens (10–15 minutes), the natural fiber (L4 in vertical orientation) is installed over the surface of the kevlar fibers reinforced polymer. Next, L3 is placed horizontally over L4 and L2 is mounted horizontally over L3. For problematic specimens, the procedure is repeated. By applying the bio epoxy adhesive over the whole surface, the air holes that were formed between the layers during this process are sealed off. By applying intense pressure to the composite and drying, extra resin is removed. After being placed in the hydraulic press, these specimens are held for a few hours in order to force the air gap and remove any excess air that might have been present between the fibers and resin in order to achieve the optimal samples. Layer by layer configurations of composite specimens are shown in the Table 1.

The Water Absorption Test

The specimens of the hybrid composite were first dried in an air oven at 45 to 55°C. They were subsequently submerged in distilled water at 25 to 35°C for around 144 hours. The samples were collected from the water at regular intervals, dried with filter paper to remove any remaining surface moisture, and weighed with a 0.01 mg resolution digital scale. In order to reduce evaporation errors, the weighing procedure took only thirty seconds to complete. The specimen's swelling was measured using the ASTM D570 test procedure. The test specimens were once more removed from the water bath and weighed after five days. Using the method [18], The weight gain in the sample has been determined as a percentage increase in weight.

Mechanical Testing

The mechanical tests that followed ASTM guidelines are listed in Table 2

Table 2. Testing of composite specimens as per ASTM standard [19–20].

Test	**Tensile test**	**Flexural test**	**Impact test**
Machine Used	Universal testing machine	Universal testing machine	Impact testing machine
Procedures	ASTM D3039	ASTM D790	ASTM D256
Composite specimens			

Tensile Test

The tensile test specimen was manufactured according to the ASTM D3039 standards. Its dimensions were 25 mm (1 in) in width and 250 mm (10 in) in length. An FIE universal testing machine, model UTE-40, with a 400 KN capacity, a 150 mm gauge length, and a 1 mm/min cross speed, was used to conduct tensile tests. The experiments were conducted at 35 °C with a 50% relative humidity on average.

Dynamic Mechanical Analysis (DMA)

Dynamic mechanical evaluation was conducted using DMA Q800 V20.6 Build 24 at the Institute of Plastic Technology in Chennai, India. At a frequency of 1 Hz, testing was conducted in bending mode. For the experiments, rectangular specimens with dimensions of 65 mm by 12.7 mm were cut from fabricated bi-layer composite materials. With a heating rate of 4 degrees Celsius per minute, the objective of the experiment's temperature range was between 28 and 200 degrees Celsius.

Statistical Analysis

To investigate substantial variations among treatment groups, Tukey's multiple range tests (significance at p0.05) was employed. The final results were then plotted in Microcal Software (Sigma plot 11) using the Minitab®17 application.

RESULTS AND DISCUSSIONS

In this investigation, two different chemical treatments are used to combine kevlar fibers with natural fibers to form materials that are manufactured, evaluated, and compared for their effects on tensile, impact, and flexural properties in dry and wet conditions.

Water absorption of bio-composite fibres

The chemical treatment 2 (0.5% NaOH+0.5% *with distilled water*) showed the highest capacity for water absorption in specimens 1 (4.7 g), 2 (4.4 g), and 3 (4 g), and it was significantly different from treatment 1 (1% NaOH+0.5% *with distilled water*) (Figure 1). Chandramohan et al. [21-24] made a similar suggestion regarding the water absorption capability to our results regarding water absorption.

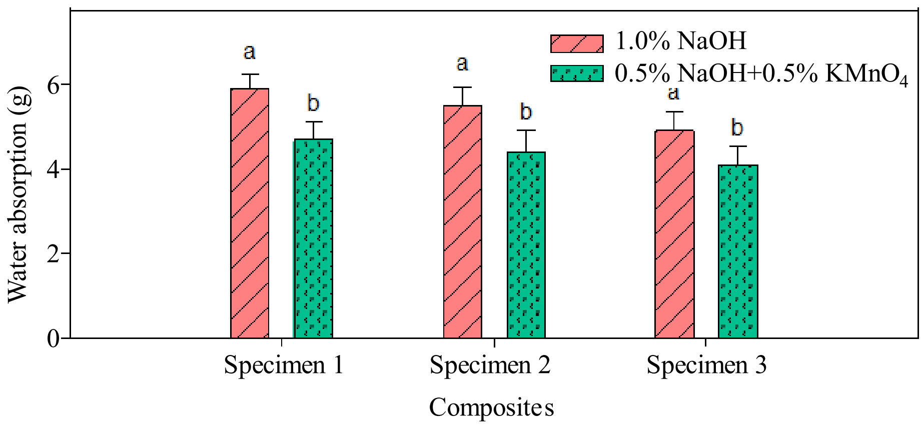

Figure 1. Water absorption (g) of different chemical treatments (1% NaoH and 0.5% NaOH+0.5% $KMnO_4$) of fibres with three different specimens. Means (± (SE) standard error) followed by the same letters above bars indicate no significant difference ($P \leq 0.05$) in a Tukey test.

Tensile Properties

Utilizing the universal testing apparatus to test the sisal-kevlar fiber, banana-kevlar fiber & sisal-banana kevlar fiber hybrid composites specimen samples. The hybrid composites were left to break until the ultimate tensile strength was reached. Figure 2(A) displays the breaking load of dry specimens during a tensile test. In the tensile test breaking load, the hybrid sisal-kevlar fiber, banana-kevlar fiber, and sisal-banana-kevlar fiber composite (fibres treated by 1% of NaOH with distilled water) failed at

4.14 KN, 5.23 KN, and 6.58 KN, respectively. These failures were relatively lower than those of the composites, which failed at 6.32 KN, 7.53 KN, and 8.23 KN (fibres treated by 0.5% of NaOH with distilled water) respectively in tensile test breaking load. Banana-kevlar fiber and sisal-kevlar fiber Samples of the sisal-banana-kevlar fiber composite were made by hand layup. According to ASTM standards, tensile, flexural, and impact tests have been completed. Our earlier discoveries [25-28] provide strong support for the discussion that follows.

Similar breaking loads for wet specimens in tensile tests are shown in Figure 2(B). In the tensile test breaking load, the hybrid sisal-kevlar fiber, banana-kevlar fiber, and sisal-banana-kevlar fiber composite (fibres treated by 1% of NaOH with distilled water) failed at 5.41 KN, 6.11 KN, and 7.78 KN, respectively. These failures were relatively lower than those of the composites, which failed at 7.92 KN, 8.89 KN, and 9.11 KN (fibres treated by 0.5% of NaOH +0.5% of $KMnO_4$+99% distilled water) respectively in tensile test breaking load.

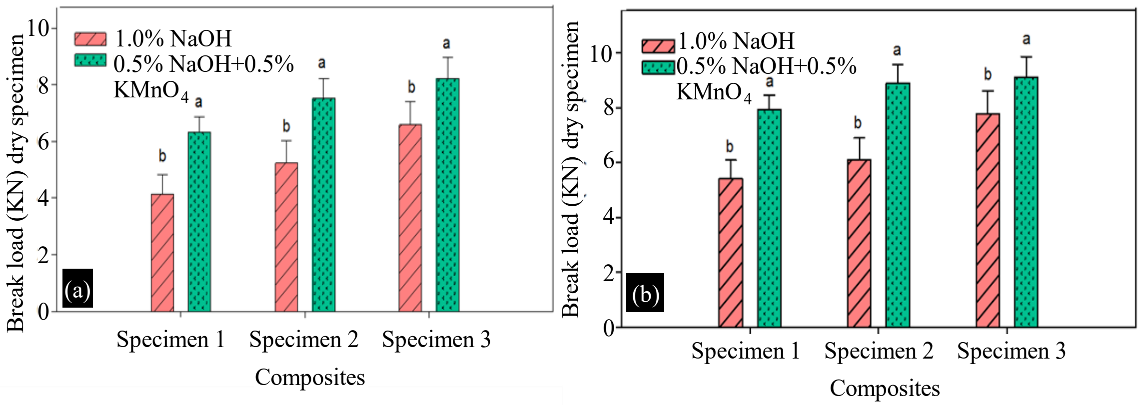

Figure 2. (A) Breaking load of dry specimens in tensile test and (B) breaking load of wet specimens in tensile test. Means (± (SE) standard error) followed by the same letters above bars indicate no significant difference (P≤0.05) in a Tukey test.

Contrasting the Dry and the Wet the Composites' tensile strength was assessed, and the results are exposed in Table 3& in Figures (3A&B). Tensile strength of sisal&kevlar fiber hybrids, banana-kevlar fiber, and sisal-banana-kevlar fiber composites (fibres treated by 1% of NaOH with distilled water) are 55.6 MPa, 58.2 MPa, and 60.2 MPa (dry), and 56.8 MPa, 59.5 MPa, and 60.8 MPa (wet), correspondingly. These values are relatively lower than those of composites (fibres treated by our earlier findings [21] provided strong support for the outcomes presented above.

The evaluation of the composites' dry and wet tensile modulus was done, and the results are shown in Table 4 and in Figures 3C and D. The tensile modulus of the hybrid sisal-kevlar fiber, banana-kevlar fiber, and sisal-banana-kevlar fiber composite is 290.11 MPa, 270.23 MPa, and 300.47 MPa (dry), and 292.41 MPa, 272.56, and 305.45 MPa (wet), respectively. This is relatively lower than the composites (fibres treated by 0.5% of NaOH + 0.5% of $KMnO_4$ with distilled water)

Table 3. Comparison of the Dry and Wet Tensile strength of the Composite.

Chemical treatment	**Sample I (G-S-S-S-G)**		**Sample 2 (G-B-B-B-G)**		**Sample 3 (G-SB-SB-SB-G)**	
	Dry Specimen	***Wet Specimen***	***Dry Specimen***	***Wet Specimen***	***Dry Specimen***	***Wet Specimen***
	Tensile Strength (MPa)					
1% of NaOH with distilled water	55.6	56.8	58.2	59.5	60.2	60.8
0.5% of NaOH +0.5% of $KMnO_4$ with distilled water	57.8	58	59.9	60.2	61.9	62

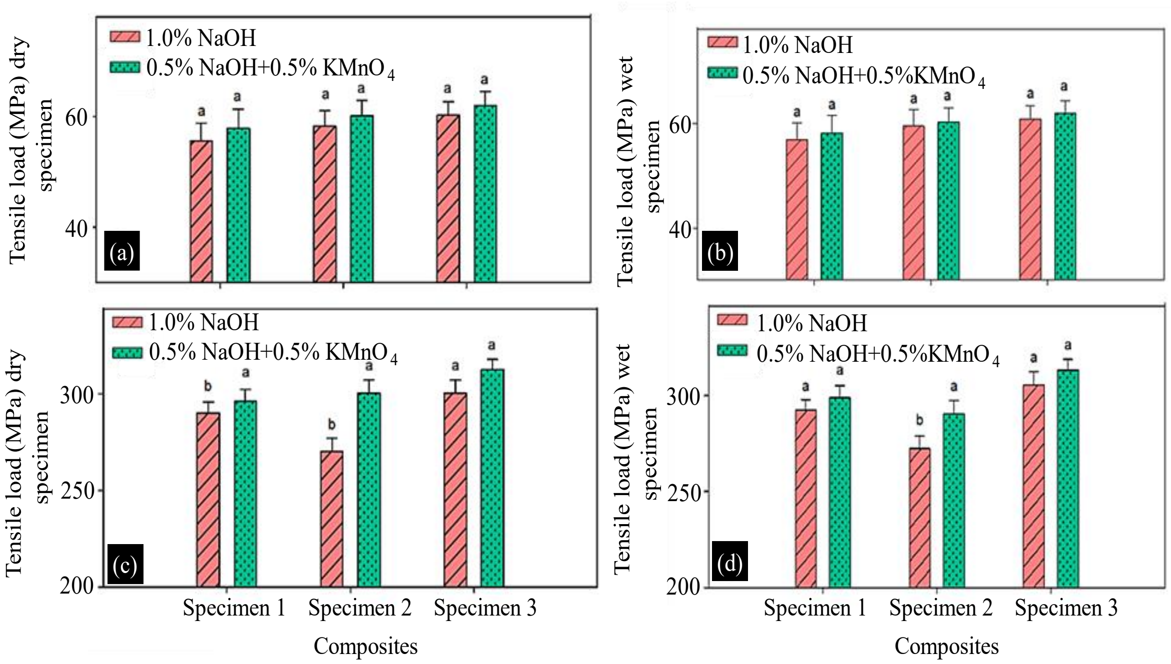

Figure 3. (A) Tensile strength (MPa) of dry specimens in tensile test. (B) Tensile strength (MPa) of wet specimens in tensile test. (C) Tensile modulus (MPa) of dry specimens in tensile test and (D) Tensile modulus (MPa) of wet specimens in tensile test. Means (± (SE) standard error) followed by the same letters above bars indicate no significant difference (P≤0.05) in a Tukey test.

Table 4. Comparison of the Dry and Wet Tensile modulus of the Composite.

Chemical treatment	**Sample I (G-S-S-S-G)**		**Sample 2 (G-B-B-B-G)**		**Sample 3 (G-SB-SB-SB-G)**	
	Dry Specimen	***Wet Specimen***	***Dry Specimen***	***Wet Specimen***	***Dry Specimen***	***Wet Specimen***
	Tensile modulus (MPa)					
1% of NaOH with distilled water	290.11	292.41	270.23	272.56	300.12	305.45
0.5% of NaOH +0.5% of $KMnO_4$ with distilled	296.96	298.78	288.43	290.48	312.47	313.88

The Dynamic Mechanical Analysis

Storage Modulus (E')

The bio-composites' storage module (E') contains a ratio of different types of natural fibers at a maximum frequency of 1 Hz. Statistics were used to compare the storage module values for sisal-kevlar fiber hybrids, banana-kevlar fiber hybrids, and sisal-banana-kevlar fiber composites (fibers treated with 1% NaOH with distilled water) (Figure 4A).

The values were significant for sisal-banana-kevlar fiber at the highest temperature of 90.27°C, and they are also significant for sisal-kevlar fiber at 89.58°C and banana-kevlar fiber at 82.11°C after treatment with 1% NaOH with distilled water, respectively. Similar results were observed in fibres composites treated by 0.5% of NaOH +0.5% of $KMnO_4$ with distilled water with significant values in *(E')* the Sisal-banana-kevlar fibres (91.57ºC) as compared to other two fibres (Figure 4B). In addition, the temperature was somewhat higher in the fibers treated with 0.5% NaOH + 0.5% $KMnO_4$ with distilled water than in the 1% NaOH with distilled water treated fibers (Figure 4B). The use of natural composites significantly increases the E' values, as the storage modulus curves further demonstrated. We found that our findings were consistent with previous studies on kenaf/epoxy composites from sustainable sources [22].

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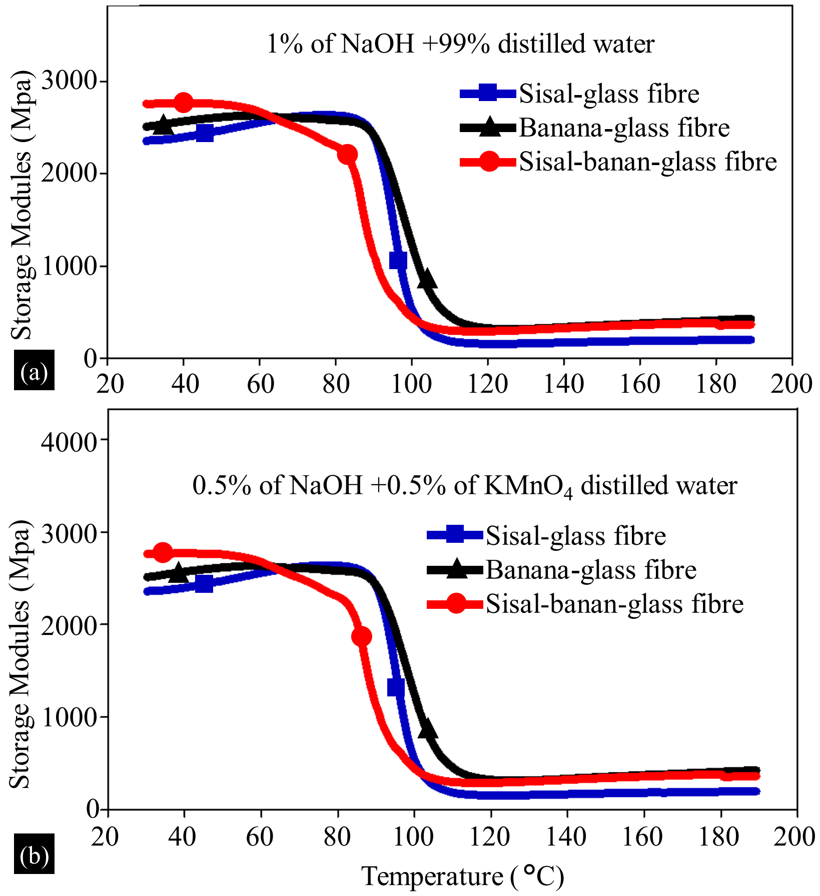


Figure 4. (A)Dynamic mechanical analysis (Storage modules) of different composite specimens treated with 1% of NaOH with distilled water. (B) Dynamic mechanical analysis (Storage modules) of different composite specimens treated with 0.5% of NaOH +0.5% of $KMnO_4$ with distilled water.

Loss Modulus (E")

In comparison to sisal-kevlar fiber and banana-kevlar fiber composites treated with 1% of NaOH+99% distilled water, which had 330.11 Mpa and 303.42 Mpa respectively, the sisal-banana-kevlar fibers reached the maximum mechanical energy dissipation (362.0 Mpa), according to DMA curves of loss modulus (Figure 5 A). Similar patterns were seen in composites treated with fibers treated with 0.5% NaOH + 0.5% $KMnO_4$ with distilled water, with sisal-banana-kevlar fibers having a substantially higher value (368.1 Mpa) (Figure 5B). It is also unmistakably demonstrated that the combination of various bio-composite composition types underlies the extension of the loss modulus peak %, which results from an increase in chain partitions, in the loss modules data. Similar drifts were seen in other studies that used dynamic mechanical analysis and various nano oil palm empty fruit bunches [22].

Tan Delta

Based on the relationship between the storage and loss moduli, E', damping results were taken into account. The general combination of natural fibers ratio grades indicates that the viscoelastic energy absorption in the natural fiber matrix together with the shear stress dosage in the fibers frequently cause the behavior of damping in bio-composites.

When compared to sisal-kevlar fiber (0.3907 at 105.56°C) and banana-kevlar fiber (0.3540 at 96.36°C) in 0.5% of NaOH + 0.5% of $KMnO_4$ with distilled water, respectively, our results for sisal-banana-kevlar fibers support the above findings (Figure 6 A). Similar results were obtained using sisal, banana, and kevlar fibers, which yielded a peak area of 0.437 at 102.11°C in 1% NaOH with distilled water (Figure 6B).

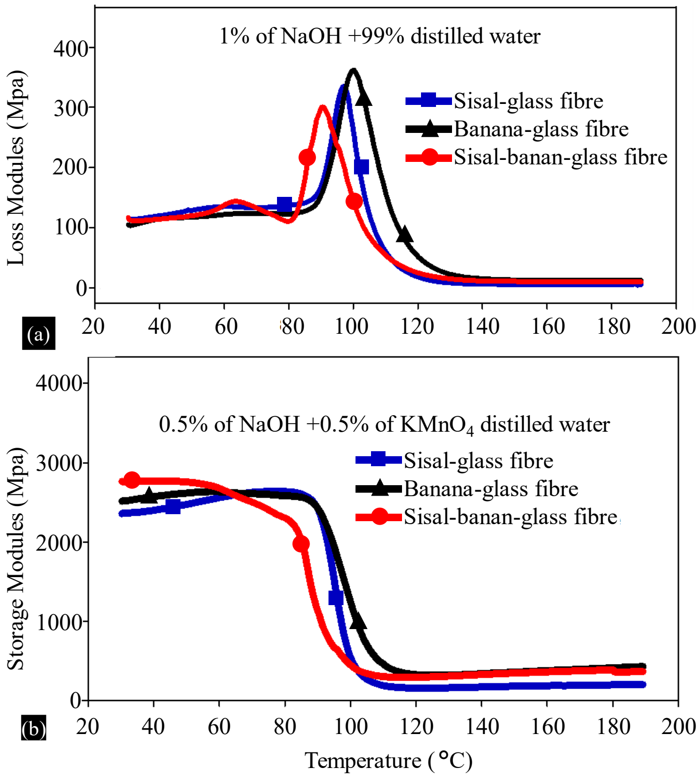
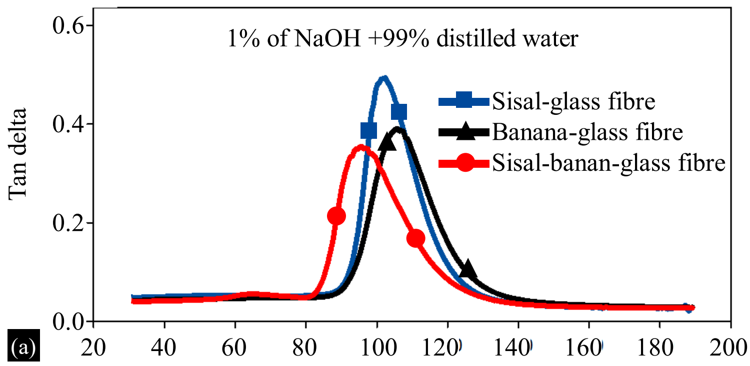


Figure 5. (A) Dynamic mechanical analysis (Loss modules) of different composite specimens treated with 1% of NaOH with distilled water (B) Dynamic mechanical analysis (Loss modules) of different composite specimens treated with 0.5% of NaOH +0.5% of $KMnO_4$ with distilled water.

SEM Analysis

The internal structure, internal surfaces, and shattered surfaces of the composite materials were discovered using SEM examination. The constructed sisal-banana-GFRP hybrid composite material is shown in cross section (Figure 7A). Figure (7B) shows how the fibers were arranged after breaking. Figure (7C) shows the SEM image for the sisal-banana-GFRP composite materials that was subjected to tensile load.

It shows discontinuities in the fibers and voids that were created on the cracked surface in the specimens as a result of the tensile load. The sisal-banana-GFRP composite material's SEM picture after it was put through a flexural test is shown in Figure 7D. The hybrid composite material's fiber bundle breaking and partial fiber and matrix scattering are depicted in the figure. The fiber breakage in the hybrid composite materials is clearly depicted in the figure. Figure 7E displays the SEM picture of the sisal-banana-GFRP composite material that was utilized in the impact test. It demonstrates how the specimen's impact caused the fibers in the composite material to break and disintegrate.



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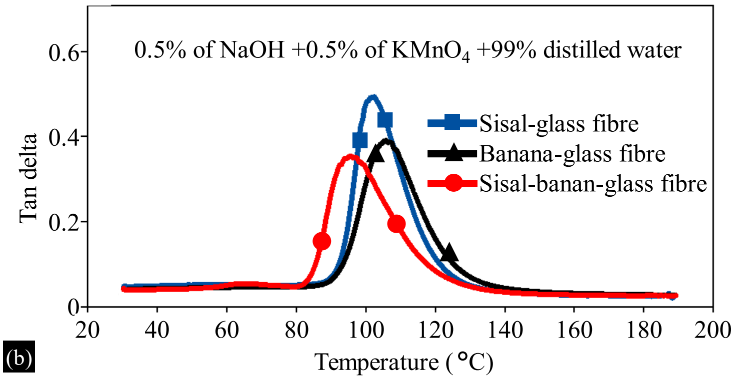

Figure 6. (A) Dynamic mechanical analysis (Tan delta) of different composite specimens treated with 1% of NaOH with distilled water (B) Dynamic mechanical analysis (Tan delta) of different composite specimens treated with 0.5% of NaOH +0.5% of $KMnO_4$ with distilled water.

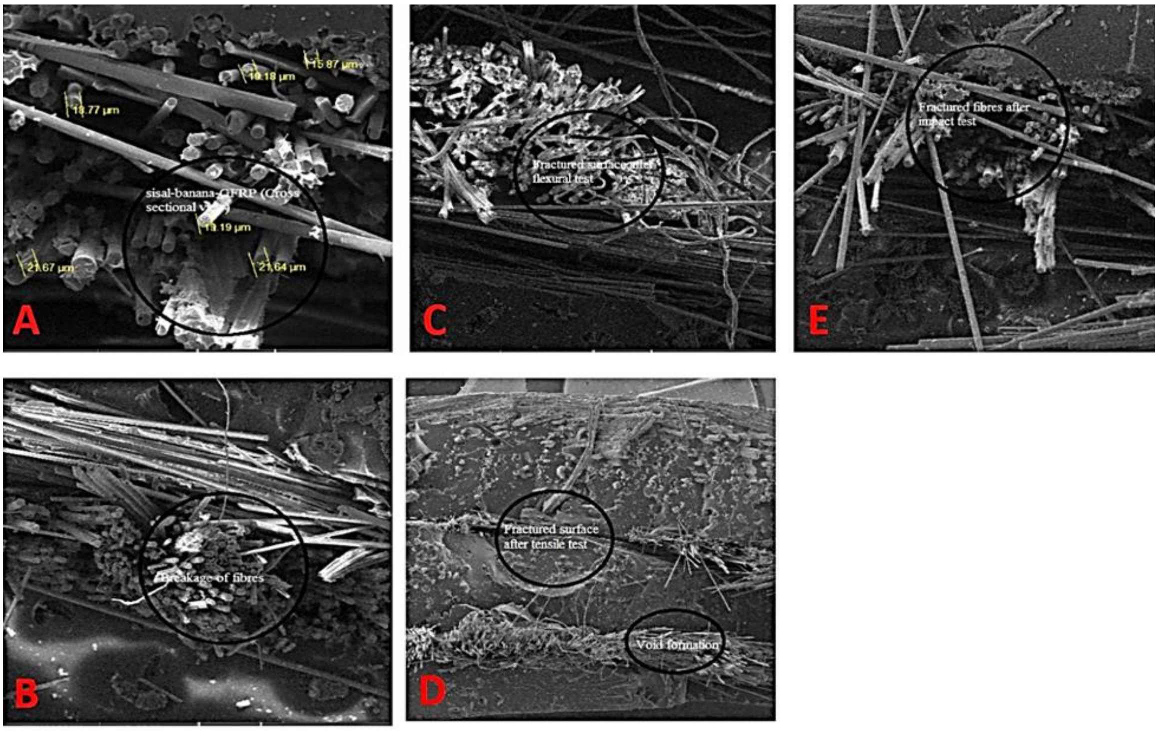

Figure 7. (A) Scanning electron microscopy (SEM) image of sisal-banana-GFRP (cross sectional view). (B) SEM image of arrangement of fibre after breakage. (C) SEM image of fractured fibres after tensile test. (D) SEM image of fractured fibres after flexural test and (E) SEM image of fractured fibres after impact test.

CONCLUSION

Thus, the current experimental inquiry offers a baseline evaluation of hybrid reinforced composite materials, focusing primarily on environmentally benign agricultural waste materials like sisal and banana stem. The fact that biologically generated materials may be recycled and have biodegradable qualities often gives them an advantage. The hybrid composite was also discovered to have a much lower water absorption capacity and increased elasticity. The water absorption is typically reported to be 4g over a test period of 144 hours. Additionally, the DMA showed that the chosen fibers of sisal-banana-kevlar fibers treated with 0.5% of NaOH + 0.5% of $KMnO_4$ in distilled water had good viscoelastic qualities. Our current findings from tests on the hybrid composite's tensile strength with varying load conditions, along with the result of the DMA, have shown that the bio-composite can be used in a variety of industries, including the automotive, furniture, upholstery, home goods, and computer products, while also being more environmentally friendly and lowering our society's chemical burden.

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