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Research Article

Experimental Study on the Mechanical Properties of Hybrid Areca and Abaca Fiber Reinforced Polymer Composites

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ABSTRACT

Renewable-source composites have become important substitute materials for industrial and technical applications in design and production. Natural fiber (NF) composites have emerged as premium materials relative to standard fiber composites, owing to their direct production process, improved fiber content, reduced polluting base content, lightweight qualities, and incineration capabilities. The growing concern for environmental cleanliness necessitates the search for maintainable alternative materials to substitute conventional ones already in use. Natural fibers function as a viable alternative reinforcement material owing to their wide availability in fibrous form and minimal extraction expenses. This study involves the preparation of environmentally friendly green composites using Areca fiber (ARF) and Abaca fiber (ABF) with epoxy and the assessment of their mechanical behaviours. The incorporation of nano-SiO_2 as a filler in hybrid fiber composites plays a crucial role in enhancing mechanical properties by reinforcing the matrix and improving fiber-matrix bonding. The findings demonstrated that the flexural, tensile, and impact characteristics of the hybrid composites were significantly improved at 76% ABF, 20% ARF and 4% nano-SiO_2, and that hybridization mitigated environmental impacts. The inner composition of the broken surface, failure morphology and fiber delamination are examined by SEM examination.

Keywords: Hybridization; Mechanical behaviors; Green composites; Natural fibers; SEM analysis.

1. INTRODUCTION

Synthetic fibers originating from petrochemicals are non-biodegradable, emit detrimental microplastics, and possess a substantial energy footprint, resulting in prolonged environmental impact. Conversely, natural fibers are biodegradable, renewable, and require less energy; they may adversely affect water consumption and soil health if not cultivated sustainably. Synthetic fibers last in the environment, while natural fibers undergo natural decomposition. Microplastic contamination is a significant concern associated with synthetic materials, whereas natural fibers circumvent this issue. Overall, natural fibers are more environmentally friendly. Natural fibers are currently gaining the interest of academic and industrial researchers owing to their accessibility, ecological sustainability, and biodegradability. Natural fibers sourced from plants, including jute, areca, banana, flax, hemp, coir, kenaf, and others, have undergone substantial research in the past two decades and are increasingly favored over synthetic fibers (Naik *et al.* 2021). Intricate structural design is common in composite materials because of the trade-off between lightweight performance and manufacturing costs. The importance of doing early structural design trade-off studies and material selection cannot be overstated. Additionally, this finding supports the use of novel fiber systems in relatively inexpensive applications requiring moderate stiffness (Hagnell *et al.* 2020). For the sustainable automotive sector to progress, it is crucial to utilize natural fibers or agricultural waste. The construction and automotive industries have found the most versatile material in natural fiber-reinforced composites. Because of lightweight c, these materials improve gas mileage and overall vehicle efficiency. Natural fiber composites are being used by many prominent automobile manufacturers to make a variety of parts for their vehicles (Verma *et al.* 2019). Fibres extracted from plant parts such as stems, leaves, bast, and fruits are used in composites for applications like packaging, automotive, and aerospace industries. This review highlights the

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potential of leaf fibers, which are often discarded but have equivalent strength and better mechanical properties when used in green composites (Ramesh *et al.* 2022).

For structural applications, the hybrid fiber/bio-ceramic reinforced polyester composites were used to improve the mechanical strength, fatigue resistance, and creep behavior (Jesumanen *et al.* 2024). The study examines hybrid fiber-reinforced polymer composites incorporating carbon and kenaf fibers. The C/C/K/C/C stacking sequence demonstrated a tensile strength of 170 MPa, with carbon fibers displaying superior qualities; nevertheless, kenaf fibers were recognized for their reduced cost and environmental advantages (Karthik *et al.* 2022). The carbon/flax hybrid had excellent mechanical capabilities, including tensile and flexural strength, and displayed improved water absorption characteristics due to the arrangement of synthetic fibers with flax (Yashas *et al.* 2022). The areca/carbon hybrid composites demonstrated improved mechanical and thermal properties, whereas the use of synthetic fibers augmented water absorption and adhesion, rendering them appropriate for semi-structural applications (Yashas *et al.* 2022).

The main objective of this endeavor is to create epoxy composites reinforced with hybrid areca, carbon, and basalt fibers. Researchers looked at mechanical qualities including tensile and flexural strength, and found that carbon-areca fiber composites performed better than other materials, particularly for structures that had to withstand medium loads (Yashas *et al.* 2022). Abaca fiber is noted for its mechanical strength and flexibility, rendering it appropriate for polymer composites utilized in automotive and industrial applications. The paper examines alkali and silane treatments to improve the characteristics of abaca-based composites for enhanced use across diverse sectors (Kurien *et al.* 2023). The results show that increasing the paper yarn proportion enhances air permeability and thermal conductivity, suggesting the potential for eco-friendly textiles, particularly for clothing worn close to the skin (Karasawa *et al.* 2022). The Manila hemp paper yarn serves as a sustainable alternative to cotton and petroleum-based fibers, emphasizing its little shrinkage and resistance to pilling. Nevertheless, issues such as inadequate handleability, excessive stiffness, and difficult grip must be addressed for broader uses in the textile sector (Peterson *et al.* 2021). An epoxy bio-composite utilizing areca fiber, nano-silica, and neem oil is used as a bio-blender. The composite is appropriate for medical components and food storage containers because of its antibacterial and thermo-mechanical characteristics (Ben *et al.* 2021). The amalgamation of 2.5 wt% and 7.5 wt% nano-Al_2O_3 and areca nut shell powder attained optimal tensile, yield, and compressive strengths, positioning the composite as a viable commercial alternative to wood-based materials (Thangaraj *et al.* 2022).

The fatigue damage in basalt fiber non-crimp fabrication composites, identifying fiber breakage from tensile stress interactions between transverse and longitudinal fiber bundles as the primary material of stiffness deterioration (Mortensen *et al.* 2022). The composite materials are made from nonwoven fabric impregnated with latex SKN-40, demonstrating that tensile strength increases in the transverse direction and at higher degrees of impregnation (Nazarov *et al.* 2023). The study assesses abaca fiber-reinforced polyamide composites, demonstrating enhancements in permeability and mechanical properties attributed to the inclusion of a less robust tex spacer, which leads to elevated tensile strength and modulus (Ramezani-Dana *et al.* 2021). This study explores auxetic fabrics in geopolymer composites, highlighting their potential for impact applications due to their energy dissipation properties, enhanced by a helical auxetic yarn structure that increases mechanical strength and thermal stability (Constâncio *et al.* 2023). The results indicated that non-crimp carbon textiles provide remarkable stiffness, rendering them appropriate for spar caps in wind blade manufacturing.

The mechanical characteristics of PET needle-punched nonwoven fabric elaborate on the fact that the transverse and longitudinal directions exhibit the strongest increases in tensile strength as the degree of water vapor sorption increases (Leshchenko *et al.* 2023). Weaved carbon fiber epoxy composites with varying stacking orientations were studied for their mechanical characteristics. The study found that tensile and flexural properties were highest for [(0/0/0/0) and 0/+90/-90/0] configurations, while impact resistance was superior in 0/+45/-45/0 stacking. The presence of MWCNTs reduced fiber and matrix damage as well as improved flexural strength in laminated composites, with a sensitivity analysis validating the simulation results (Bhowmik *et al.* 2022). This study explores the chemical treatment of abaca fibers to remove non-cellulosic components. The raw fibers exhibited high tensile strength and stiffness, but these properties significantly decreased after alkali treatment, as cellulose and hemicellulose content altered the mechanical behavior of the fiber (Custodio *et al.* 2020). A hybrid form of self-compacting concrete (SCC) that incorporates abaca, polypropylene, and natural fibers was used to prepare the composites. Microstructural analysis confirmed decreased voids and increased hydration components, and the mixture with 1% and 0.25 % abaca fiber demonstrated better flexural and tensile strength (Vivek *et al.* 2022). Composites made of high-density polyethylene (HDPE) and abaca fiber are the focus of this study. The abaca/PP composites, which made use of chemically treated fibers, were ideal for usage in automobiles due to their enhanced mechanical and thermal characteristics (Shakir *et al.* 2024).

The blending of nylon and areca fibers with vinyl ester composites, with NaOH treatment, enhances fiber-matrix bonding. The mechanical properties peaked at 10-15 wt% fiber content, but defects like fiber agglomeration reduced performance at higher fiber fractions (Sai *et al.* 2023). The biochar and areca fiber-reinforced polymer composite rebar for construction demonstrates enhanced mechanical and thermal properties with minimal water absorption. Rebar composite ‘C’ displayed superior bending strength, while ‘E’ exhibited excellent hardness and hydrophobicity (Kumar *et al.* 2024). Sodium alginate (SA) and xanthan gum (XG) coatings for areca nuts improved gloss, wettability, and water resistance. The 50:50 SA-XG combination formed denser films with better mechanical properties, making it a promising edible coating (Wen *et al.* 2022). The hybrid fiber offering a balance of high strength, stiffness, and toughness, leveraging Abaca's superior tensile strength (980 MPa) and Areca's impact resistance. Unlike synthetic fiber composites, it is lightweight, biodegradable, and eco-friendly, while outperforming single natural fiber composites in mechanical properties due to the synergy of the hybrid reinforcement, such as enhanced fiber-matrix bonding and reduced voids.

This experimental study used the hand lay-up technique to produce environmentally sustainable green composites reinforced with areca and abaca fibers as reinforcement and nano-SiO_2 as filler. This results in two types of specimens that are manufactured with the fiber in both the longitudinal and transverse orientations. The mechanical behaviors, including Tensile, Flexural and impact strength were assessed. The findings demonstrated that the integration of ARFs with ABF with nano-SiO_2 filler substantially enhances strength, and the composite fabrication technique mitigates environmental concerns. These eco-friendly hybrid ARF-ABF with nano-SiO_2 filler green composites are recommended as alternative materials.

2. MATERIALS AND METHODS

2.1 Materials

This research employs areca and abaca fiber mats to fabricate the hybrid composite sample. ARF, which ranges in diameter from 100 to 300 µm. The areal weight of the unidirectional ABF mat is 400 gsm, and the manufacturing method utilizes LY556, a commercial-grade epoxy resin. The catalyst and accelerator used in this research are Cobalt Naphthenate and Methyl Ethyl Ketone Peroxide. The abaca fiber mat, areca fiber mat and nano-SiO_2 powder particles were procured from Go Green Enterprises, Chennai, Tamilnadu, India. Physical behaviors of the materials utilized for production are specified in Table 1.

Table 1. The materials' characteristics

Physical behaviors	Units	Areca fiber	Abaca fiber	Nano-SiO_2	Epoxy resin
Density	g/cm^3	1.0	1.4	2.6	1.3
Tensile strength	MPa	200	980	40	85
Modulus of elasticity	GPa	5	41	75	4
Stiffness	kN/mm	2.5	12	High	2.5
WA		70	65	-	-
Apparent porosity	%	20	25	-	-

2.2 Preparation of Composite Samples

The composite samples are produced using the hand lay-up method. It is among the most direct and efficient techniques for composite processing. Five distinct specimens are created with varying ARF compositions of 0%, 10%, 20%, 30%, and 40% and nano-SiO_2 by 0%, 2%, 4%, 6%, and 8% by weight. The resin is combined with a certain amount of silica powder with a 1% catalyst and 1.5% accelerator to facilitate rapid setting and prompt blending, which also decreases the amount of heat produced by the exothermic reaction. To remove moisture, the woven mat fibers are dried in 80ºC heated air for a full day. The base of the mold is coated with a releasing agent to aid in the specimen's extraction, and the initial layer of the sample (fiber) is placed above the dried coated surface. Ten fiber layers were used to create each composite, with the proportion of areca and abaca fiber layers. Prior to the composite samples being processed, the resin with filler is measured in equal volumes during the fabrication process and kept in a container. Upon completing the layering of the sample with areca or abaca fiber, the resin is cured, followed by compression of the samples in a press to eliminate extra air trapped between the layers, achieving optimal specimens. At the pressing operation, no resin runoff occurs. A woodruff file is used to carefully shape the edges of composite plates, which have dimensions of 30 × 30 cm and a thickness restriction of 4 ± 0.02 mm. The hybrid composites reinforced with ARF and ABF with filler are prepared at 30ºC with a mean relative humidity of 65%. The matching density and weight percentage were used to calculate the volume fractions of composites utilizing the rule of mixes.

2.3 Analyzing the Mechanical Properties

The mechanical behaviors are greatly influenced by the matrix, fiber and filler characteristics, content of fiber, and fiber orientation, which are the main parameters in this experiment. The composite specimens are manufactured in compliance with ASTM D790 for the flexural test and ASTM D638 for the tensile test. The impact test sample is constructed in compliance with the ASTM D6110 standard. In each instance, multiple samples are evaluated, and the mean values are employed. Tensile tests are performed using an F150 series UTM conforming to the specifications specified by ASTM standards, as previously noted. The elongation of gauge sector is documented during load application. The three-point static flexural test is conducted to determine the FS utilizing the same UTM. The specimen's deflection is measured by applying force until fracture, utilizing the crosshead position.

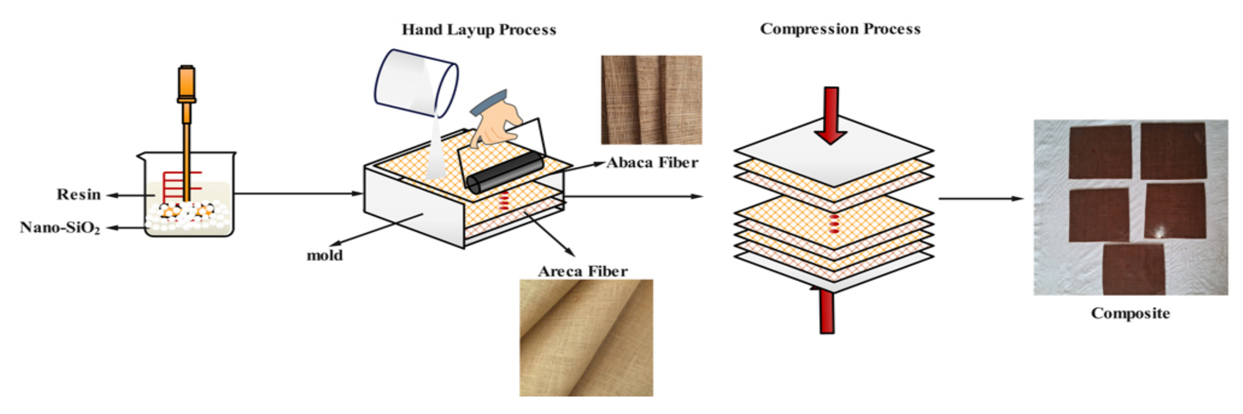


Fig. 1: Preparation of Composites

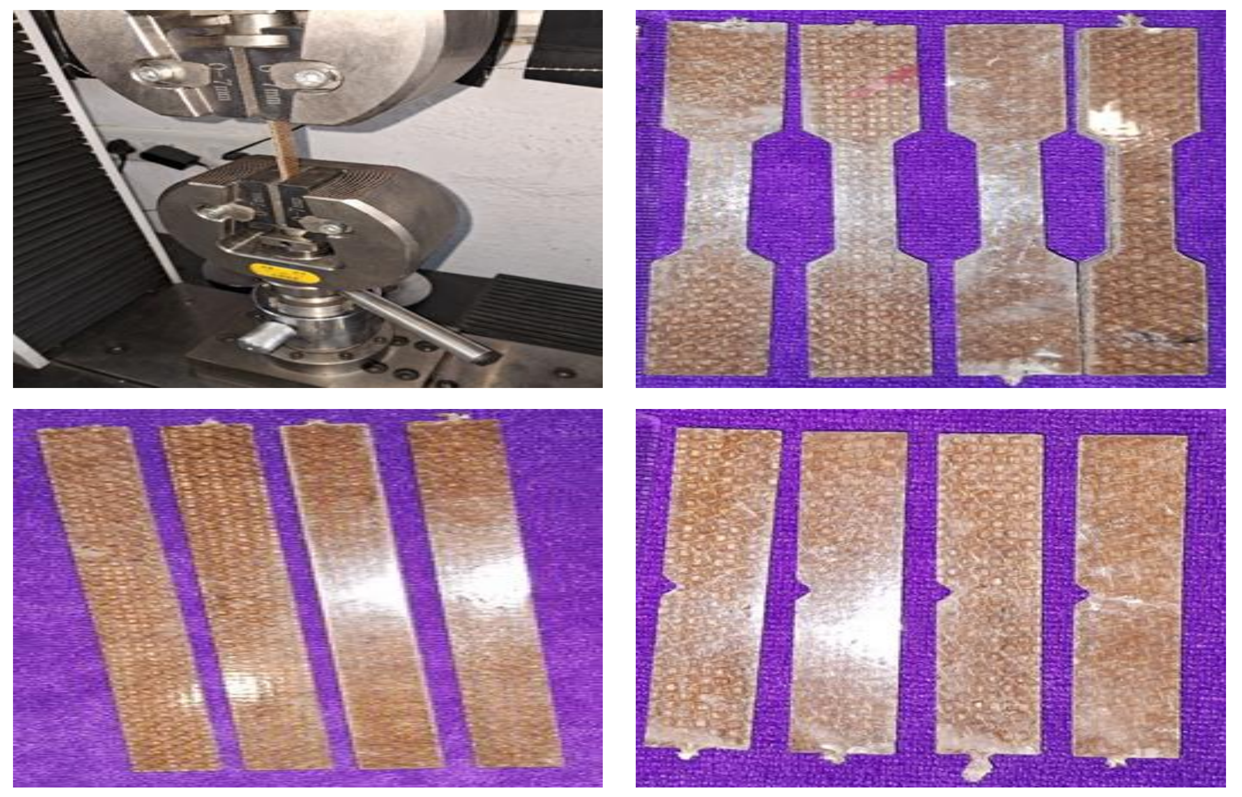


Fig. 2: (a) Universal Testing Machine and Specimens of (b) Tensile strength (c) Flexural strength (d) Impact strength

Impact test specimens that meet the required dimensions are manufactured, and tests are conducted utilizing an impact-testing machine manufactured by Charpy (Model: KI-300, Serial Number. 2013/1006). In the testing procedure, the sample is positioned in the testing apparatus, and the pendulum is activated to deliver a substantial impact load to the samples. It is possible to quantify the energy required to fracture the material.

3. RESULTS AND DISCUSSIONS

This study employs ARF and ABF as reinforcing materials with nano-SiO_2 as fillers. Various percentages of fiber weight are employed to examine their effect on mechanical qualities. The experimental data for TS, FS, and IS loading for the ARF, ABF and nano-SiO_2 reinforced hybrid composite in both the transverse and longitudinal directions are shown in Table 2.

Table 2. Values of various composite specimens from experiments

Sample No.	Composition of materials			TS (MPa)		FS (MPa)		IS (Joules)	
	ABF	ARF	Nano SiO_2	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
S1	100	0	0	188.21	185.42	295.35	278.72	24.57	21.33
S2	88	10	2	176.20	181.11	276.80	266.07	24.58	24.10
S3	76	20	4	179.73	193.77	220.79	241.13	26.90	24.04
S4	64	30	6	167.94	144.04	243.60	226.95	24.51	21.55
S5	52	40	8	152.01	147.76	218.08	214.60	22.92	21.29

3.1 Flexural Strength Analysis

Fig. 3 illustrates the comparison of flexural strength across various composites based on their directional orientations. The results specified that ARF reinforced ABF hybrid composites display enhanced performance in the longitudinal orientation relative to the transverse orientation. The graph clearly indicates a progressive drop in strength with a rise in the amount of areca fiber. The previously reported FS is superior at 0% ARF and 0% nano SiO_2 filler incorporation with ABFs, indicating that ABFs outperform areca fibers. Natural ARF could be utilized as reinforcing fibers if the FS is insufficient. The hybridization of these fibers leverages their complementary properties: Abaca fibers provide high tensile strength and stiffness, while Areca fibers contribute impact resistance and toughness. This synergy enhances mechanical performance compared to single-fiber composites. However, the composite's performance is influenced by the proportions of the fibers; excessive Areca fiber content reduces tensile strength, while optimal combinations (e.g., 76% Abaca, 20% Areca, and 4% nano-SiO_2) maximize flexural and impact strength. This indicates that fiber interactions, influenced by their distribution and bonding with the matrix, are critical to achieving balanced and enhanced composite properties. Fig. 4 illustrates the strain- stress curve produced by the apparatus during the flexural loading of the specimen composed of 4% nano SiO_2 + 20% areca fiber and 76% abaca fiber. The figure clearly illustrates that the stress rises to 4.0 N/mm² at a strain of 0.165, after which it begins to decline due to the failure of specimen. Nano-SiO_2 filler in hybrid fiber mat composites significantly improves tensile strength**,** flexural strength, and impact resistance by enhancing fiber-matrix bonding and stress distribution.

3.2 Tensile Strength Analysis

The analysis of the experimental results reveals that the tensile strength in the fiber direction surpasses that recorded in the transverse direction. The strength of fiber-matrix adhesion is superior in the transverse direction relative to the fiber direction. Figure 5 illustrates the TS comparison of the specimens tested with two distinct fiber orientations. The data demonstrates that the TS in the direction of longitudinal fiber is superior to that of the composite specimens made of transverse fibers due to the fiber mats not being entirely unidirectional, leading to minimal variations in properties assessed in both orientations. This may be attributed to the variations in manufacturing technique, compatibility with synthetic polymers, insufficient dimensional stability, or issues with processability. The findings also reduced that the augmentation of ARF in hybrid composite diminished the TS. Significant TS is noted for the composite of 76% ABF, 20% ARF and 4% nano-SiO_2. ABFs support more loads than areca fibers. Although abaca fibers exhibit superior performance, areca fibers may serve as a reinforcing material owing to their ecological benefits. The fabricated composite panels with arecanut fine fiber fabric (AFFF) show good mechanical properties with tensile and compression strengths of 10.8 MPa and 55.6 MPa, respectively (Poornima *et al.* 2022).

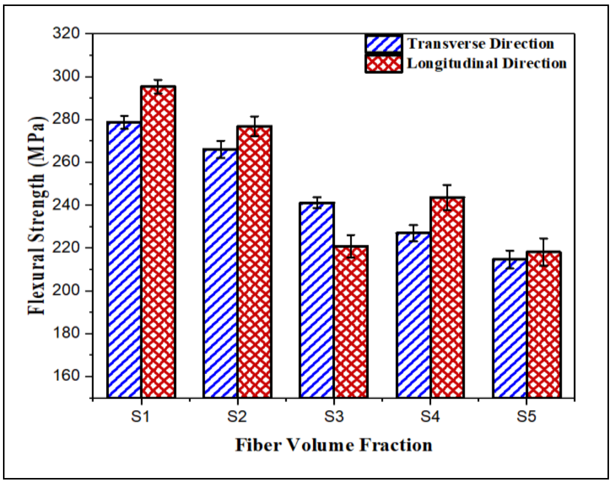


Fig. 3: FS comparisons of various composite specimens

3.3 Impact Strength Analysis

Charpy impact test is utilized to ascertain the impact energy absorbed by composite specimens. Fig. 6 depicts the comparative IS of the various composite specimens. The data demonstrates that the amalgamation of ARF with ABF effectively absorbs substantial impact energy. Longitudinally fiber-oriented samples have a higher energy absorption capacity than transversely fiber-oriented composite specimens. The findings specified that a higher percentage of ARF diminishes the impact energy for transverse specimens, while a contrasting pattern is noted for fibers that are longitudinal. The transverse hybrid showed the highest mechanical enhancements, demonstrating positive hybrid effects in non-laminated composites (Dong *et al.* 2023).

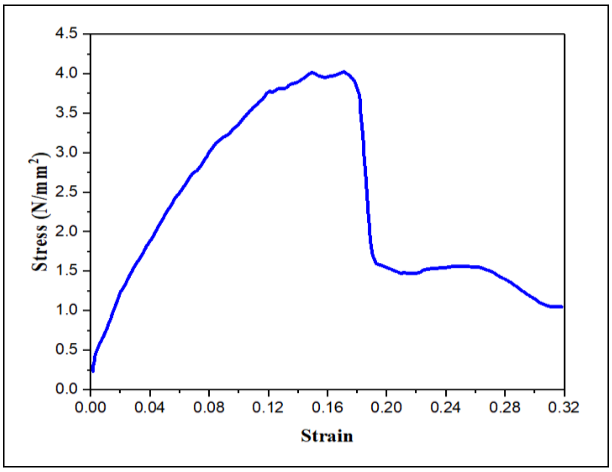


Fig. 4: An example of a stress-strain curve from flexural loading that is produced straight from the machine

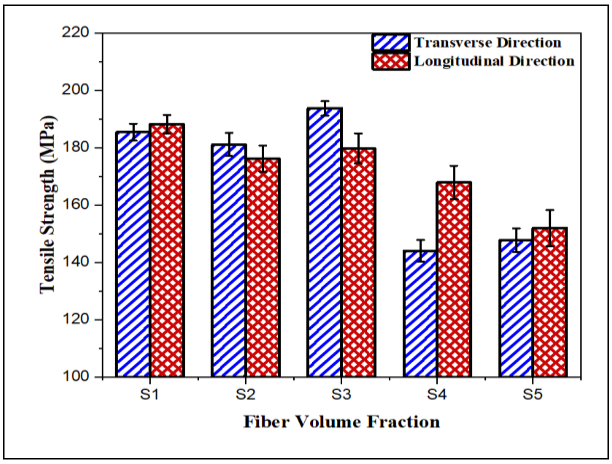


Fig. 5: TS comparisons of various composite specimens

3.4 SEM Analysis

The specimen undergoing the mechanical test is studied utilizing a Scanning Electron microscope (model ZEISS). Fig. 7 shows the SEM of images nano silica powder that utilized in this study. Fig. 8 (a)& (b) presents specimens comprising 76% ABF, 20% ARF and 4% nano-SiO_2 that underwent tensile stress along the specimen's longitudinal axis and the fiber's transverse axis, as analyzed by scanning electron microscopy. Fiber breakage transpires in the longitudinal direction. The data reveal projecting fibers and cavities inside the matrix components. The samples are produced using the hand lay-up method. The dispersion of the fiber and matrix materials is still insufficient even when pressure is applied through rollers to achieve uniform delivery of matrix materials. Fig. 7 (b) illustrates the fibers' transverse direction, wherein the matrix layer and fibers are disrupted, resulting in an uneven fiber structure. The data unequivocally demonstrate the distorted fibers and their configuration. SEM analysis revealed significant surface changes in fibers after NaOH treatment, with the alkali treatment improving tensile properties by removing connective materials from the fiber surface (Valášek *et al.* 2021).

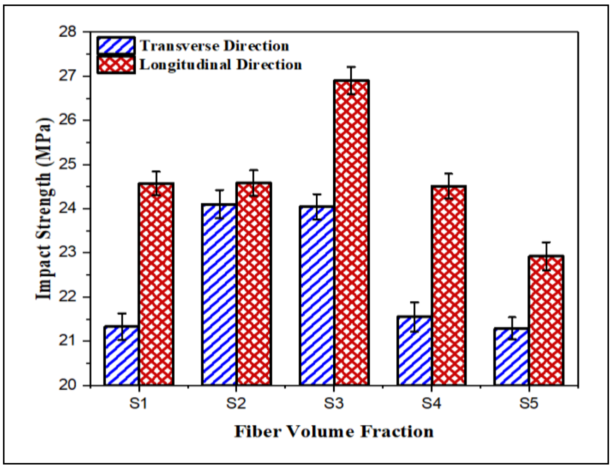


Fig. 6: IS comparisons of various composite specimens

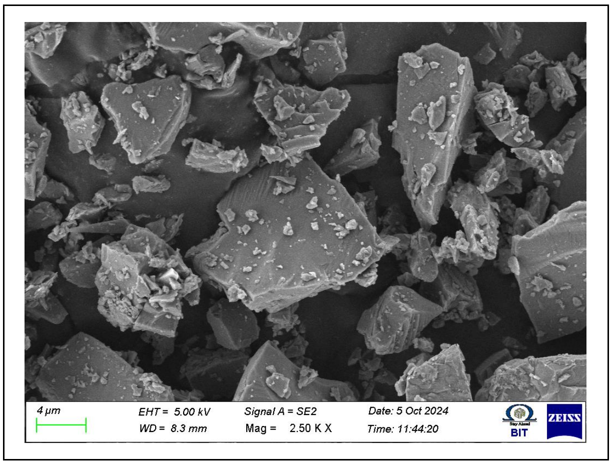
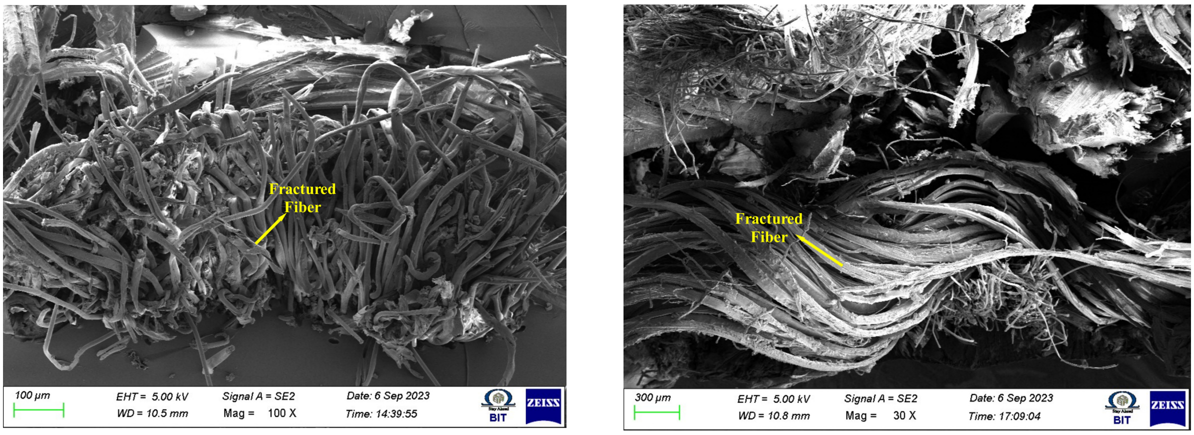


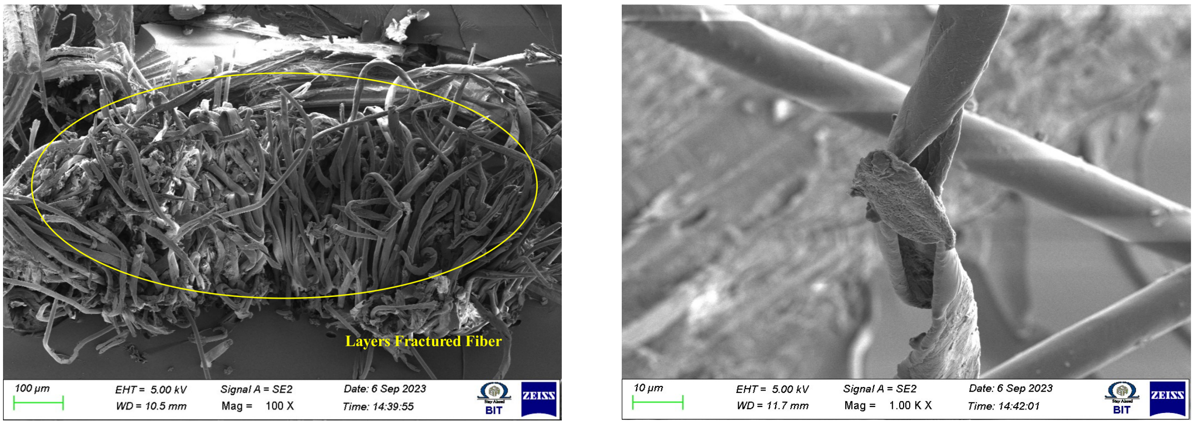
Fig. 7: SEM images of nano-SiO_2 particles

Fig. 9 (a) & (b) presents the scanning electron microscope images of composites comprising 64% ABF, 30% ARF and 6% nano SiO_2 subjected to flexural loading in both transverse and longitudinal direction of fibers. Fiber extraction as a result of flexural pressure and its directional alignment are depicted in Fig. 8(a). As the sample is squeezed, a crack occurs after it attains the yield point; the breaking differs from that of a tensile sample. Figure 8 (b) shows the layer organization, the cracked fiber surfaces, and fiber's dispersion inside the matrix.



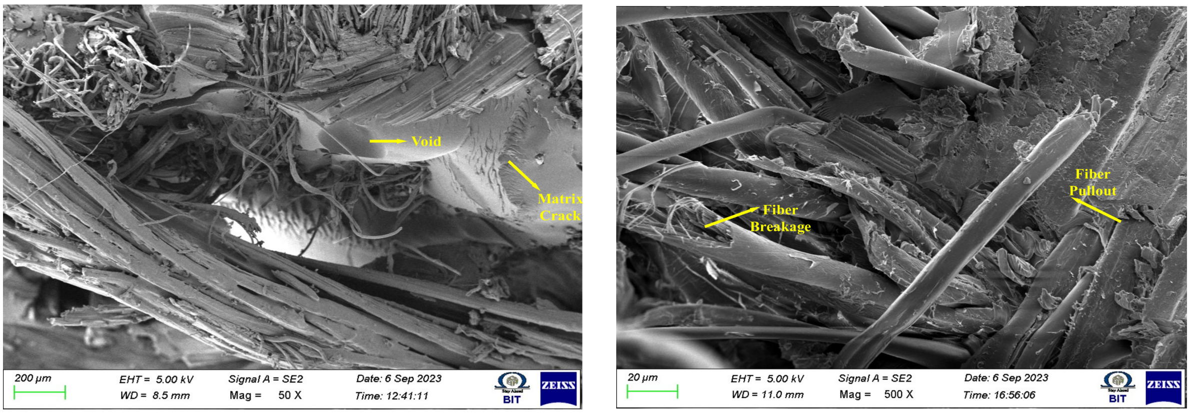
(a) (b)

Fig. 8: SEM images of the composite specimens exposed to tensile loading (a) Transverse and (b) Longitudinal directions



(a) (b)

Fig. 9: SEM pictures of flexural-loaded composite specimens (a) transverse direction (b) longitudinal direction



(a) (b)

Fig. 10: SEM images of impact-loaded composite samples (a) Transverse direction (b) Longitudinal direction

It is clear from comparing Figures 8 (a) and (b) that damage is more severe when fibers are oriented transversely. The findings also show that the material's compressive pressure caused matrix failure and fiber debonding. The areca fiber-reinforced concrete (AFRC) showed that 2% areca fiber improved compressive strength by 2.89% and tensile strength by 18.16%. SEM and EDX analyses confirmed strong fiber-matrix interaction and cost savings. Fig. 10 (a) & (b) present the scanning electron microscope images of the sample comprising 76% ABF, 20% ARF and 4% nano-SiO$_2$ under impact loading conditions. The images indicate fiber breakage, matrix debonding, and the formation of voids within the specimen's surface. Examining the SEM images clearly shows fiber dislocation, longitudinal fiber pullout, and transverse fiber breakage.

4. CONCLUSION

This study involves the fabrication of areca, abaca fiber mat reinforced with nano-SiO$_2$ hybrid composite specimens utilizing the hand lay-up technique, with samples ready in both transverse and longitudinal fiber orientations. Specimens are subjected to TS, FS, and IS loading tests. The findings that follow are drawn from the analysis of the data.

- The composite specimens perform more effectively in the longitudinal direction related to the transverse direction. Furthermore, composites comprising 76% ABF, 20% ARF and 4% nano-SiO$_2$ demonstrate enhanced tensile loading capabilities, while pure ABF composites excel in flexural loading performance.

- The maximum TS of the pure ABF reinforced specimen is 188.21 MPa, while maximum FS is 295.35 MPa.

- The hybrid composite sample with 76% ABF, 20% ARF and 4% nano-SiO$_2$ had the highest recorded impact strength, measuring 24.57 J.

- The SEM pictures distinctly reveal fiber dispersion inside the resin, fiber pullout, loading-induced fibre dislocation, fiber orientation, interfacial adhesion between the matrix and fibres, and fibre fracture.

The results demonstrate that eco-friendly hybrid composites reinforced with abaca and areca fibers provide a feasible substitute for composites made only of synthetic fibres.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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