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Exploring the Environmental Implications and Mechanical Optimization of Kevlar/Waste-Based Piassava Fiber Nano-SiO_2 Hybrid Composites: Toward Sustainable Material Solutions

GIRIDHARAN MALAYANKULAM RAVICHANDRAN, SIVAGANESAN SELVARAJU*
Department of Mechanical Engineering, School of Engineering, Vels Institute of Science, Technology & Advanced Studies (VISTAS), Pallavaram, Chennai, 600 117, Tamil Nadu, India

Abstract: *This research describes the development of a new sustainable and high-performance hybrid polymer matrix composite (HPMC) that reduces ecological impact by adding waste-based piassava fiver as a key reinforcing, sustainable, and biodegradable material. The composite contains Kevlar and waste based-piassava fibers in an epoxy matrix with nanosilicon dioxide particles (SiO_2 NPs) to have the desired mechanical properties for uses in aerospace, railway cabins, structural frameworks, sports, medical equipment, and so on. Employing the hand lay-up method and compression moulding, six-layered composites were made with different stacking sequences (A to O type) and SiO_2 nanoparticle content (0, 0.5, 1, 1.5, and 2 wt.%). N-type stacking (KKPPKK) at 1.5 wt.% SiO_2 NPs achieved the highest level of performance. The optimized composition produced impressive tensile strength (336 MPa), and flexural strength (381 MPa). Further, M-type composites with 1 wt.% SiO_2 NPs had the highest impact strength of 263 J/m. Among all the combinations, the N-type composites absorbed less water, with 8.96% absorption, making them more useful in wet conditions. By incorporating waste-based piassava fiber and optimal nano SiO_2 filler, this research creates a new way to achieve lightweight, durable, and environmentally responsible composite hybrid materials, positioning with the aims of sustainable engineering and waste valorization.*

Keywords: *Waste management, Kevlar fiber, piassava fiber, SiO_2 filler, stacking sequence*

1. Introduction

Over the years, the rapid development of industries and the expansion of urban areas have resulted in higher waste management rates. Such waste generation has proven to be a significant obstacle to being environmentally sustainable [1,2]. Dilapidated disposal mechanisms lead to pollution, resource shortages, and even habitat destruction; hence, there is a pressing need for new paradigms in waste management. Out of a plethora of options, the transformation of waste materials into valuable commodities and the biorefinery sectors have received a considerable amount of attention as a means of creating value [3]. As a principle, this fits into the overall concept of a circular economy, where resources and minimizing harm to the natural environment are paramount. Due to being lightweight, cost-effective, and biodegradable, natural fibers from renewable plants and animals have become suitable reinforcements in composite materials. Composite materials made from waste-sourced natural fibers, such as those from agricultural waste or industrial waste, are a promising greener substitute for synthetic fibers [4]. These fibers, which are often treated as end-of-life materials, can be reused to mitigate complicated mechanical properties with reduced environmental issues. Such waste-derived natural fibers include piassava, coir, sisal, jute, hemp, and many others sourced from the agriculture and forestry industry. Piassava fiber, for example, has been considered a waste material from broom-making and other activities since it is derived from the leaf stalks of palm trees. Utilizing such natural waste fibers into composite materials makes it possible to develop high-performance and eco-friendly materials

email: sivaganesanme@gmail.com

for engineering purposes while also addressing issues with waste management [5]. Moreover, waste-based fibers would also alleviate reliance on non-renewable synthetic materials, and it will leverage cost by giving a monetary value to waste materials. In addition, composites with natural waste-derived fibers have good mechanical properties such as tensile strength, impact resistance, and thermal stability, making them appropriate for the automotive, building, packaging, and aerospace industries [6,7].

To overcome the constraints of natural fibers for advanced applications, the hybridization of natural and synthetic fibers using nanofillers is proposed. Natural and artificial fibers can be incorporated into a single polymeric matrix to create hybrid materials that maximize the benefits of each component [8]. Reducing the amount of synthetic fiber used in polymer composites is the idea behind hybridizing artificial and organic fiber. Research by Alkhatib et al. [9] claims that adding unprocessed date palm fibers improved the impact resistance of a carbon fiber and Kevlar hybrid composite. To significantly reduce the weight of the resulting hybrid composites, treated natural fiber must be used, since the study found that the untreated hybrid composites were heavier than their treated counterparts. In addition to fiber surface treatment, the hybridization process has demonstrated enhanced natural fiber characteristics for ballistic purposes. Dhakal et al. [10] assessed the mechanical properties of composites composed of carbon, flax, and a blend of the two materials. The test showed that breaking at extension improved compared to carbon fiber composites, while flax and carbon fibers were included in the composites. However, the flexural strength of carbon composites was decreased by including flax fibers because of their intrinsically lower strength. Glass fiber, jute, and sisal were used to create composites by Ramesh et al. [11]. On such composites, tension and bending tests were carried out. Based on the results, he discovered that sisal fiber composites have a higher tensile strength than jute fiber composites. However, both are inferior to glass fiber composites in tensile strength. As a reinforcing phase in modern composites, silicon nanoparticles are considered the most preferred nanofiller amongst available nanoparticles, surpassing metallic and metallic oxide nanoparticles [12]. Silicon dioxide (SiO_2) is a particularly appealing nanoparticle form due to its extremely high specific area, strong adsorption capabilities, excellent dispersion ability, outstanding thermal stability, and high chemical purity. However, the most frequent drawback of these nanofillers is their high price. However, this drawback is offset by using a modest quantity of nanofiller (2.5–5% weight percentage). Generally, low filler content may produce the highest mechanical characteristics [13].

The mechanical characteristics of woven hemp and SiO_2 with up to 8 weight percent zinc oxide (ZO) were studied by Velmurugan et al. [14]. The study found that the tensile and flexural performance of the hybrid composites with 4 weight percent SiO_2 and ZO combinations is improved by 10.36% and 3.21%, respectively. In a different study, Matheswaran et al. [15] examined the mechanical characteristics of composites made of agricultural waste, nano SiO_2, and clay up to 4.5 weight percent. Mechanical properties rose most at 4.5 wt.% SiO_2 loading and 3 wt.% clay loading, according to the study. Glass-kenaf and glass-banana fibers are the two distinct mixtures of fibers that Kumar et al. [16] manufactured, with graphene (0–1.5 wt.%) as the nanofiller particles element. Glass-kenaf fiber combined with nanofiller graphene was discovered to have greater durability than glass-banana fiber combined with nanofiller particles graphene after mechanical features were identified. Data from earlier research showed that several variables, including fiber-matrix interaction, stacking order, orientation, and reinforcement materials qualities, affect how hybrid composites behave. Layers of material were piled one after the other to create woven hybrid laminated composites. Goods made from hybridized composite laminates include building substances, sporting items, automobiles, and seatpacks [17]. Furthermore, woven kenaf/Kevlar hybrid composites were created for anti-ballistic composite material in earlier work by Jambari et al. [18]. Additionally, woven laminated composites were used in the construction of the domestic telephone stand, according to Sapuan and Maleque [19]. Furthermore, employing natural fibers to reinforce concrete can help manage steel corrosion and generate cost-effective building materials. Lertwattanaruk and Suntijitto [20] have also conducted a mechanical evaluation of the sandwich design of the material.

Research on how well composite buildings function under various loading scenarios has attracted much attention lately. Only a small number of research, meanwhile, highlights how the stacking order affects composite laminate behavior. The impact of stacking order on the flexural and Charpy impact of carbon fiber-reinforced polymer composite (CFRP) laminates was investigated by Caminero et al. [21]. It was found that the laminate's stiffness and impact performance were affected by the stacking arrangement. The impact performances and failure mechanisms of glass fiber-reinforced polymer composites with varying curvatures and stacking sequences were investigated by Kaboglu et al. [22]. It was found that the applied force is dampened by the fiber direction. Jesthi et al. [23]. Noted how the symmetric interaction sequence of carbon glass fiber affected the mechanical performance of the polymer matrix composite. The hybrid stacking pattern enhanced the composite's tensile, flexural, and impact resistance, according to the data. Mlyniec et al. [24] investigated how CFRP laminate behavior was affected by thickness, stacking order, and thermal aging. It was discovered that the stacking pattern had an impact on the composites' damping and aging period. Singh and Mahesh [25] investigated how changing the ply location affected the quasi-historical glass fiber-reinforced polymer composite's impact performance. The findings showed that the impact reaction is influenced by the lamina's location. As a result, not enough research has been done on how the stacking order affects the composite laminate's flexural, tensile, and impact damage.

According to literature reviews and analyses, there are significant gaps in utilizing piassava-based waste fibers for developing HPMCs in conjunction with Kevlar and SiO_2 nano-fillers. There is a dearth of research on how waste-based fibers, nanofillers, and synthetic fibers can be utilized in a single matrix to foster environmental eco-friendliness and mechanical optimization. In addition, further research is still needed to come up with optimal stacking sequences and filler weight ratios for these kinds of matrices to increase mechanical strength and environmental conservation. This paper intends to address those gaps by investigating the utilization of Piassava waste fibers in conjunction with SiO_2 NPs and Kevlar fibers for hybrid composite preparation. Composite materials will be hand-lay-up and compression molding and go through the different stacking and SiO_2 NPs weight ratios to reduce waste generation and optimize the composites through gradation adjustment.

2. Materials and methods

2.1. Extraction of waste-based piassava fiber

To align with the utilization of waste-derived piassava fibers in hybrid composite development, the fibers were sourced from industrial broom manufacturing waste. This included trimmings and low-grade fibers typically discarded during processing. The collected waste was sorted to remove non-fibrous content and then subjected to an eco-friendly water wash to eliminate dirt and surface impurities. The cleaned fibers were air-dried to maintain natural structure and conditioned to achieve uniform moisture content. Subsequently, they were cut to consistent lengths suitable for composite fabrication. Fiber mats were prepared using needle-punching and thermally bonded with minimal binder additives to ensure compatibility with resin matrices. These mats were later cut to match the mold dimensions for composite stacking and fabrication. This streamlined process enables the effective reuse of industrial fiber waste while supporting the study's aim of enhancing composite performance through environmentally sustainable materials. Figure 1 shows the waste-based piassava fiber-making process.

2.2. Materials and constituents

To fabricate the composite, bidirectional Piassava (200 gsm) and Kevlar (K-29, 200 gsm) fiber mats are utilized as reinforcement materials. A thermoset epoxy system in two parts is utilized, with a weight ratio of 1:10 for hardener (HY 951) and resin (LY 556). As a mould release agent, regular semisolid wax is employed. We obtained the epoxy resin and synthetic K-29 Kevlar fiber from GVR enterprises in Madurai, Tamil Nadu, India. Conversely, there has been comparatively little study so far on the use of SiO_2 NPs implanted in Kevlar and piassava fibers in epoxy-based matrix composites. The unique

aspect of this investigation is how it compares the mechanical and physical characteristics of composites constructed of piassava and Kevlar fiber that have been reinforced with epoxy and have SiO_2 embedded in the matrix material. With a density of 2.1 g/cm^3, the nano silicon dioxide (SiO_2 NPs (≥99.52% silicon)) was supplied by CRK Nano Solution Ltd., Bangalore, Karnataka, India. This SiO_2 NPs is pure white and in solid form as well. The obtained SiO_2 NPs had a melting point of around 1670°C and a size of 20–30 nm. Figure 2 shows the photographic images of reinforcement, filler, and matrix materials.

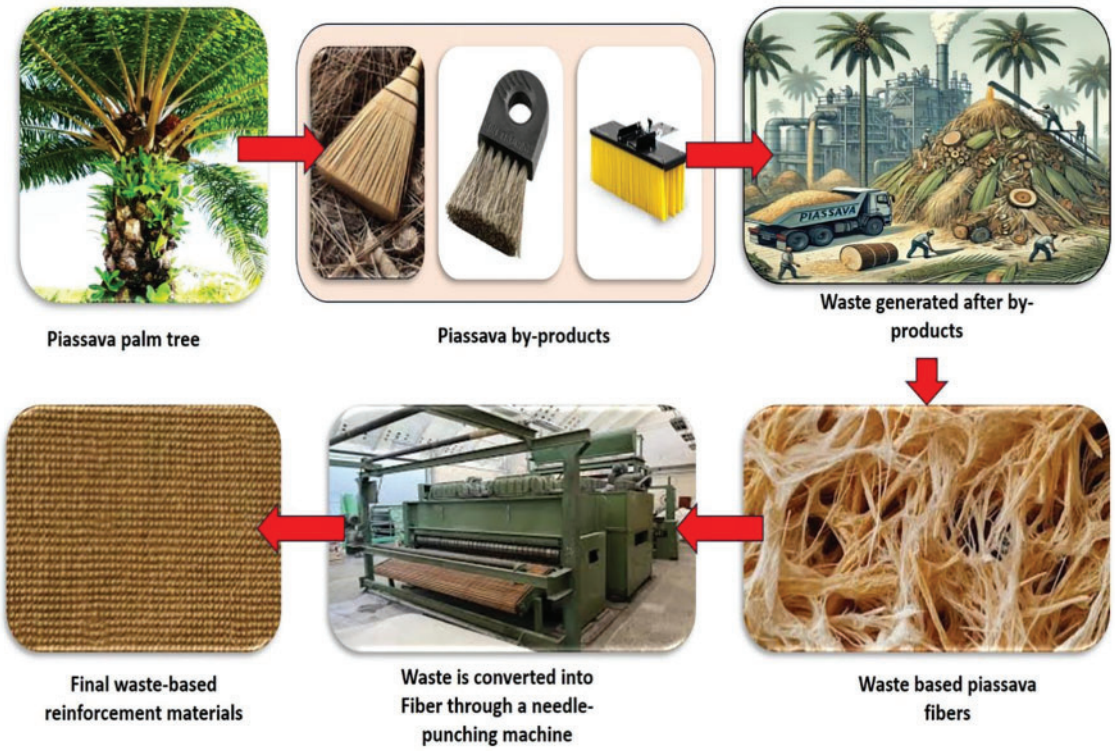


Figure 1. Process of making the waste-based piassava mat fiber

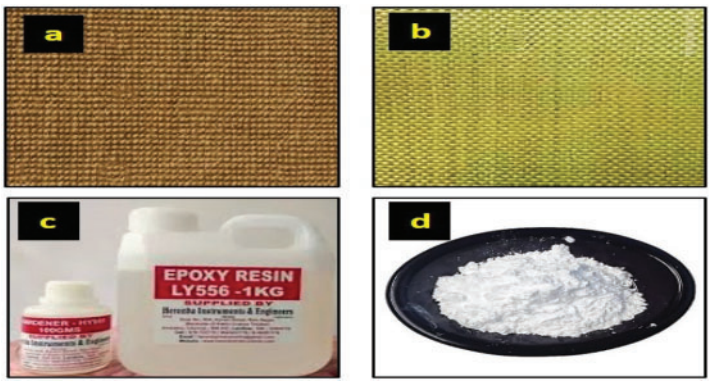


Figure 2. Photographic images of (a) Piassava fiber; (b) K-29 Kevlar fiber; (c) LY556 epoxy matrix with hardener and (d) SiO_2 NPs

2.3. Composite fabrication

To make a hybrid nanocomposite, the SiO_2 NPs were taken in the following weight percentages: 0%, 0.5%, 1%, 1.5%, and 2 wt.%. SiO_2 NPs were warmed for 120 min at 80°C in the muffle furnace to eliminate the moisture content. Following this, the viscosity in the muffle furnace was decreased by preheating thermosetting epoxy (LY-556) for 30 min at 70°C. Following this procedure, two tablespoons of epoxy and SiO_2 NPs were combined in a single vessel. The vessel was placed on a magnetic stirrer to properly disperse the nanomaterials in the polymer matrix. The mixing was completed with the aid of a magnetic bit. The material on the magnetic stirrer was held at 80°C and 500 rpm. The magnetic stirrer was operated for 30 min at a gradual pace until it reached 500 rpm. The vessel was placed in an ultrasound chamber set at 80°C for 45 min to improve dispersion, achieve homogenization within the filler and the matrix substance, and remove the acetone that was present. Using the hand lay-up method, the epoxy mixture was poured into the mould. Six layers of fibers were then sequentially organized with the aid of a convenient metal roller to eliminate excess material and air spaces from each layer throughout the sequence. Figure 3 shows the composite fabrication process along with a list of mechanical testing that is going to be carried out.

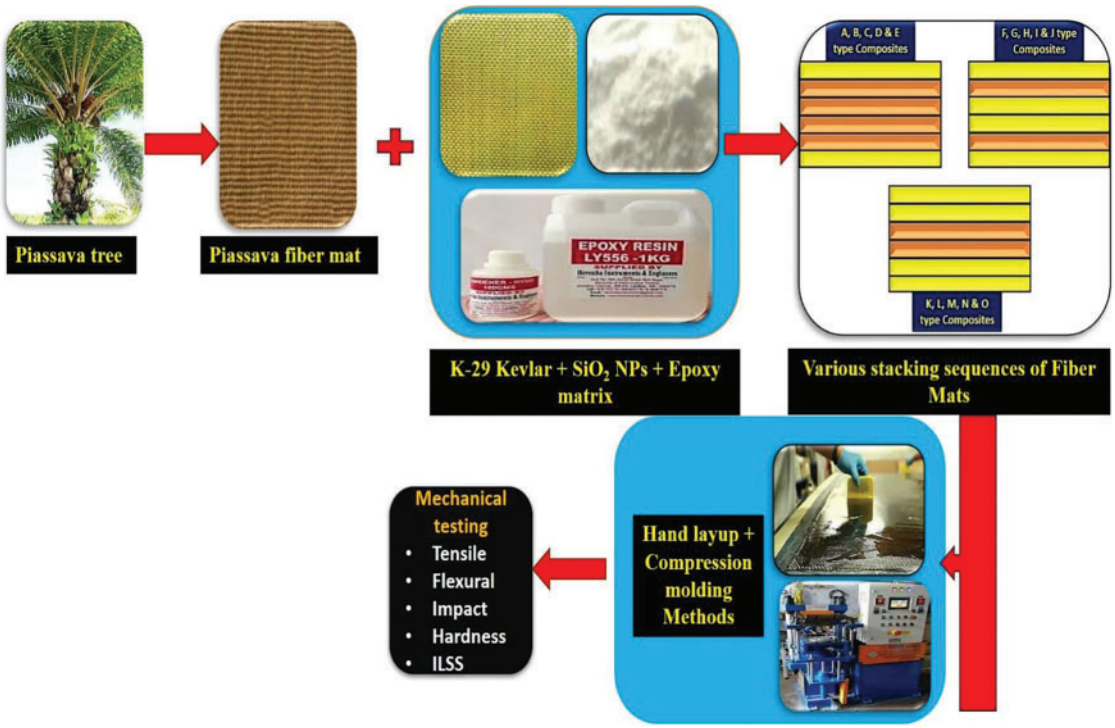


Figure 3. Kevlar/Piassava/SiO_2 NPs-based hybrid composites fabrication process

Furthermore, the pressure was applied for 24 h using a compression moulding machine (KZCMP-II, 30-tonne capacity, 300 kg/cm^2 pressure output, hydraulic power control) with a 30 kN load. The equipment operates between room temperature and 250°C, with a working platen of 300 × 300 × 3 mm^3. Five distinct weight proportions of SiO_2 NPs and three distinct stacking sequences of piassava and Kevlar fiber were combined to create a total of 15 specimens, each of which was labeled with an individual name as indicated in Table 1.

Table 1. List of symbols used for different composite fabrication

Sl. No.	Symbols	Stacking sequence	Weight percentage of Nano SiO_2
1	A	KPPPPK	0
2	B	KPPPPK	0.5
3	C	KPPPPK	1
4	D	KPPPPK	1.5
5	E	KPPPPK	2
6	F	KPKKPK	0
7	G	KPKKPK	0.5
8	H	KPKKPK	1
9	I	KPKKPK	1.5
10	J	KPKKPK	2
11	K	KKPPKK	0
12	L	KKPPKK	0.5
13	M	KKPPKK	1
14	N	KKPPKK	1.5
15	O	KKPPKK	2

2.4. Material characterization

2.4.1 Nanocomposite characterization

We used scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy dispersive X-ray (EDX) spectroscopy to characterize the hybrid polymer matrix composites (HPMCs). The hybrids' nanocomposites and SiO_2 nanoparticles (NPs) were also analyzed using XRD (BRUKER USA D8 Advance, Davinci, 20 kV) with a 4°/min scanning rate. The quantitative angle 2θ was set at 5° to 100°. To identify the presented elemental composition of the composite materials the EDX was used. EDX analysis was performed using an integrated JEOL JSM-5600 SEM equipped with an Oxford Instruments EDX detector. The system operated at an accelerating voltage of 20 kV. Dispersion of the nanomaterials into the polymer composites was studied using SEM (JSM 5600 type). SEM enabled the study of the various bonding types, such as the matrix/filler, fibers/fillers, and filler/matrix interactions. The characterizations mentioned above were performed at SRM University, Chennai, Tamil Nadu, India.

2.4.2 Mechanical testing

The mechanical properties of hybrid polymer matrix composites (HPMCs) were assessed via tensile, flexural, and impact testing. Each evaluation was conducted at room temperature. The pulling forces a material can withstand, in addition to properties like tensile strength and elongation, can be evaluated using a tensile test. For the tensile tests, specimens were cut to the dimensions specified in ASTM D3039-76 (250 × 25 × 3 mm³). The material's resistance towards bending, flexural strength, and stiffness can be evaluated by performing a flexural test. Flexural test specimens were prepared by ASTM D7264 (70 × 12.7 × 3 mm³) standards. Both tensile and flexural exercises were performed on a universal testing machine (INSTRON 3382/50 kN), which is calibrated between 20°C and 180°C and has a maximum load capacity of 50 kN. Impact tests are conducted to evaluate the toughness of a material and its ability to absorb sudden or shock loading. The tests were performed at room temperature using a pendulum-type impact testing machine with a maximum capacity of 25 J. Impact test specimens were also prepared following the standards set by ASTM D256 for a scope of 60 × 12.7 × 3 mm³. To improve the accuracy of each test, measurements were taken five times and averaged to obtain a single representative value. All mechanical testing was conducted at SRM University, Tamil Nadu, India.

2.4.3 Water absorption testing

The water absorption of hybrid composites was measured according to the ASTM D570 ($50 \times 50 \times 3$ mm^3) standard. The samples were placed in distilled water for 24 h, then taken out and dried to remove surface moisture. Measurements of the specimens were taken after the immersion period to ascertain their weight. This method was continued at set intervals of 24, 48, 96, 196, and 312 h. The percentage of water absorption was calculated using Eq. (1).

$$Water\ absorption\ (\%) = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

where
W_1= weight of the specimen before immersion
W_2= weight of the specimen after immersion

3. Result and discussion

3.1. Mechanical properties

3.1.1 Tensile strength and its modulus

The correlation of the mechanical properties of the composites with the stacking order, the weight percentage of Nano SiO_2, and the resulting performance has been well established. It is worth mentioning that composites, in this particular instance, peak their tensile strength at 1.5 wt.% of the particulate nano SiO_2. For the KPPPK stacking pattern, tensile strengths rise from 158 MPa at 0 wt.% to quite an impressive 204 MPa at 1.5 wt.% and then taper slightly to 198 MPa at 2 wt.%. Also, during tests for the KPKKPK sequence, a maximum tensile strength of 336 MPa was observed at 1.5 wt.% nanoSiO_2, up from 212 MPa (0 wt.%) and 291 MPa (2 wt.%). This explains why the tensile strength of the composite cavity, in this case, increased from 1.5 wt.% of the particulate Nano SiO_2; the configuration of the nanoparticles reinforced the ductile matrix without overwhelming it. NanoSiO_2 particles at that concentration level are also thought to help improve the bonding at the interface between the fiber and the matrix, enhancing bondability and thereby promoting stress transfer without agglomeration that may create stress points. The elongation at break values above supports the use of 1.5 wt.% of Nano SiO_2 to enhance the composites' ductility. Figure 4 shows the tensile strength and modulus of Kevlar/Piassava/SiO_2 NPs based hybrid composites. The improvements in tensile strength, elongation, and tensile modulus at 1.5 wt.% nano-SiO_2 in the current hybrid composites of Kevlar/piassava fiber-reinforced piassava fiber composite materials are also in agreement with other literature. Yildirim et al. [26] investigated 3D glass fiber/epoxy composites with nano-SiO_2 and reported improvements in tensile strength between 6%–10% at optimum loadings, which was attributed to uniform dispersion as well as enhanced bonding at the interface between fiber and matrix. In the same fashion, Gupta et al. [27] showed that incorporating 3 wt.% nano-silica into glass fiber-reinforced epoxy composites improved their tensile and fatigue strength by altering the failure modes and increasing the resistance to cracking.

Elongation has dramatically increased, from 4.9 mm at 0 wt.% in the KPPPK sequence to 7.8 at 1.5 wt.%, indicating a significant enhancement in toughness. At the same time, the KPKKPK sequence indicates that elongation reaches the highest value of 9.3 mm at 1.5 wt.%, indicating that the composite can resist deformation before rupture. The increased reduced ductility can be attributed to the optimized concentration of Nano SiO_2, which, when added, gets homogeneously dispersed between polymer chains. The introduction of Kevlar, Piassava fibers, and especially 1.5 wt.% nano SiO_2 enhancement are practical in strengthening the interface between the fiber and the matrix, bridging cracks in the composite, and affording high strength and higher elongation. The findings complement those obtained for tensile strength and elongation while highlighting the tensile modulus changes. For the KPPPK sequence, as the wt.% of the filler increases from 0 to 1.5 wt.%, the tensile modulus increases from 3.1 to 4.6 GPa. In contrast, the KPKKPK sequence demonstrates increased modulus, elevating from 3.6 GPa

to 6.3 at 1.5 wt.% Nano SiO_2 loading. Figure 5 shows the elongation of Kevlar/Piassava/SiO_2 NPs based hybrid composites

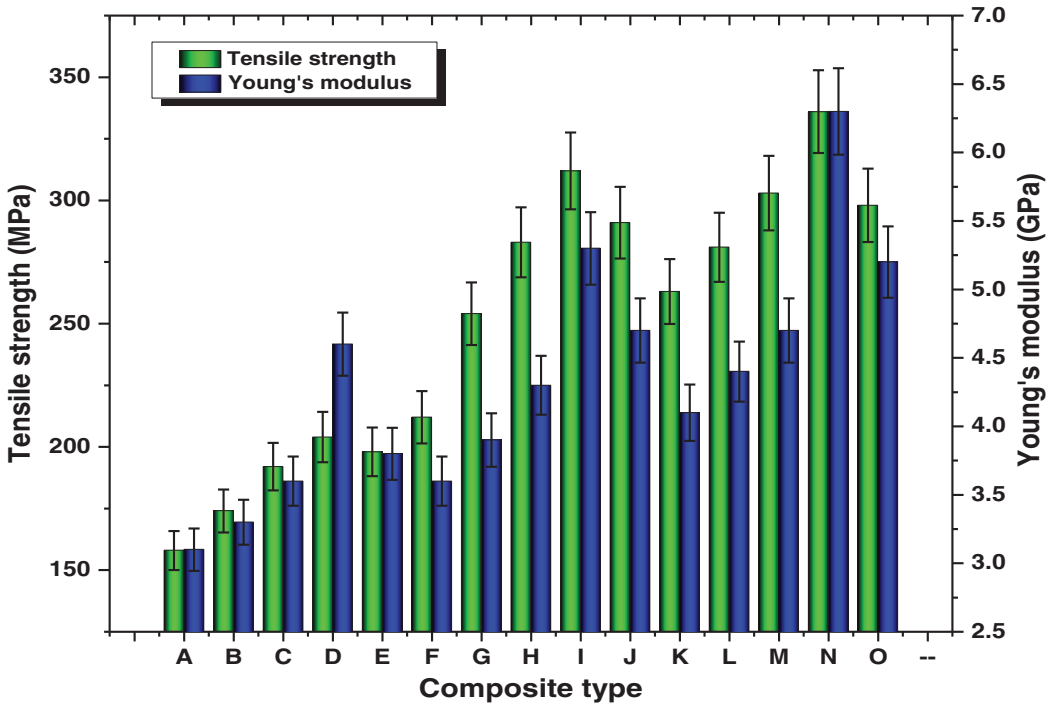


Figure 4. Tensile strength and its modulus of Kevlar/Piassava/SiO_2 NPs based hybrid composites

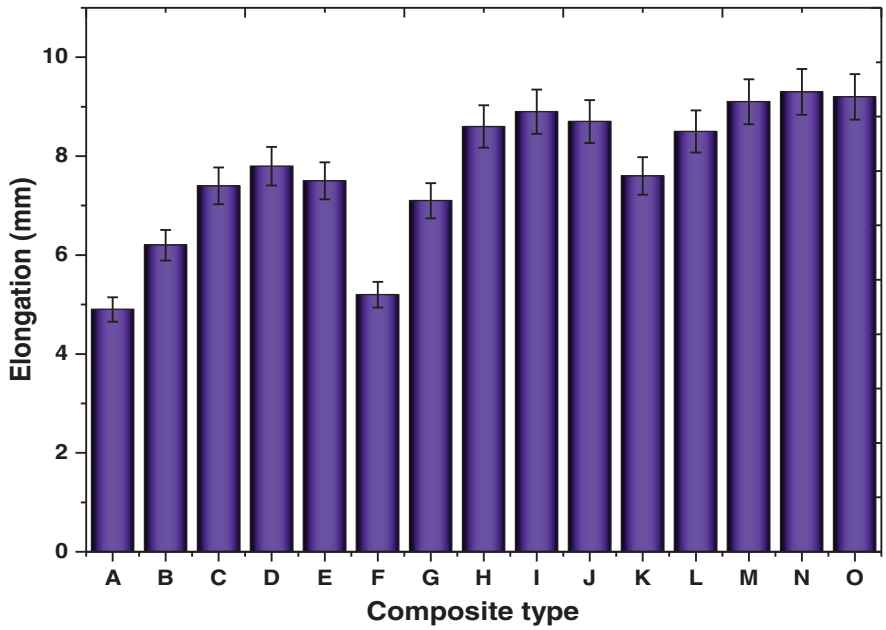


Figure 5. Elongation of Kevlar/Piassava/SiO_2 NPs based hybrid composites

These values also demonstrate that the composites become considerably stiffer, to a value greater than the original, with subsequent incorporation of 1.5 wt.% of Nano SiO_2, providing better resistance to

elastic deformation. Achieving high modulus values at such concentrations can be attributed to the fact that Nano SiO_2 acts as the reinforcement, which increases the stiffness of the matrix while still allowing for reasonable ductility of the material. This finding further corroborates the key role that a 1.5 wt.% of Nano SiO_2 has in ensuring the optimum mechanical properties of the composites. The performance metrics also explain that 1.5 wt.% of Nano SiO_2 is the best loading in the composites, where the material gave the highest tensile strength, elongation, and tensile modulus in both stacking sequences. The rise in tensile strength from 204 MPa with 1 wt.% to 336 MPa with 1.5 wt.% indicates a significant role that Nano SiO_2 has on the mechanical characteristics of the composite. At this concentration, the Nano SiO_2 particles help to improve the fiber-matrix interface, which results in enhanced load-carrying capacity of the composites [28,29]. They enhance the bonding between the fibers and the matrix, essential for effective stress transfer during tensile load application. At 2 wt.%, what's concerning, however, is the slight decrease in tensile strength to about 291 MPa, which suggests that too much of Nano SiO_2 may be detrimental. At this high level, nanoparticle aggregation may occur and lead to high-stress localization areas within the matrix. Such agglomerates could serve as defect sites that would start cracks when stressed and thus create weakness in the overall strength and composite structural integrity of the material. As a consequence, the performance decline beyond 1.5 wt.% points out the need for appropriate optimization for Nano SiO_2 content so that mechanical enhancements are realized and the adverse effects are avoided.

3.1.2 Flexural strength and its modulus

The flexural properties of the composites are also strongly related to the weight percent of Nano SiO_2 and the stacking order of the reinforcing fibers. The flexural strength is at a high of 241 MPa for the KPPPK stacking sequence with 1.5 wt.% of Nano SiO_2, representing an increase from 195 MPa at zero wt percent. On the other hand, the KPKKPK sequence shows an increase and maintains the highest flexural strength of about 381 MPa at the same concentration. The variation in the structure performances between the two stacking sequences can be explained in terms of the arrangement and position of the fibers, which dictate the load distribution and stress transfer during a flexural load application. The KPKKPK sequence consists of Kevlar and Piassava fibers that are stacked in alternating layers, which form stronger interlaminar and increase interlaminar shear strength resistance to bending forces. Figure 6 shows the flexural strength and modulus of Kevlar/Piassava/SiO_2 NPs based hybrid composites. An increase in flexural strength and modulus observed in this work are correlated with previous literature Gupta et al. [27] noted increases in flexural qualities at 3 wt.% of nano-silica, describing it as an outcome of improved stress transfer and stiffening of the matrix. Yildirim et al. [26] also noted enhancement in the flexural strength of glass fiber composites with the incorporation of nano-silica owing to its better dispersal and stronger interfacial bonding. This study also notes that other studies noted, like this work, an increase in the agglomeration of the nanoparticles beyond a certain limit, which would deteriorate the overall performance.

Similar trends are also shown by the flexural modulus, a parameter that indicates the material's stiffness. For the KPPPK sequence, the flexural modulus gradually grows from 7.2 GPa at 0 wt.% concentration to 19.65 GPa at 1.5 wt.% concentration. In the case of the KPKKPK sequence, the increase is even more substantial, starting from 80 GPa at 0 wt.% to 35.74 GPa at 1.5 wt.%. The raised modulus for both sequences suggests enhanced rigidity because, in all cases, the KPK sequence does better than the KPPPK sequence. This improvement in performance is due to the combined influence of the orientation of the fibers and the contribution of nanoSiO_2 reinforcement [30,31]. The KPKKPK configuration may enhance load transfer among fibers rovings, leading to increased stiffness and strength when the fibers experience bending. Additionally, the wrapping of fibers around the central core helps dissipate energy during flexural loading, thereby improving the mechanical performance of the bond. It is curious that when the content of Nano SiO_2 is increased to 1.5 wt.%, very good flexural values are achieved; however, if this concentration is exceeded, both the flexural strength and the flexural

modulus start to decrease. The mentioned findings were correlated with Amirabadi-Zadeh et al. [32] findings. For instance, in the case of the KPPPK sequence, flexural strength goes down to 235 MPa when a 2 wt.% concentration is used. In KPKKPK flexural strength drops down to 291 MPa.

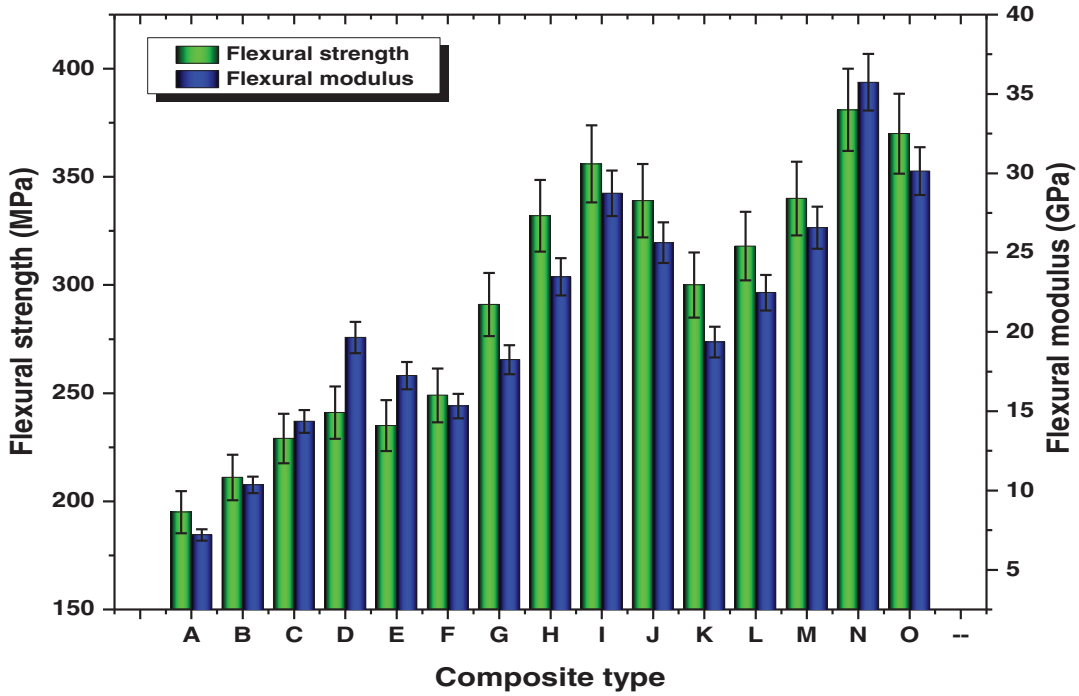


Figure 6. Flexural strength and its modulus of Kevlar/Piassava/SiO_2 NPs based hybrid composites

3.1.3 Impact strength

The impact strength of composite materials is one of the critical properties that makes them able to withstand energy absorption during shocks or loads applied suddenly. In the present research, the impact strength of the hybrid composites exhibited considerable differences depending on the weight percentage of Nano SiO_2 and stacking sequence. The findings highlight that a composite with 1 wt.% of Nano SiO_2 had the highest impact strength, and this means that this property is different from other characteristics in which 1.5 wt.% was the optimum. The impact strength results show that interconnected factors, including improved energy absorption, interfacial bonding and uniform nanoparticle dispersion in the polymer matrix, explain the dominance of impact performance at 1 wt.% of Nano SiO_2. For the KPPPK stacking sequence, the impact strength was 169 J/m at 0 wt.% SiO_2 and increased to 231 J/m at 1 wt. For the KPKKPK sequence, the trend was similar, and impact strength increased from 182 J/m at 0 wt.% to 263 J/m at 1 wt.%. Many interconnected factors, including improved energy absorption, interfacial bonding and uniform nanoparticle dispersion in the polymer matrix, explain the dominance of impact performance at 1 wt.% of Nano SiO_2. Figure 7 reveals the impact properties of Kevlar/Piassava/SiO_2 NPs based hybrid composites. Current observations on impact strength peaking at the value of 1 wt.% in nano-SiO_2 correlate with Sagari and Prasad [33], where an increase in impact resistance with the incorporation of 1.5 wt.% nano-silica in woven jute/kenaf hybrid composites has been noted. It was suggested that a higher filler content would lead to reduced energy absorption capacity without increasing the toughness of the composite due to the incompatibility of greater filler content. This effect was also achieved with 2 wt.% of silica nanoparticles added in a study containing natural fiber-reinforced epoxy composites, where it was noted to have the highest impact energy relative to the

control, about 3 times greater than the control. After reaching that concentration, the composite's impact strength suffered due to the agglomeration of the nanoparticles and increased brittle characteristics.

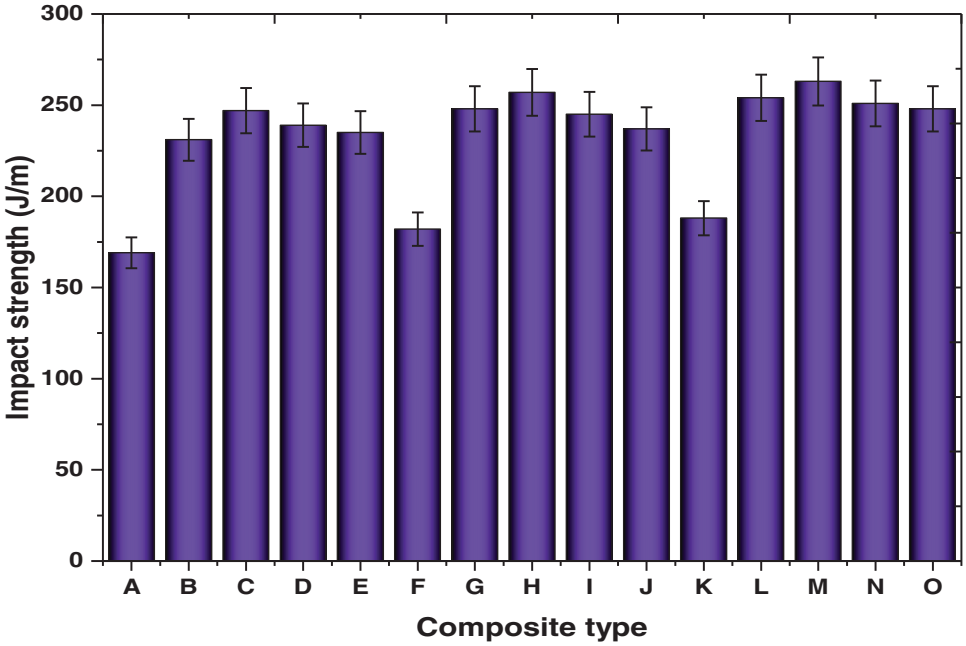


Figure 7. Impact strength of Kevlar/Piassava/SiO_2 NPs based hybrid composites

When a polymer is fortified with 1 wt.% of Nano SiO_2, the particles are most probably uniformly distributed in the polymer matrix, thus permitting efficient enhancement without any tendency for agglomeration. This well-dispersed phase helps in enhanced energy absorption during impact loading as the Nano SiO_2 particles may fill and redistribute the surface and interfacial stresses [34]. The effectiveness of these nanoparticles contributes to an increase in the toughness of the matrix, which allows it to undergo plastic deformation under stress and therefore absorb larger amounts of energy before failure. However, at higher concentration levels, such as 1.5 wt.%, improvements in tensile strength and modulus are noted, but the ductility and energy absorption capabilities of the material may be diminished by agglomeration and higher brittleness. The optimal performance at 1 wt.% also represents the delicate equilibrium of rigidity and flexibility of the composite. Hence, while improving the rigidity of the matrix by Nano SiO_2, higher loading may result in an even stiffer composite, which is more brittle and will fail under impact loading conditions. At this concentration, the improvement in impact strength suggests that the composite contains an optimum amount of flexibility and therefore can absorb and dissipate a large amount of energy when sudden loads are applied [35].

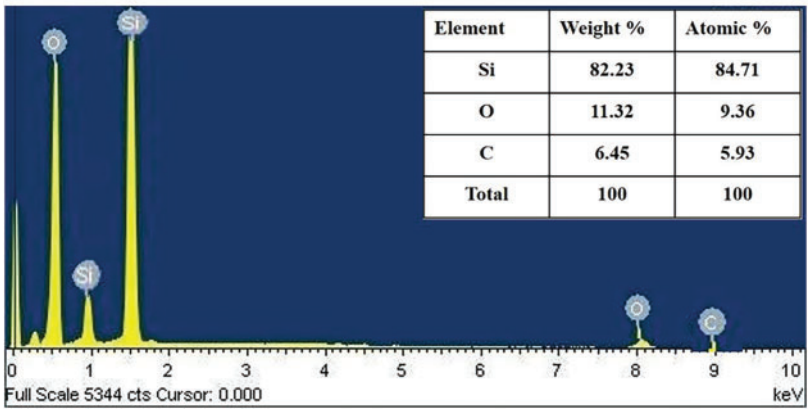
In addition, the stacking sequence amplifies the impact strength of the composites and should not be overlooked. Comparing the KPPPPK and KPKKPK stacking arrangements, it appears that the KPKKPK is more effective for energy absorption since it combines Kevlar and Piassava fibers. Such interleaving guarantees that the load bears evenly throughout the structure during impact and also enhances the crack-bridging mechanisms. This arrangement assists in preventing the growth of cracks and thus improving the impact performance of the composite. The results further suggest that beyond 1 wt.%, say at 1.5 wt.%, the impact strength begins to decrease due to the reasons given above of agglomeration and poor ductility [36]. An excessive amount of Nano SiO_2 has the opposite effect, increasing rigidity, so the material has less capacity for deformation and thus the response to impact forces is more brittle. Consequently, the composites are less efficient in energy absorption, and this results in a decrease in impact strength.

3.2. Microstructural analysis

We used energy-dispersive X-ray (EDX) analysis and scanning electron microscopy (SEM) images to identify the morphological features. While SEM images demonstrated the failure processes associated with fiber and matrix, EDX analysis confirmed the chemical composition as depicted in the same image. Understanding the properties of Piassava and Kevlar fiber nanocomposite matrix-fiber interactions is necessary to appreciate the composite's endurance. As a result, SEM images were obtained from the fractured surfaces of the composites.

3.2.1 EDX analysis

In Figure 8, the EDX analysis of the SiO_2-based hybrid composite, including Kevlar, a passive fiber, the epoxy resin, and the SiO_2 particles, as shown, was composed mainly of silicon (Si) 82.23 wt.% with an atomic of 84.71%, oxygen (O) 11.32 wt.% with an atomic of 9.36%, and carbon (C) 6.45 wt.% with an atomic of 5.93%. Such high levels of silicon and oxygen support the fact that the composite contains a large volume of SiO_2 particles, which are important for better mechanical strength, thermal stability, and rigidity. The SiO_2 particles impart hardness and strength, and the carbon epoxy and carbon fibers provide impact strength, toughness, and flexibility to the materials, which enables composites to be used in applications where a combination of high stiffness, strength, and toughness is needed. The epoxy matrix and Kevlar-reinforcing fibers came from carbon, which provides toughness, flexibility, and impact strength to the composite [37]. The elemental composition revealed by the EDX analysis in this study shows a significant presence of silicon (82.23 wt.%) and oxygen (11.32 wt.%) in the SiO_2-based hybrid composite, which is consistent with what Natarajan et al. [38] found. In their research, the EDX analysis indicated a similar high percentage of silicon (~80 wt.%) and oxygen (~10 wt.%) in the epoxy/nano-silica systems. These figures were linked to the well-dispersed SiO_2 nanoparticles that played a crucial role in enhancing mechanical properties like hardness, stiffness, and wear resistance. Additionally, they noted the presence of carbon from the epoxy matrix and reinforcing fibers (6–7 wt.%), which contributed to improved toughness and energy absorption during mechanical stress. These findings strongly back up the current results, highlighting that combining both organic (epoxy/Kevlar) and inorganic (SiO_2) components creates a well-balanced hybrid composite that's perfect for high-performance applications [14,39].



Element	Weight %	Atomic %
Si	82.23	84.71
O	11.32	9.36
C	6.45	5.93
Total	100	100

Figure 8. EDX analysis of Kevlar/Piassava/1.5 wt.% of SiO_2 NPs based hybrid composites

3.2.2 SEM analysis

The composites showed remarkable improvements in tensile strength, flexural strength, and Young's modulus for symbols N and O, where high Nano SiO_2 weight percentages (1.5% and 2%) were applied, up to about 336 MPa and 298, 381 and 370 MPa, and 6.3 and 5.2 GPa, respectively, in Young's

modulus as compared to those of composites without Nano SiO_2 (A and F). SEM images (Figure 9) for these samples; we can expect a strong fiber-matrix adhesion concerning these enhanced mechanics. Homogeneous dispersion of the Nano SiO_2 particles in higher weight percentages may have caused the cavities to decrease and the stress transfer created between the fibers and the matrix to improve—this, in turn, enhanced the load-bearing ability. So should the SEM images, as there will be lesser/smaller gaps at the fiber-matrix interface and uniform fiber absence of fiber pullout or big voids. Therefore, over the matrix with the increasing Nano SiO_2 content from 0% to 2%, an SEM analysis would likely show changes in the distribution within the polymer matrix of the nanoparticle. For A, 0% Nano SiO_2 (even for F, 0% Nano SiO_2), SEM images should show a smooth matrix surface without any particles, and if this is the case for them, these particles do explain their poor mechanical properties caused by the absence of the reinforcing nano SiO_2. According to SEM, for composition samples C, D, G, H, M, and N (with nano-silica concentration varying from 1% to 1.5%), there should be a better separation of nanoparticles and a lesser extent of agglomeration occurring. These microstructural characteristics would be responsible for the enhancement of tensile and flexural strength because the nanoparticles are well dispersed and act as reinforcement, increasing the stiffness and strength of the material. But for 2% formulation (O), it is possible that the SEM with the highest Nano SiO_2 content (W%) and O would indicate the presence of some agglomeration of dark particles, which should be the nanocomposites due to the increased content of the filler, which can cause localized stress concentrations resulting in the slight decrease in the tensile strength, although the modulus should be elevated.

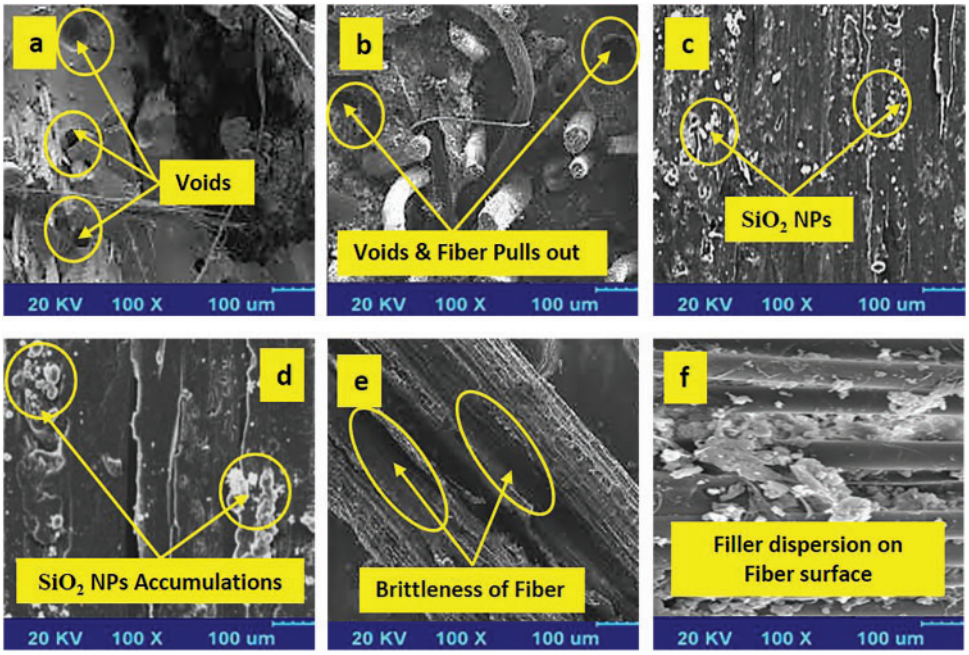


Figure 9. Microstructural analysis of (a) A-type specimen; (b) L-type specimen; (c) N-type specimen; (d) O-type specimen; (e) I-type specimen; and (f) J-type specimens after tensile test

For samples containing higher Nano SiO_2 concentrations N and O, SEM fracture surface images may display more toughening mechanisms such as crack deflection, crack pinning, or pull-out of nanoparticles as reinforcements. These mechanisms help dissipate energy and correlate well with the enhanced impact strength observed. In SEM photographs, we will probably see less brittle fracture accents, such as cracks spread everywhere evenly and straight, and rather more impressively uneven fracture lines, which are more persistent. In contrast, for A and F samples containing no Nano SiO_2, the fracture surface would be more brittle, having smooth surfaces and probably characteristics of fiber

pull-out or breakage proving to be weak bonding between the fiber and matrix. This may justify the relatively lower impact strength and tensile properties exhibited in these samples. The above results were correlated with Jose et al. [40] reports.

Small as well as larger magnifications of SEMs can indicate the void content or porosity present within the composite structure. N-type (1.5% Nano SiO_2) composites having high strength and toughness probably have fewer voids and better compaction, which results in higher tensile, flexural, and impact strengths. Samples with poor mechanical properties such as A and F will, on the other hand, have more porosity, which is clear, and this lowers performance since voids act as stress concentrators. The stacking sequences of KPPPPK, KPKKPK, and KKPPKK, for example, can effect on fiber alignment and the general performance of the structure. To the sequence, SEM images may differ in terms of the fiber types that are contained and the level of coherence to an extent. To demonstrate, those with KKPPKK sequence N composite and O exhibit higher mechanical properties, while SEM might show a better orientation of fibers with fewer voids, while KPPPPK sequence composite A to E has some level of non-cohesiveness of fiber due to pullout, hence lower mechanical properties. Similar results were achieved by Awad and Khalaf & Sadik et al. [41,42].

3.2.3 XRD analysis

The analysis of the XRD peaks (Figure 10) corresponding to the materials yields useful information concerning the crystallinity and amorphousness of the elements. The most intense peak for SiO_2 at 23.35° (2θ), which is typical of the crystalline structure, was recorded. Based on the elevation, Figure 10a shows a sharp and well-defined peak, which is indicative of a relatively higher degree of crystallinity in SiO_2 NPs. Crystallinity in SiO_2 contributes to narrow, sharp peaks since, due to the ordered atomic structure, X-ray diffraction can take place in selective positions, resulting in constructive interference of the X-rays. This is a result of the lattice structures of SiO_2, which are uniformly set to facilitate the formation of high-intensity peaks [43].

On the other hand, the XRD of the hybrid polymer matrix composites containing different mass SiO_2 NPs differing in 1.5 wt.%, as seen in the composite XRD of figures (Figure 10e), peaks at 21.36°. Such peaks tend to be expected in polymer composites, which rarely have ranges of 15 to 25°. However, the compounds reveal a peak at 21.36°, which means the introduction of SiO_2 NPs partially orders the polymer matrix. Polymers usually exhibit much higher molecular movement; therefore, the peaks of the polymers will always be broad because of their semi-crystalline or amorphous structure. Peaks in the polymer matrix become broader due to the diffusion of X-ray scattering, which is a consequence of the absence of a regular repeating atomic structure in amorphous materials. A notable peak was observed at 16.23° (Figure 10b) when making the composite without SiO_2 NPs. In comparison to SiO_2 NPs, this peak is lower, wider, and broader because it demonstrates how the polymer matrix is amorphous without crystalline SiO_2 presence. Both epoxy as well as polymer matrices are mostly amorphous, and hence, diffuse XRD rather than sharp scattering occurs in XRD. Similar results were achieved by Bichanga et al. [44].

In Figure 10b, the sample containing 0 wt.% of SiO_2 NPs shows its XRD pattern, and Figure 10c to 10f display 18.06° for the 0.5 wt.% and 1 wt.% SiO_2 NPs, 18.23° for the 1.5 wt.% ones, and 21.36° and 20.01° for the 2 wt.%. The vicinity of these peaks, even so close to $2\theta \cong 21°$ for samples of varied SiO_2 proportions, is an indication that the SiO_2 NPs get well-solubilised into the polymer matrix, yielding a sound structural consistency. Sufficiently narrow primary peaks around the same 2θ values for samples of solute-varying concentration also tend to favor the presence of homogeneous dispersion; otherwise, agglomerated SiO_2 unavoidably gets localized regions of a higher degree of crystallinity before being followed by more sintering and lower degree regions. The secondary peak for HPMCs, which is in the region of 36° to 40° (i.e., 37.36°), had their ordinal sharper and more intense, respectively, meaning the secondary weaker ordering was about polycrystalline composite structure. This wider second peak was also encountered in polymer composites with filler content, which suggests that it possesses a

longer range of atomic order compared to pure SiO_2 NPs. The wider peak in HPMCs indicates enhanced structural coherence and prolonged atomic ordering, demonstrating the strengthening impact of filler integration within the composite matrix and consistent with previous results on polymer composites including inorganic fillers.

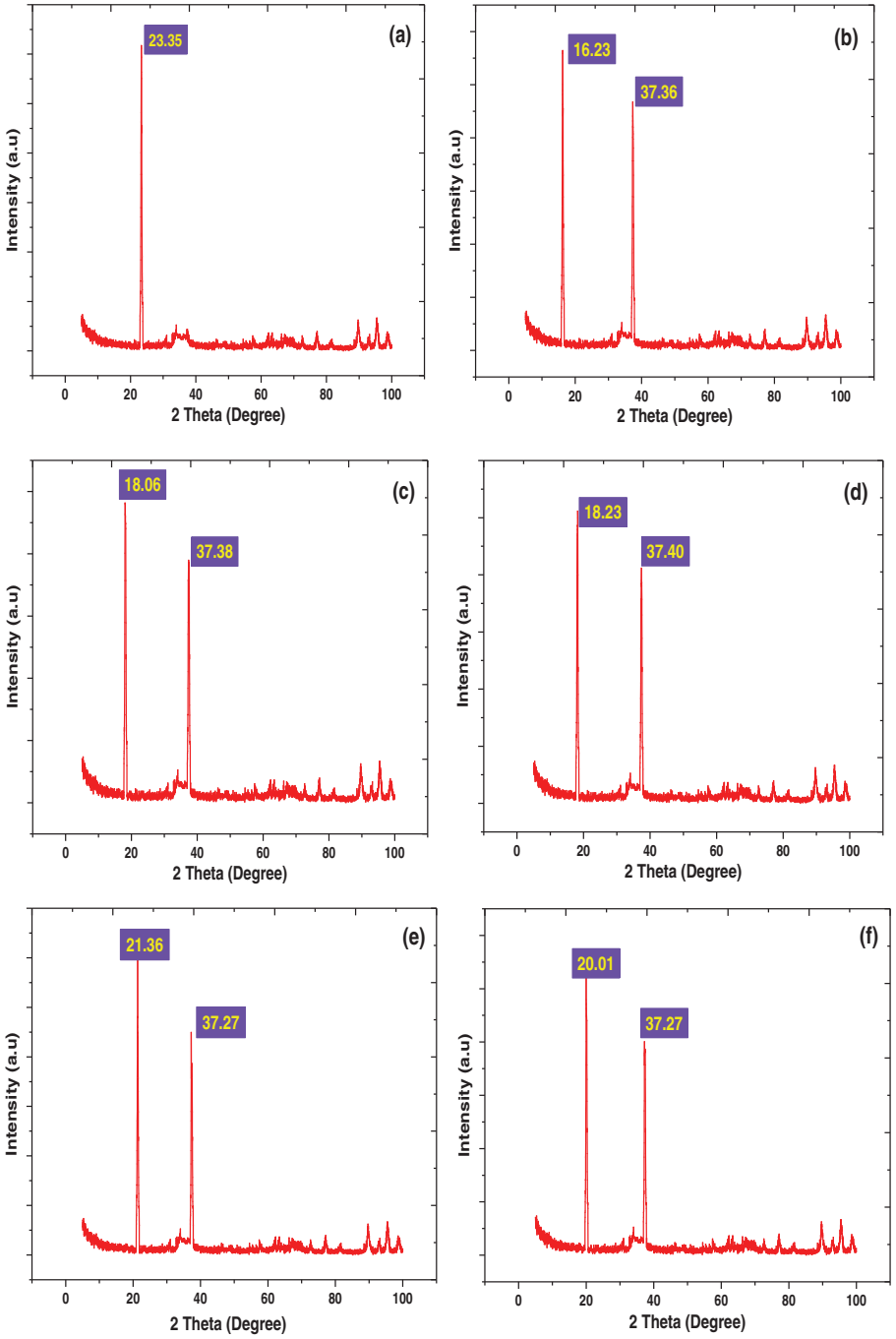


Figure 10. XRD analysis of (a) Nano SiO_2 Powder; (b) Kevlar/Piassava/0 wt.% of SiO_2 NPs; (c) Kevlar/Piassava/0.5 wt.% of SiO_2 NPs; (d) Kevlar/Piassava/1 wt.% of SiO_2 NPs; (e) Kevlar/Piassava/1.5 wt.% of SiO_2 NPs and (f) Kevlar/Piassava/0.5 wt.% of SiO_2 NPs based hybrid composites

In the end, it should be highlighted that the XRD peaks belonging to HPMCs were less sharp and broader as compared to the peaks seen for pure SiO_2 NPs. The scattering is therefore more diffuse owing to the amorphous character of the epoxy matrices, which have no clearly defined crystal lattice. The amorphous structure of the epoxy is a major contributing factor for the broadening and weakening of the XRD peaks because these come from amorphous materials that have irregular atomic arrangements. This broadening effect in the presence of epoxy elaborates on the amorphous structure within the composite, as there was only slight crystallinity, which was due to agglomerated SiO_2 NPs.

3.3. Water absorption characteristics

The moisture absorption behavior of the Kevlar/Piassava/SiO_2 NPs based hybrid composites is presented in Figure 11. Which is determined according to the combination of the nanofiller content and the stacking sequence. For all times and after the immersion, the composites' water absorption increased, indicating that moisture infiltration was dependent upon the composite structure. The results indicate that the increase in the weight percentage of Nano SiO_2 supports reduced water absorption levels for some stacking sequences. For example, Source N, earning maximum nanofillers amounting to relatively upper percentage stacking sequences, performed by significantly reducing absorption rates. Source N, having 1.5% of Nano SiO_2 by weight, combined with the KKPPKK stacking sequence absorbed just 8.96% of water after 312 h; thus, the least water-absorbing composite among all the tested samples. This is consistent with the results of Poormohammadian et al. [45], who found that by increasing the matrix density and forming tortuous diffusion pathways, functionalized SiO_2 nanoparticles decreased moisture absorption in polymeric films. Therefore, sample A exhibited a lower nanofiller volume (0% Nano SiO_2), hence high absorption rates of materials cementing up to 13.67% at the same immersion period. This trend suggests that embedding of Nano SiO_2 enhances both the mechanical properties of the composite, as evidenced by increased tensile and flexural strengths, and the resistance of the composites to water absorption. A denser microstructure is limited to the water pathways for ingress due to the likely contribution of the nanofiller.

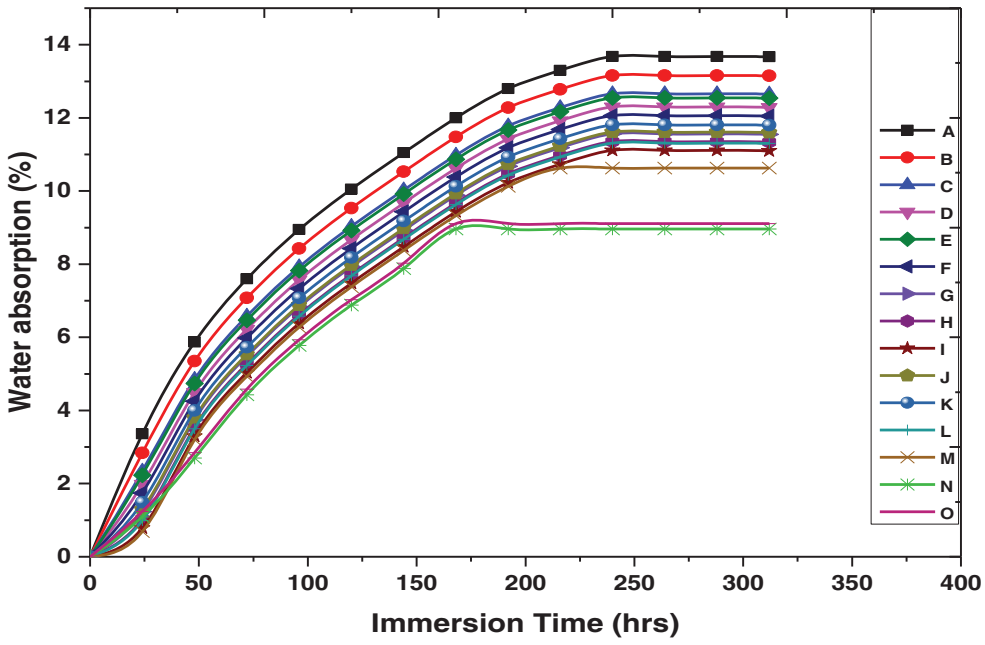


Figure 11. Water absorption properties of Kevlar/Piassava/SiO_2 NPs based hybrid composites

Also, sequencing in stacking is very important since it affects the water absorption characteristics of composites. KKPPKK, the KKPPKK sequence used in Sample N, was found to be better than

KPPPK and KPKKPK in moisture resistance. The samples were found to have absorbed more water than required during experiments. For example, after 312 h, sample J was able to absorb water at 11.61% where the KPKKPK sequence was used, while sample N absorbed only 8.96% after 300 h. Additionally, Karimzadeh et al. [46] found that alternating stacking patterns, like PALF/glass (PGPG) composites, showed lower moisture absorption because of improved interfacial bonding and minimized capillary pathways. These findings are consistent with the observed influence of stacking sequence on water resistance. This difference indicates that the arrangement of the layers in the composite may affect how water saturates the material. KKPPKK layer configuration too, the polymer composite possessed low water absorption, indicating better barrier property towards moisture over the polymers. Time has also been shown to have an effect with structural composites, so as the time of soaking increases, there may be a rise in the absorption of water, as was shown in the samples after 3 days. These results were however different for the KPPPK stacked structure, showing up to over twenty-eight percent above water absorption due to a less dense structure [3,4]. In conclusion, the results emphasize the important role of both the content of the nanofiller and the stacking sequence in affecting the water absorption properties of the composites. The N-type composite (KKPPKK) recorded the maximum amount of water being the least absorbed, confirming the suitability of the stacking sequence along with the best concentration of Nano SiO_2. Our findings are further supported by Zhang et al.'s [47] investigation of hybrid CFRP/Al laminates, which found that layer sequencing and material design are crucial in regulating moisture diffusion. This interrelationship of factors is important in designing composites with specific characteristics for moisture-proof applications [48].

4. Conclusion

The research identified the synthesis of Kevlar/waste Piassava fiber reinforced one polymer matrix composites with improved mechanical properties, better structural integrity, and lower water absorption due to the incorporation of nano-SiO_2 particles, which are said to have been handled efficiently. This strategy not only enhances material performance but also underscores the usefulness of natural fibers based on waste, thus aiding in sustainable materials and environmental issues.

- Weight proportions of 1.5 and 2% of nano-SiO_2 particles (samples N and O) noticeably increased the tensile strength (up to 336 MPa), flexural strength (up to 381 MPa), and Young's modulus (up to 6.3 GPa). This was due primarily to the reinforcing role of SiO_2, which enabled partial matrix-fiber bridging between cracks and loads in the structure of the composite material, thereby strengthening it.
- Determination of water absorption also showed that higher SiO_2 content composites had lower moisture contact, with the composites of N-type having absorption values as low as 8.96% for saturation. This is an important factor when it comes to application in environments with moisture, as it would improve the dimensional stability of the composite and prevent its degradation over time.
- The existence and distribution of SiO_2 particles were also confirmed by EDX with the mass fraction of silicon as high as 82.23 wt.% and oxygen of about 11.32 wt.% in the composites. This is expected as a significant content of SiO_2 was supplied by the sand, which enhanced the mechanical properties, rigidity, and thermal stability of the composites.
- SEM analysis revealed significant fiber-matrix bonding and even distribution of SiO_2 particles as their weight percentages increased, while there were fewer gaps and improved stress interaction between fibers and the matrix. The images reduced fiber pull-out and agglomeration of samples N and O, implying the existence of sufficient particle-matrix compatibility that is desirable for toughness and mechanical property improvements.
- XRD patterns of SiO_2 composites have shown a distinct peak at 23.35° for SiO_2, attributable to its crystallinity that increased the rigidity of the composite material. This was not the case with HPMCs, which recorded wider peaks that were indicative of the amorphous structure of the epoxy matrix, which again improved impact strength and flexibility. Well-developed narrow peaks

also suggested that SiO_2 was evenly dispersed in the polymer and structurally adhered to avoid mechanical instability.

In conclusion, the addition of SiO_2 nanoparticles into the /Kevlar/Piassava fiber composites achieved high mechanical strength, good water absorption, and structural stability, which makes these HPMCs ideal for applications that require strength, low moisture absorption, and lightweight properties, such as in the aerospace, automotive, and marine industries.

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