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Exploration of Mechanical Properties of Enset–Sisal Hybrid Polymer Composite

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Abstract: Enset and sisal fibers are among the most widely used reinforcement to fabricate natural fiber-based composite materials. Hand lay-up techniques were employed in this study to fabricate enset–sisal (E/S) hybrid fiber composite with volume ratios of 100/0, 75/25, 50/50, 25/75, and 0/100 and constant polyester resin. The tensile, flexural, impact strength, water absorption and morphological properties of the fabricated composite were investigated experimentally. The effects of hybridization to volume ratio were determined and the results show that hybrid composites excel in mechanical properties, compared with single composites. For better mechanical properties, the enset fiber has been hybridized with sisal fiber. Tensile and flexural strengths were enhanced by 47.3% and 41.03%, respectively, at 50/50 E/S volume ratio compared with 100/0 E/S composite. The impact strength of sisal fiber composite was improved by adding enset fiber in the composites. The inherent benefits and limitations of these two fibers were balanced out by each other in a positive way. While sisal fiber helped the composite intermesh of tensile, flexural, and reduction of water absorption, enset ensured impact strength. Morphological analysis was carried out in order to observe the fracture behavior and fiber pull-out of the samples by means of scanning electron microscopy.

Keywords: hybrid composite; enset fiber; sisal fiber; mechanical properties; water absorption; scanning electron microscopy

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1. Introduction

Polymer-based composites reinforced with natural fibers are considered the alternative options to substitute the synthetic-based composite because they are cheaper, renewable, and environmentally friendly [1]. The most application areas of natural fiber composites are building and construction, furniture, electronics, automotive and everyday appliances due to having low density, renewable, low manufacturing cost, biodegradable, and optimum mechanical properties [2,3]. Though the natural fiber-based composites are attractive to replace the synthetic fiber composite materials, their mechanical performance is still not sufficient. Because the mechanical performance of a composite material depends on the fiber loading, nature of the fibers and matrix, the bonding between fibers and the matrix as well as the fiber hybridization play important roles [4]. Hybridizing involves combining two or more fibers in a polymer matrix, which can be artificial–artificial, natural–artificial, and natural–natural fiber types. Fiber hybridization is a potential method of combining two or more fiber types in a matrix of composite materials to mitigate the drawbacks of a composite of a single fiber type, while retaining the benefits of the others. The fiber volume percentages fraction, stacking sequence of the fiber layers, fiber treatment, and effect of external variables are the primary elements affecting the mechanical properties of hybrid composites [5].

Hybridizing two or more different polymers or fibers has been recent focus of research to improve the mechanical properties of composites. For instance, a recent study on hybrid polymer composite was investigated under fatigue [6] and static [7] loading conditions. Hybridization of fibers is also seen as the best option to improve the mechanical performance of natural fiber polymer composites [8]. The properties of a single fiber composite can be improved by hybridizing with other fibers [9], where double or multiple reinforcing phases with a single phase matrix or single reinforcing phase with double or multiple phased matrix are used. These composites are more flexible than other fiber-reinforced composites. The investigation of the dynamic mechanical capabilities and water absorption characteristics of jute and sisal hybrid reinforced epoxy composites were reported [10], with the conclusion that natural fibers are better substitutes for synthetic fibers due to their exceptional mechanical properties. While hybridizing two natural fibers, the focus is frequently on achieving a superior mechanical, chemical, and physical balance, rather than improving the hybrid effect [5,11,12]. The mechanical properties of hybrid composites are influenced by the weight fraction or fiber volume of the fibers. Many researchers conducted the study by altering the fiber volume fraction and analyzing the positive and negative effects on the hybrid composite's mechanical properties as a result of the variation [13].

The mechanical properties of kenaf–pineapple leaf fiber-reinforced HDPE (high-density polyethylene) composite has been studied and the result showed that pineapple leaf fiber increased the tensile and flexural strength, but kenaf fiber improved the impact strength and the water absorption. The effect of hybridization on the mechanical performance of short banana–sisal hybrid fiber-reinforced polyester composites was studied, and it was discovered that adding banana fiber increased the tensile properties of natural fiber composites (NFCs) [14]. A similar study [15] reported on a manually operated hot compression banana/jute-fabricated composite mold and the result indicated that tensile and flexural strength enhanced up to a certain level of fiber loading, and impact strength was improved as the fiber volume increased. In the same study, the mechanical properties of the hybrid composite increased slightly with the increased thickness of the composite. The mechanical and moisture absorption qualities of banana epoxy composite and banana and sisal hybrid composite were investigated [16], with the results indicating that hybrid composite has superior mechanical properties to banana epoxy composite. The hybridization of jute/sisal and jute/curaua impact properties were analyzed and the results showed that the properties in all hybrid composites are better when compared to pure jute [8]. Previous studies [2] also show that the impact strength of the fiber-reinforced polymeric composites depends on the nature of the fiber, polymer, and fiber-matrix interfacial bonding. The reduction in water uptake is not entirely due to the natural fiber; rather, it is due to the compatibility and synergistic behavior of fiber and matrix, which increased their adhesion to the matrix and improved their covalent bonding, resulting in a reduction in overall water uptake by the hybridized composite [17].

The diverse research worked reviewed and reported on different natural fiber hybrid composites indicated that the fibers are responsible for the mechanical and water absorption properties, which need closer studies for the diverse hybridization and fiber arts. In this study, the composite was fabricated from enset, sisal and an enset–sisal hybrid by varying weight ratios (100/0, 75/25. 50/50, 75/25 and 0/100) with constant polyester resin. By comparing single enset and sisal fiber composites to hybridized composites, the impacts of hybridization on mechanical and water absorption properties are investigated. The fractured surfaces of the composites were analyzed using scanning electron microscopy (SEM). The results are expected to provide guide to get the optimum weight ratio to develop enset–sisal hybrid polyester composite.

2. Materials and Methods

The enset and sisal fibers were collected from south-western Ethiopia, where these plants are abundantly available. The enset fiber was extracted from pseudostem section of enset plant, and sisal fiber was extracted from leaf parts of *Agava sisalana* plant, while polyester resin, wax, and hardener were used to prepare the composite plate. Polyester resin with the brand name (TOPAZ-1110 Phthalic Anhydride) was utilized. This unsaturated polyester resin, wax and hardeners were purchased from the local supplier World Fiber Glass and Ethio-plastic industry in Addis Ababa, Ethiopia. The chemical compositions and mechanical properties of enset and sisal fibers are tabulated in Table 1. Universal test machine (UTM), Charpy impact machine and SEM were used to determine the tensile, flexural, impact strengths, and microstructure studies, respectively.

Table 1. Chemical composition and mechanical properties of enset and sisal fibers (Data reproduced from [18], permission [5236490867881] copyright ©2022 Elsevier; and from [19], open access with unrestricted use under the terms of the Creative Commons CC-BY license.

Properties	Cellulose (%)	Hemi Cellulose (%)	Lignin (%)	Moisture Contents (% w.b)	Density (kg/cm^3)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
Enset fiber	56.05	24.04	12.21	11.8	1.53	513 ± 57.7	26.7 ± 3	1.92
Sisal fiber	65	12	9.9	10	1.45	600–700	9–20	2–3

2.1. Mould Preparation and Composite Fabrication

The enset and sisal fibers were extracted and washed properly, and the composite was prepared by hand lay-up method. The samples were prepared on a steel sheet plate of dimension 300 × 300 × 5 (mm). Five different samples of the composite were prepared from 100/0, 75/25, 50/50, 25/75 and 0/100 of enset/sisal. A spray of release wax was applied on the mold's surface to prevent the sticking of fibers. The resin was prepared in 10:1 ratio with hardener and poured onto the wax painted mold surface. After orienting the measured enset and sisal fibers in the orientation of ($0^E/0^S/0^E/0^S/0^E/0^S$), i.e., continous unidirection, a roller was used to distribute the resin. This operation was repeated until the targeted thickness was obtained. Then, the composite was compressed for 24 h with 30 kg weight. This was done to ensure that the polyester resin had entered the fibers and samples to reduce the porosity. To strengthen the composites, the sample was cured for 24–48 h. After the curing process, test samples were prepared as recommended by ASTM standards. Figure 1 shows the process flow of composite fabrications from extraction to mechanical tests.

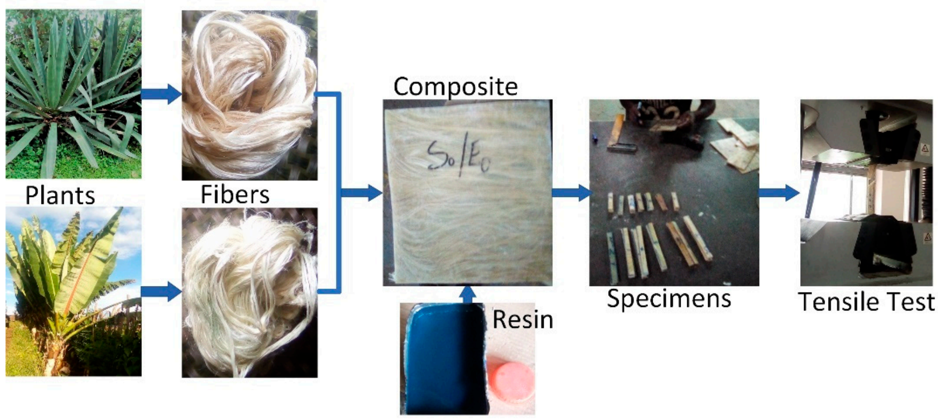

Figure 1. The composite fabrication process flow diagram.

2.2. Mechanical Testing

The prepared test specimens were subjected to the planned mechanical tests namely tensile, flexural and impact tests according to the ASTM standard [20–22] recommendations. The specimen size and shape for corresponding tests are described in the following sections. Five specimens per each set of samples were tested and the average values were taken for analysis.

Tensile, Flexural, and Impact Strength

Tensile testing, with the load acting in the axial or fiber direction was used to measure the breaking force understanding that the mechanical properties of the composite can be obtained when the fiber orientation is aligned in the load direction [23]. The specimen dimension, length × wide × thickness, used for the tensile tests is 250 × 25 × 5 mm as per ASTM D3039 standards [20]. The test was carried out on (Bairoe, Shanghai, China Universal test machine) having 50 kN capacity with the test speed of 5 mm/min crosshead speed and 150 mm gauge length. A sample specimen for the tensile test is given in Figure 2a.

(**a**) (**b**) (**c**) (**d**)

Figure 2. (**a**) Tensile, (**b**) flexural, (**c**) impact test specimen and (**d**) UTM.

Flexural strength was measured to investigate the material resistance to deformation under a given load. The cross-section of the test specimens is rectangular, as they are directly molded or cut from molded parts. To investigate failure by inter-laminar shear, a three-point bend test was done according to recommendations of ASTM D790 standard [21] on UTM (WP 310 universal material tester, Gunt, Barsbüttel, Germany) with a test speed between 0.5 and 1 mm/min. The specimen dimension is 127 × 13 × 5 (mm). The specimen for the flexural test is given in Figure 2b. Calculation of flexural strength was performed by using the formula given in Equation (1):

$$\sigma_f = \frac{3F_{max}L}{2bh^2} \tag{1}$$

where, F_{max} = maximum load at failure, b = sample width, h = sample thickness and L = sample length between the two support points.

The impact test is a single-point test measuring the resistance of a material against impact load from swinging pendulum on the specimen until fracture. The specimen dimension for this test is 65 × 13 × 5 (mm) and the impact strength was determined using Charpy impact tester (Ceast Torino, Italy) as per ASTM D256 standard [22] was used. The specimen for the impact test is shown in Figure 2c.

2.3. Water Absorption

Water absorption test of enset–sisal hybrid composites at room temperature were recommended. The test was carried out as per ASTM D570 standard [24] by taking out the samples from water at regular intervals and weighing immediately before being cleaned with a dry cloth. The samples were then weighed using a 4-digit balance to determine how much water had been absorbed. Before being re-immersed in the water, all of the samples were dried in an oven until they attained a constant weight. The percentage of water absorption was determined using the formula in Equation (2):

$$WA = \frac{m_2 - m_1}{m_2} \tag{2}$$

where WA = Water absorption, m_1 and m_2 are the weight of dry and wet samples, respectively.

2.4. Scanning Electron Microscopy Analysis

To conduct the morphological characterization of the composite fracture surface, the scanning electron microscope (SEM) from (Model JEOL, Kyoto, Japan) was used. The samples were sufficiently cleaned; air-dried and coated with 100 A° thick platinum in JEOL sputter ion coater and observed in SEM at 10 kV. The fracture surface morphology of the composite specimens was then observed.

2.5. Weight Fraction of Materials

The hybridization was employed to determine the weight proportion of reinforcements and matrix material used in the manufacturing of the hybrid composites. It is defined as the production of composites containing two or more distinct fibers in the same polyester resin matrix volume (70% with the addition of hardener) with a total fiber loading of 30%. In this study, five distinct composites were fabricated, with weight proportions of 100/0, 75/25, 50/50, 25/75, and 0/100 for the eenset–sisal hybrid samples.

3. Experimental Results and Discussion

3.1. Tensile Test

The following results were obtained from experimental studies on the tensile strength of fabricated enset, sisal, and enset–sisal hybrid composites materials. Sisal–polyester composites have a higher tensile strength (152.3 MPa) than enset and enset–sisal hybrid composites, as shown in Figure 3. The tensile strength of the enset–polyester composite is lower (69.7 MPa) than that of sisal and enset–sisal hybrid composites. As can be seen from the data, hybridizing with sisal fiber improved the tensile strength of the enset fiber composite, resulting in higher tensile strength. In comparison to the enset fiber composite, the tensile strength of enset and sisal hybrid composites with volume ratios of 50/50 and 25/75 improved by 43.5% and 47.8%, respectively. As the volume percentage of sisal fiber increases in the hybrid composite, the tensile strength was improved. The increase in tensile strength of the hybrid composites is also due to the higher tensile properties of the fibers [19], particularly that of sisal fibers ranging from 600 to 700 MPa [17]. Furthermore, higher lignin content weakens the interfacial bond between the fiber and the polymer components, resulting in a weak composite. As a result, most researchers employed fiber treatment to lower lignin concentration in order to strengthen the inter-facial connection and increase the composite's mechanical properties. As can be seen from Table 1, sisal fiber has less lignin than enset fiber. As a result, sisal fiber composites have better mechanical properties than enset fiber composites, and increasing sisal fiber content in hybrid composites is utilized to improve tensile and flexural strength [25].

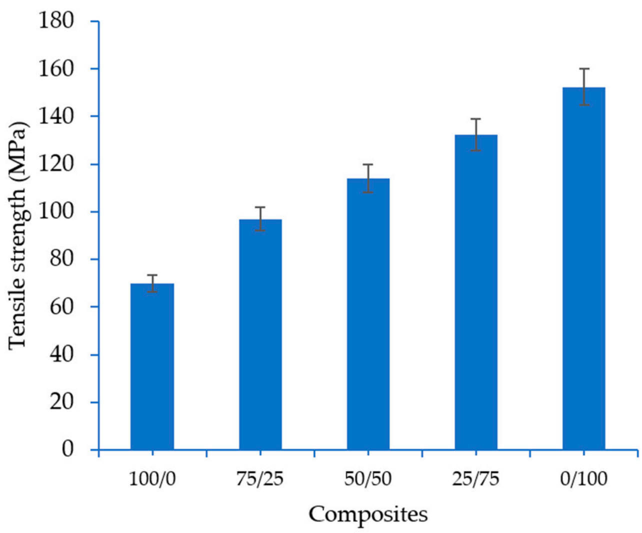

Figure 3. Tensile strength test results.

The tensile strength of pure sisal fiber (0/100) is stronger than that of enset (100/0) composites with the same ratio of 100/0 and 0/100 E/S composites, i.e., a composite of pure enset fiber and pure sisal fiber, respectively. In composites, this is most likely owing to matrix integrity loss and insufficient wetting between fiber and matrix. The tensile strength of the composite was increased when sisal fiber was added to it. This is because sisal fibers are more compatible with polyester resin, and a composite material's tensile strength is largely determined by the strength and modulus of its fibers. Figure 4 shows the force–elongation graphs for 100/0, 75/25, 50/50, 25/75, and 0/100. It is shown that all the curves first increase linearly and then behave exponentially up to the maximum force.

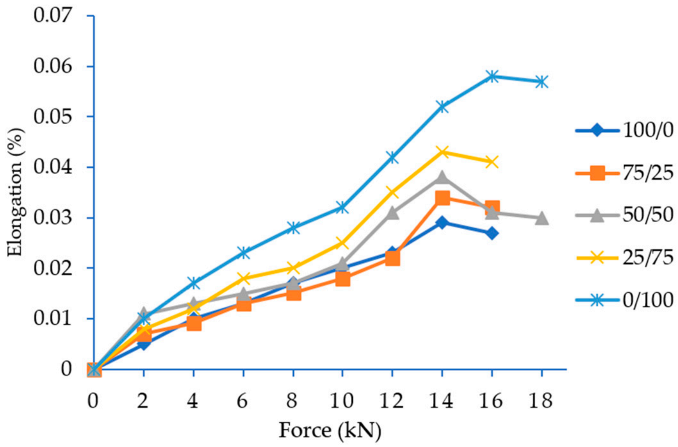

Figure 4. Force–elongation diagram for (tensile) for enset sisal hybrid composite.

3.2. Flexural Test

In the three-point bending test, the maximum load was applied in the middle of a freely supported beam specimen and the average values of the flexural test results of five samples were tabulated. These results are shown in Figure 5. As observed, sisal fiber-reinforced composite has a superior flexural strength, while flexural strength of enset reinforced composite was improved by 41.03% at 50/50 weight ratio enset–sisal hybrid composite.

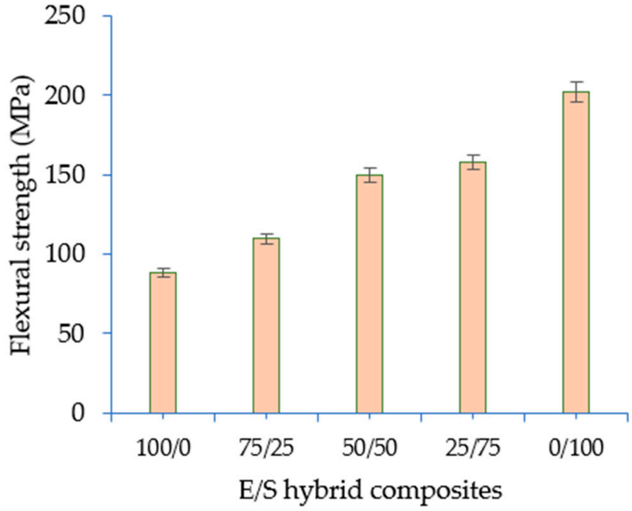

Figure 5. Flexural strength test result.

3.3. Impact Test

The Charpy impact test was used to determine the impact strength of the created composites. V-notched specimens with 1.25 mm depth were tested, and the results are presented in Figure 6. When compared to sisal reinforced and enset–sisal hybrid composites, enset reinforced polyester composites have exhibited a considerable increase in impact strength, with an impact strength of 27 kJ/m^2. However, the sisal reinforced composite has lower impact strength, which improves as enset fiber is added. The optimum (average of maximum and minimum) value (22.21 kJ/m^2) is found in 50/50 enset–sisal reinforced fibers, as shown in the data. When compared to the sisal reinforced composite, the composite's optimal values improved by 16.57%.

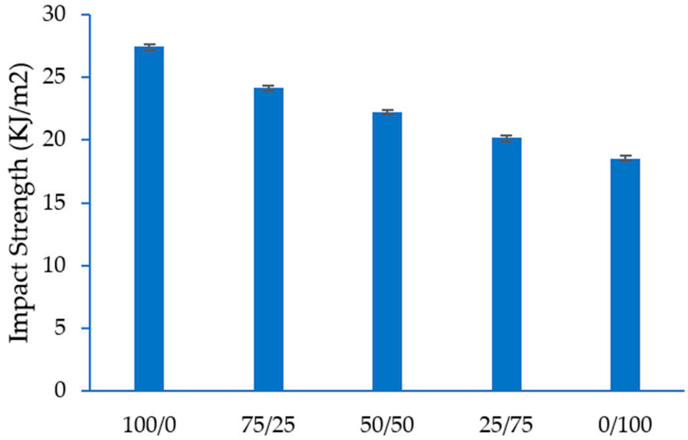

Figure 6. Impact Strength test result of enset–sisal hybrid composites.

3.4. Moisture Absorption

Representative curves of the moisture absorption composites of single and hybrid composite over time are shown in Figure 7. As observed from the results, enset fiber composite (100/0) has higher water absorption than sisal (0/100) and enset–sisal hybrid polyester composite. At 50/50 enset–sisal hybrid-reinforced composite ratio, we observe the water absorption in between 100/0 and 0/100. The water absorption properties of all composites are the same that means for the first 12 h, the range of water absorption varied from 5% to 6% and after 48 h and 72 h, the water absorption increased from 6.5% to 9% and stayed somewhat constant after 84 h. As a reinforcement in composite materials, expansion of the fiber after water absorption would lead to micro-cracks in the composite material, thus affecting its mechanical properties [26]. Without any chemical treatment of the fibers, the fiber-matrix compatibility can help to reduce water uptake in natural fiber composites.

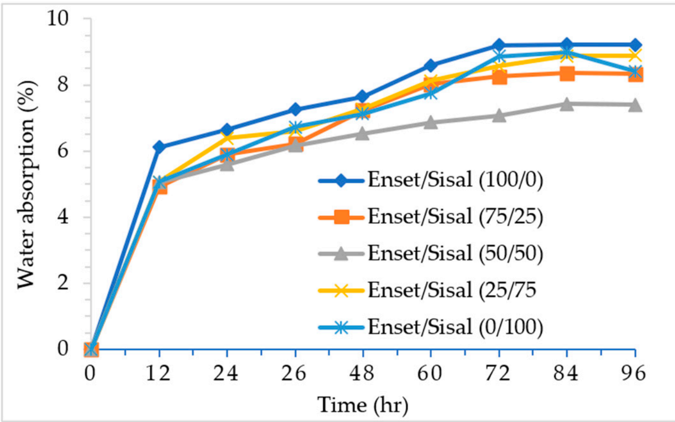

Figure 7. Moisture absorption test result of hybrid enset–sisal hybrid composites.

The types of fibers, fiber orientations, fiber length, fiber weight ratio and composite thickness, and types of matrix used are the main factors that affect the mechanical properties of natural fiber hybrid composites [27]. Table 2 shows that the comparison of the mechanical property of the results obtained in this study with existing results from literature on natural fiber hybrid composites. The results of the current study indicate that mechanical properties obtained are higher in tensile strength and lower in flexural strength. Higher tensile strength may be due to composite thickness and enset and sisal fiber weight ratio and better interfacial bonding of two fibers in the polymer resin. The impact strength of the study is similar with the existing results from the literature. Similarly, the tensile strength reported in the selected literature of sisal fiber epoxy composite is similar to the current study of sisal polyester composite (i.e., 152.32 MPa).

Table 2. Comparison of mechanical properties of natural fiber hybrid composites of the current study with existing literature results.

Hybrid Composites	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact	Reference
Sisal/Enset/Polyester	114.02	61.21	22.21 kJ/m^2	Current study
Jute/Sisal/Epoxy	66.77	114.01	332 J/m	[8]
Jute/Sisal/epoxy	66.77	114.01	32.25 kJ/m^2	
Banana/Jute/Polyester	25.83	182.34	20.1 kJ/m^2	[16]
Sisal/Jut/Epoxy	42.45	39.8	19.5 J	[26]
Sisal/epoxy	153.8	-	83 kJ/m^2	[28]
Sugarcane leaves/almond shell	12.86	39.91	0.78 J	[29]
Hemp/Jute/Polyester	50.83	73.39		[30]
Hemp/Flax/Epoxy	44.17	44.61	4.18 kJ/m^2	[9]
Jute/Curaua/Epoxy	66.77	97.67	388 J/m^2	[8]
Jute/Sisal/Epoxy	15.91	29.65	0.55 J	[22]

The ruptured surfaces of the fabricated composites after tensile testing were evaluated using SEM. The SEM image of enset polyester, sisal polyester and 50/50 enset–sisal hybrid composite are shown in Figures 8–10, respectively. The images show that better bonding was observed for enset–sisal hybrid composite. Though a strong interfacial binding is required to create materials for interior and structural applications, a weak interfacial link increases toughness by promoting the pullout effects required in energy absorption, i.e., for impact strength. As a result, the enset polyester composite outperforms the other hybrid composites in terms of impact strength. In addition to the observation done on the fiber pullout during the tensile strength test, the SEM images can be used as means of identifying the failure mechanism of the composite. Some of the observed failure mechanisms are indicated in the SEM images (Figures 8–10).

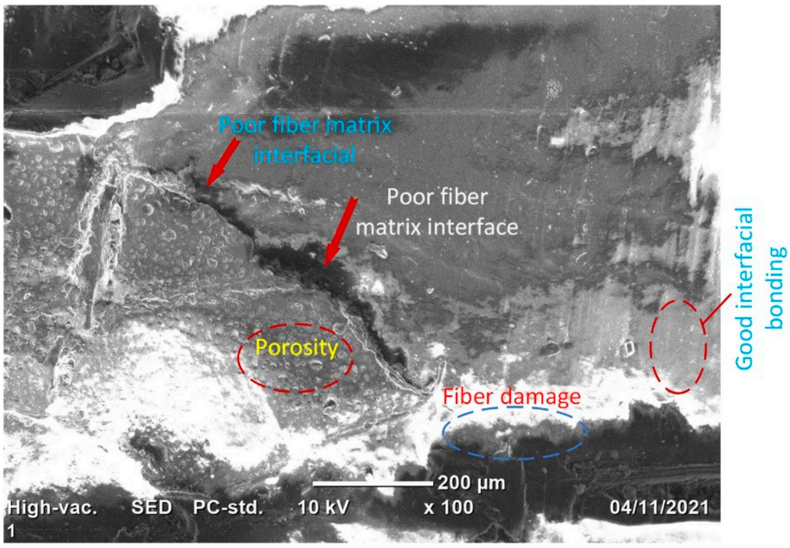

Figure 8. SEM image of 100/0 of enset–sisal hybrid composite.

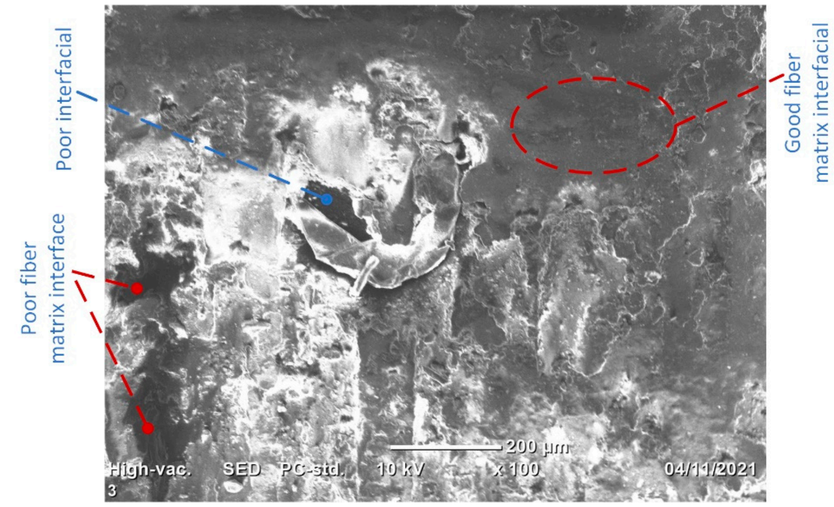

Figure 9. SEM image of 0/100 of enset–sisal hybrid composite.

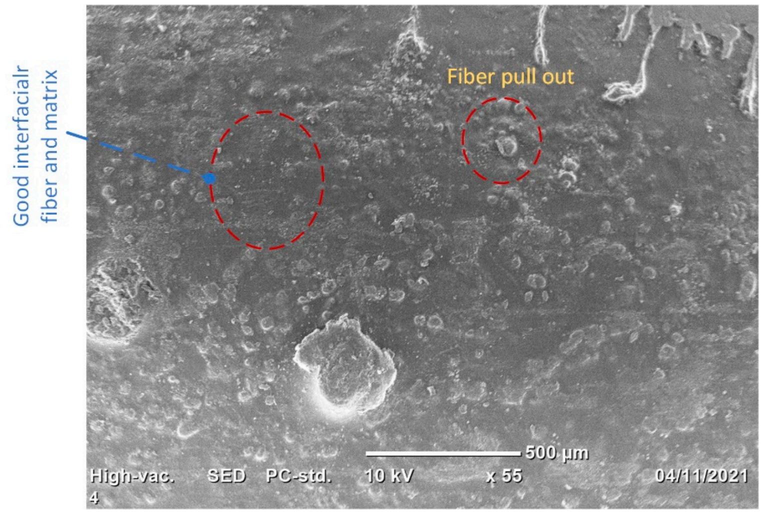

Figure 10. SEM image of 50/50 of enset–sisal hybrid composite.

4. Conclusions

This article presented the variation in mechanical properties such as tensile, flexural, and impact strengths as well as water absorption of hybridized enset- and sisal-reinforced polyester composite as a function of hybridization effect by comparing with individual fiber composites. The enset–sisal fiber was successfully fabricated hybrid composite at 30% of fibers and 70% of the resin. Based on the study reported above, the following conclusions can be drawn:

- At a same fiber weight ratio, the tensile and flexural strength of enset polyester composite is found to be lower than that of sisal polyester composite.
- Adding sisal fiber to the hybrid composite improves the tensile and flexural strength while lowering impact strength.
- At a 50/50 weight ratio, the tensile strength and flexural strength of enset–polyester composite were enhanced by 38.8% and 12.6%, respectively.
- The enset polyester composite has a higher impact strength than the sisal–polyester composite. At a 50/50 weight ratio, the addition of enset fiber increased load absorption capability by 16.6%.
- The water absorption minimum for 50/50 enset–sisal hybrid composite than enset– and sisal–polyester composites. The recommended weight percentage of enset–sisal hybrid composite is 50/50 to get adequate mechanical and water absorption properties.

- The SEM images can be used as a means of the failure mechanism of the composites.
- The results of the study can provide guides to get the optimum weight ratio to develop enset–sisal hybrid polyester composite for different applications.

Author Contributions: A.E.B.: data collection, investigation, methodology, formal analysis, and writing—original draft. H.G.L.: conceptualization, methodology, supervision, writing—review and editing, and validation. M.G.J.: methodology, resources, supervision, and validation. All authors have read and agreed to the published version of the manuscript.

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