



Effectiveness of silicon nanoparticles on the mechanical, wear, and physical characteristics of PALF/sisal fiber–based polymer hybrid nanocomposites

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Abstract

High-performance composites made from polymer matrix materials with a long-life span, durability, and low weight are needed in the automotive, household products, and aerospace industries. Lightweight, good specific stiffness, and excellent specific quality are all characteristics of polymer fiber–reinforced composites. The current study examines the mechanical and wear characteristics of PALF/sisal fiber and silicon nanoparticle (SiO₂)–reinforced hybrid polymeric composites with various weight percentages, such as 0–8 wt%. Employing mechanical mixing and sonication, SiO₂ NPs are dispersed inside a polymer matrix throughout the production process. After that, the nanocomposites are thoroughly characterized to determine their mechanical characteristics, such as their tensile strength, bending strength, and impact strength. Furthermore, tribological experiments like pin-on-disc and wearing measurements of volume are used to evaluate the wear resistance of the hybrids. The C-type hybrids had the greatest mechanical characteristics among the five distinct types of hybrids (i.e., 53.36 MPa tensile, 61.25 MPa flexural, and 4.98 J of impact energy). Adding 4 wt.% silicon nanoparticles decreases volumetric degradation by 8–13% even under typical loading conditions when compared to A-type hybrids. The presence of silicon nanofillers in the fiber matrix composition could be responsible for the lower tendency for volumetric degradation. The rate of wear was noticed to decrease as silicon content increased, and then, after reaching the minimum values for C-type composites, wear started rising as silicon content increased further. To comprehend the entire performance of the nanocomposites, the physical variables, such as density and retention of water, are also investigated. The theoretical and experimental densities of nanocomposites are 1.221–1.253 g/cm³ and 1.211–1.24 g/cm³, respectively, and have been observed to rise with increasing silicon particle concentration. The findings will aid in the creation of environmentally friendly and high-performing materials for use in a variety of industries, including the packaging sector, construction, and automobile sectors, where enhanced mechanical features and durability against wear are important. In the end, this study provides expanded knowledge of the viability of using SiO₂ nanoparticles to improve the performance of organic fiber–reinforced polymeric composites.

Keywords PALF · Silicon nanoparticles · Wear behavior · Tensile strength · Moisture absorption

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1 Introduction

Natural fibers may naturally dissolve and be returned to the environment without posing long-term contaminants since they are recyclable. To address the challenge of plastic waste on a worldwide scale, this quality is crucial. On the other hand, artificial fibers linger in the environment for a long time and help accumulate non-biodegradable debris. We can lessen our reliance on synthetic substances and encourage more sustainable waste disposal techniques by incorporating natural fibers into biocomposites. Energy-intensive procedures used in the manufacture of artificial fibers result in large carbon dioxide releases [1, 2]. On the other hand,

because they demand less power and frequently require fewer chemical reaction steps, natural fibers offer a reduced carbon footprint. By incorporating natural fibers into biocomposites, we can decrease emissions of greenhouse gases and lessen the effects of global warming. A circular economy is developed through biocomposites that blend organic fibers with polymers that decompose. We may reduce waste and increase resource efficiency by using agricultural materials or byproducts as the starting point for natural fiber production. Additionally, by promoting environmentally friendly waste disposal procedures and reducing the consumption of resources that are not renewable, biological composites may be reusable or biodegradable [3]. Because of the constantly increasing consequences of environmental contamination, the usage of fiber-reinforced polymeric materials and the requirements for the materials compromised endurance and a variety of psychological and chemical qualities. Due to their superior rigidity and strength, synthetic fibers and man-made resins have been at the forefront for years but have also caused environmental concerns [4]. Numerous researchers [5–7] focused on substituting synthetic materials to address serious issues such as recyclability, health consequences, and biocompatibility. Natural fabrics have lately received attention; thus, a reasonable alternative for artificial reinforcements is envisaged in the future. Such fibers develop spontaneously and are abundantly connected with organisms of all kinds. Plant-based natural fabrics may generate hybrids with improved characteristics, and these substances are inexpensive, recyclable, and readily accessible [8]. Nevertheless, the combination of fibers and fillers will improve the material's qualities in all dimensions, including fracture toughness, rigidity, chemical inertness, and temperature resistance. Plant fibers' greater moisture content and poor compliance have pushed investigators to hybridize with other botanicals, filler, or traditional fibers. Furthermore, rigid microscopic or nanoparticle additions were studied to enhance the mechanical characteristics of lightweight materials. Pineapple leaf fiber (PALF) is a sustainable and abundant resource. Positive mechanical characteristics of PALF include excellent durability, rigidity, and low densities. With both thermosetting and thermoplastic polymer matrix structures, PALF has demonstrated excellent compatibility. It is simple to integrate into many polymeric structures, providing a variety of alternatives for composite materials. Particular characteristics of PALF include strong moisture absorption, effective insulation against heat, and sound absorption. Because of these distinctive qualities, PALF-based composites may be appropriate for particular uses where such traits are required [9, 10]. For those reasons, it acts as a primary stress transmitting medium in the current research.

A hybrid material is one that is made up of fibers, nanoparticles, and matrix components [11]. Whenever a

fracture forward is trapped by two or more scattered stages, its fracture face lengthens and deflects, increasing the fracture toughness. The usage of silicon fillers has resulted in a considerable improvement in fracture toughness inside the polymer matrix phases. The hardening method that occurs when silicon nanofillers are diffused could be credited to highly localized foam stress concentration begun by tensile stress from around the fringes of the nanofillers, as well as delamination of the nanomaterials that results in polycarbonate void expansion inside the epoxy [12]. Nanoparticle distribution has also been identified as a key component in improving the mechanical characteristics of biocomposites. Nanoparticles have a strong propensity to agglomerate between themselves and around spherical particles (wall effect) [13]. Comparing silicon dioxide (SiO_2) nanomaterials to various other forms of tiny particles, silicon dioxide nanomaterials are both readily accessible and reasonably priced. They are simple to spread and combine with a polymer matrix, which enhances the hybrids' mechanical and practical qualities. Because of their hardness and ability to withstand abrasion, SiO_2 nanoparticles can improve the wear ability and endurance of composites. SiO_2 nanoparticles can be used to minimize wear and friction among composite parts, which makes them appropriate for purposes requiring high resistance to wear [14]. The high specific surface area induced by particle shape and molecule arrangement makes it challenging to achieve a non-aggregated nanoparticle structure as a whole. To date, many chemical and mechanical dispersal techniques for nanofillers have been suggested, such as ultrasonic, drying systems, various dispersion devices, and liquid hydrocarbons or polymers [15]. The united component materials remain capable of withstanding their very own identity, flawlessly keeping each other together. The composites have much more negative qualities than the individual constituents. For instance, pineapple or flax fibers supplemented with peanut oil cake showed increased tension, bending, impacting, and bending capacities [16]. The combination of sisal and pineapple fibers mixed with fillers will minimize mass, and silicon additives will improve the material properties of composites. The chemically processed pineapple leaf fiber (PALF) containing 4 wt% additives raised its tensile strength by 20% as well as the bending by 22.39% because of the increased high-density dissolution rate and outstanding adhesive properties [17, 18]. The conglomerations can be removed with prolonged ultrasonic treatment. The failure surfaces morphogenesis to the reinforcements, which, on the other hand, modify plain epoxy's glassy as well as multi-crack performance by applying manual layout [19]. By introducing particulates up to 8% of a weight percentage, PALF has bridged the micro-level disconnect between two strands. Such characteristics lead to greater flexural, tensile (31.52%),

compressive (33.6%), and toughness (62%). Nevertheless, the polymer became stiff at 10% particle concentration and lacked adhesion capacity. PALF particle addition in composites enhances thermostability and water permeability, leading to improved recyclability [20].

The normal tensile strength of PALF mixed with cellulose fibers is 20.7 MPa, the flexural strength is 23.5 MPa, and the flexural modulus is 717.6 MPa. While viscose is the major component leading to tensile loss, the introduction of PALF increased it. Young's modulus decreased as a result of the improper dispersion of the epoxy coating [21]. PALF/viscose fiber is employed to produce grocery bags, stylish roof coverings, paper cups, beer cans, and other items because of its uniformly distributed structure, good mechanical qualities, and anti-mold absorbing properties [22]. Using epoxy resin, the PALF demonstrated good specific principles. PALF outperforms coir in terms of tensile strength by 60.25% and tensile modulus by 48.9%. This is mainly due to the fiber's 80% cellulose concentration and decreased microfibrillar inclination, which in turn encourage maximal fiber/matrix adhesion and enhance surface quality [23]. Consequently, components are employed in automotive parts, electrical packaging, and house sites. As contrasted to other natural fibers, the PALF displayed lower wear performance and anti-slip qualities due to its strong bonding. The presence of a 10% SiO₂ filler during manufacturing is mainly responsible for the composite's properties. As a consequence, low wearing parameters of 5–10% were found, and the Taguchi approach indicated that PALF provides the best circumstances for erosion and friction uses [24].

According to the previous publication, considerable research has been done on the effect of nanomaterials on the mechanical, wear, and physical characteristics of synthetic fiber-reinforced hybrid polymeric materials. Unfortunately, there has been relatively little study on the measurement of the performance of nanomaterial-loaded organic fiber-based hybrid polymeric materials. Although natural fiber-reinforced composites have been thoroughly explored, a novel method of overcoming the inherent drawbacks of natural fibers is the integration of SiO₂ NPs, especially in PALF/sisal fiber-based polymer hybrid nanocomposites. In this work, SiO₂ NPs are used as a reinforcing agent to improve the mechanical characteristics of composites made from PALF and sisal fiber. A unique element that meets the requirement for resilient materials in diverse industrial applications is the examination of wear resistance in these nanocomposites. This study advances the development of eco-friendly and high-performance materials by investigating the possible combinatorial impact of SiO₂ NPs and organic fibers in polymeric hybrid nanocomposites. The unprecedented possibilities for the creation of robust and ecologically beneficial composites are presented by the special combination of PALF, sisal fiber, and SiO₂ NPs.

2 Experimentations

2.1 Materials

GKN Fiber Industry in Chennai, Tamil Nadu, India, supplied the PALF (0.78 g/cm³ density, 72% cellulose, 16.23% hemicellulose) and sisal bi-directional fiber mat with 250 gsm (1.36 g/cm³ density, 56.28% cellulose, 11.28% hemicellulose) used as reinforcements. Before usage, these fibers were immersed for 24 h at room temperature in a 5% NaOH solution in order to achieve good mechanical interconnecting and interface adherence between the fiber and matrix, resulting in better mechanical features. Following that, the fibers were cleaned using distilled water and oven-dried for 6 h at 70 °C. The oven-dried fibers were cut into 300 × 300 mm lengths and utilized to make composites. The epoxy matrices (LY556, 1.14 g/cm³ of density, 926 mPa.s of viscosity) and curing agent (HY951, 0.90 g/cm³ of density, 60 mPa.s of viscosity) were acquired from Deeskshitha Chemicals in, Madurai, Tamil Nadu, India. Silicon nanoparticles (30 nm, 99% quality) have been obtained from Rithu Chemicals in Bengaluru, Karnataka, India. Figure 1 shows the fiber extraction procedure of fiber reinforcement. The extraction process of PALF and sisal fibers is explained below.

Both the fibers, like PALF and sisal, were prepared by the retting process. It includes the following stages [25–27]:

- Resource collection: Choose ripe pineapple leaves with lengths between 1 and 5 m. Typically, such leaves are at the point right before the plant starts to bloom. Sisal plants are usually taken out when they are between 3 and 5 years old.
- Preparation of leaves: A machete or sharp knife should be used to trim leaves near the root. Take off the waxy exterior and prickly edges from both ends of the leaves.
- Stripping: Employing a decorticator or a sharp knife, peel the leaf lengthwise while maintaining a strong grip on it. This procedure separates the leaf's fibrous portion from the inner core.
- Removal of fiber: After removal, collect the fibers and package them. To soften the fibers and make them simpler to separate, submerge the bundles in water for a few weeks.
- Retting: The non-fibrous leaf components can be broken down by retting. The stacks can either be buried in moist soil or submerged in water for a few days to accomplish this. According to the required fiber excellence, this procedure may take a few days or weeks.
- Extraction of fibers: Extract the bundles from the water or soil when the retting procedure is finished. To dis-

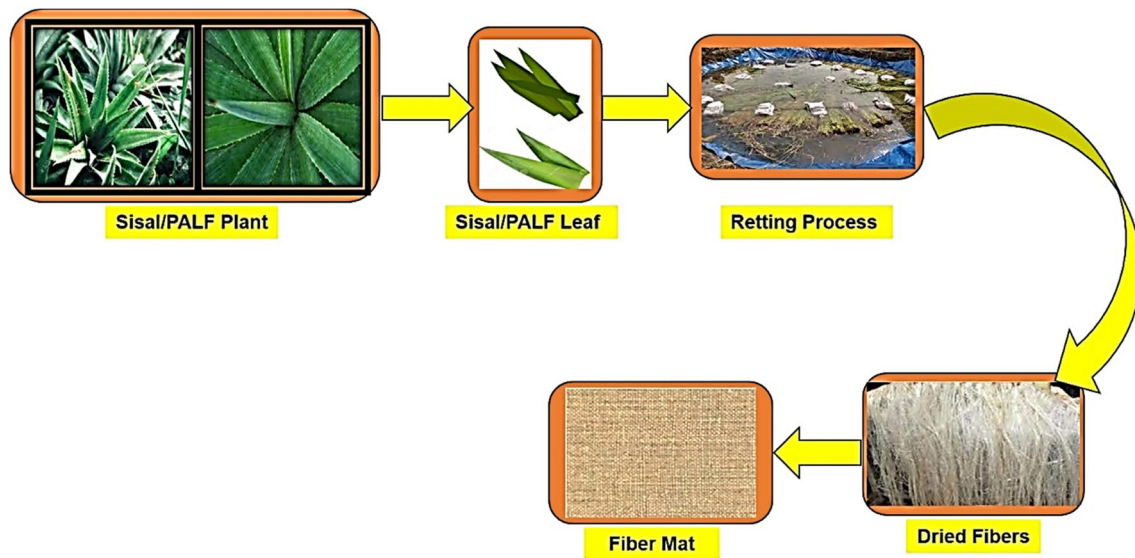


Fig. 1 PALF/sisal-based natural fiber extraction process

tinguish the fibers from the non-fibrous substance, use a wooden or metallic instrument. The term “scutching” or heckling is used for this action.

- **Curing:** It is necessary to dry the fibers after separation. Once they are totally dry, drape them up in an area with good ventilation or set them on an even surface in the sunlight.
- **Finishing:** To enhance their level and prepare for future usage, the dehydrated fibers might be further treated by combing and brushing.

2.2 Composite fabrication

To start, the needed quantity of silicon nanoparticles was combined with methanol for 10 min using a stirring rod (with an operational frequency of 400–2000 rpm and a 0.7-W rating) and then for 15 min using a probing ultrasonication. Following the pouring of the needed amount of epoxy resin, this blending procedure was repeated. The combination was vigorously blended for 20 min after introducing the needed amount of chopped natural fabrics. To eliminate the leftover methanol, the substance was heated in a 70 °C oven for 15 min. Lastly, the curing agent was automatically blended for 15 min using a 1:10 ratios. The mixture was next added to a steel mold and dried for a day underneath a 30-kg weight. Wax films have been applied all around the mold substrates to prevent the mixture from adhering to the plates. The generated materials were then machined into samples of the necessary dimensions and widely used for different characterization studies. Table 1 represents the various fiber, filler, and polymer combinations for hybrid

Table 1 Composition of natural fibers and nanofillers of a hybrid composite

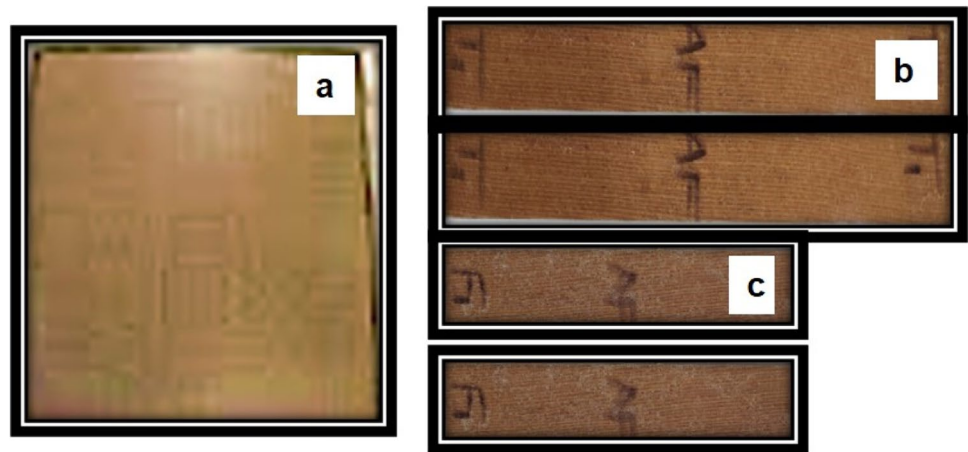
Symbols	PALF fiber wt. %	Sisal fiber wt. %	Epoxy resin wt. %	Silicon nanoparticles
A	15	15	70	0
B	15	15	68	2
C	15	15	66	4
D	15	15	64	6
E	15	15	62	8

composites. Figure 2 shows the fabricated composite plate and testing specimens.

2.3 Mechanical characterization

Mechanical properties such as tensile, impact, and bending, as well as physical properties such as densities and voids, were assessed for the fabricated composite materials. The bending and tensile strengths for every sample were determined using the Instron 1195 type Universal Testing Machine (UTM) with maximum load capacity of 5 KN and a crosshead speed of 2 m/min was used to examine flexural and tensile properties. With respect to the ASTM D 790 (125 × 12 × 3 mm rectangular specimen) and ASTM D 3039-76 (250 × 25 × 3 mm rectangular specimen), flexural and tensile test was carried out. In accordance with the ASTM D 6110-10 (127 × 10 × 3 mm) standards, the Charpy impact testing was carried out by using Tinius Olsen (Model Impact 104, 9.81 kN pendulum capacity) machine to estimate the impact strength of a specimen. All the mechanical

Fig. 2 Photographic images of **a** fabricated composite plate; **b** tensile specimen; **c** flexural specimen



characterization was carried out at SRM university, Chennai, Tami Nadu, India. ASTM D2734-09 ($25.4 \times 25.5 \times 3$ mm) was used to calculate the void content of a hybrid samples. Theoretical densities were computed using the law of mixing, whereas experimental densities were obtained using the Archimedes methods. The materials void percent was estimated by dividing the discrepancy between the experimental and theoretical densities by the theoretical densities [28, 29].

The overall dry slide wear rate of the prepared composites has been evaluated using ASTM G 99 pin-on-disc equipment. Tests were carried out on an EN-32 steel disc with a 50-mm diameter for a constant sliding distance of 1000 m with different loading conditions (7, 14, 21, 28, and 35 N) as well as sliding speeds (1, 2, 3, 4, and 5 m/s). The 20 mm \times 5 mm \times 5 mm-sized specimen was held vertically to a tool steel in the container. The specimen weight was determined using a modern digital scale prior to and following the slide-worn trials and represented as volumetric weight to use the formula (1) [30]. Three samples were collected for every test to attain the most favorable results, as well as the mean result, which is mentioned.

$$\text{Volumetric wear rate} = \frac{w}{\rho} \quad (1)$$

where w and ρ indicated as a loss of weight (g) and density (g/cm^3) of the samples [31, 32].

2.4 Moisture absorption behavior

According to ASTM 570 methodology, the moisture absorption experiment for PALF, sisal, and nano silicon-based nanocomposite was performed by immersing in distilled water at a normal temperature for 60 h. Before being tested, the nanocomposite was weighted using an algorithm that involves determination and baked at 70 °C for a day to remove any last bits of moisture. The hybrids were submerged in water as soon as they had been weighed. The

composite samples were regularly taken out of the water bath after every 24 h, and tissue paper was used to clean the sample surface.

The composite samples were then weighted to measure the amount of water collected. Composite samples were measured on a routine basis until the water uptake percentages reached saturation. In the current study, all of the composites reached saturation after 60 h of immersion. Because there was no rise in the water absorption percentage after 60 h, the water uptake percentage for 60 h is provided for study. The proportion of moisture absorption is determined by applying the Eq. (2) below [33, 34].

$$\text{Moisture absorption} = \frac{W_a - W_b}{W_b} \times 100 \quad (2)$$

where W_a is specimen weight before immersion; W_b is a specimen weight after immersion.

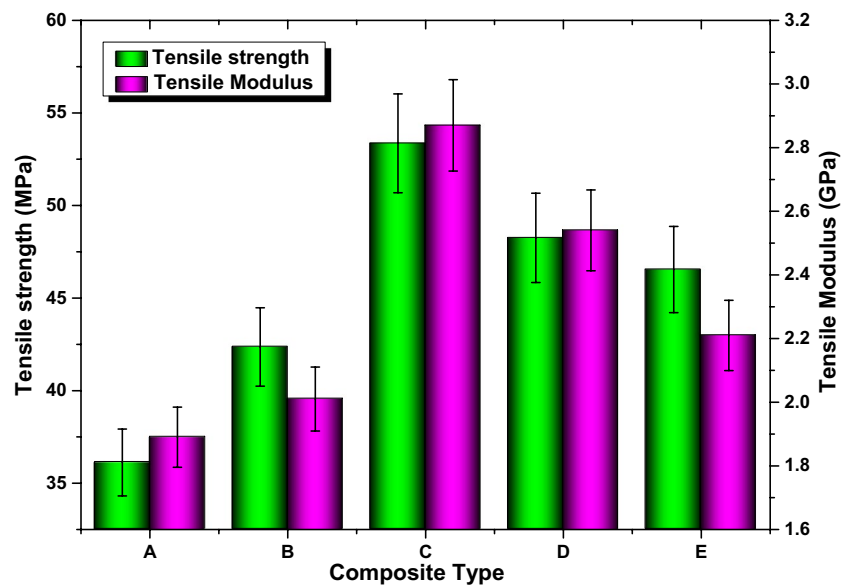
3 Result and discussions

3.1 Mechanical properties

3.1.1 Tensile strength

Figure 3 shows the outcomes of tensile and its modulus characteristics of hybrid composites. The mechanical behavior of polymeric materials is primarily determined by the type and weight proportions of reinforcement, as well as the reinforced ingredients' adhesion to the resin matrix. The tensile strength (Fig. 3) for the A-type composites without nanofillers was 36 MPa. Yet, when 2 wt% silicon nanofillers are added to the formulation, the tensile strength increases by 22% when comparing to A-type composite. The addition of silicon nanoparticles to a mixture boosts tensile strength, but only up to 4% loading. The C-type composite with 4 wt%

Fig. 3 Tensile strength and modulus of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite



silicon nanoparticles attained the greatest tensile strength of 53 MPa, an improvement of about 43% above the A-type composite. This demonstrates the capacity of silicon nanoparticles with fibers to successfully sustain stress at low concentrations. Nevertheless, after subsequently raising the silicon nanomaterial concentration above 4 wt% (i.e., D and E-type), the tensile strength reduced by 14–31% but remained greater compared to the A-type composite. This might imply that inadequate wetting of nanofillers at greater loading reduces the interfacial adhesion among fibers, additives, and matrices, resulting in lower strength properties. The investigation done by Velmurugan et al. [14] verified that introducing a modest amount of nanomaterials boosted the tensile strength of the polymeric matrix; however, even as concentrations of silicon nanoparticles increased, the tensile strength decreased. Somaiah et al. [35] investigated the effect of silicon nanofillers (2, 4, and 6 wt%) on the effectiveness of sisal-Kevlar hybrid nanocomposite. The author discovered that tensile strength continues to be greatest for 4 wt% nanoparticle-packed composites, with more increases in silicon nanomaterial composition resulting in a decrease in tensile strength. With higher nanoparticle concentrations, comparable outcomes have been documented in the research.

Figure 3 also shows the bar graph for tensile modulus for hybridized SiO₂ nano-composites at various filler loadings. The maximal tensile modulus of a hybrid SiO₂ nanocomposite with a 4-weight percent filler loading is recorded. Although the improvement in strength is smaller than the 4-weight percent (C-type) hybridized nano-composites, it is still more than the empty (A-type) composite. The binding characteristic of the oxygen molecules in SiO₂ fillers with a polymer matrix was discussed in the section above. The chemical reaction of silica with the epoxy's oxygen molecules and carbon with its hydrogen atom causes SiO₂

particles to bind to the resin [36]. Even so, when compared with hybridized SiO₂ nano-composites, the material's load-carrying ability and modulus are reduced due to a lack of oxygen-hydrogen bonds, a feature that is more important than carbon-hydrogen binding. By looking at the stress-strain curve (Fig. 4), it is evident. There is a greater likelihood of agglomerating, which is the development of clusters or aggregations of nanoparticles, as the SiO₂ nanofiller concentration rises (over 4 wt%). Agglomerates may serve as stress concentrators, resulting in localized weaknesses and a decrease in the composite's total tensile modulus. The likelihood of filler-to-filler interaction improves as the quantity of nanofillers increases. The effectiveness of the composite's capacity to transmit stress may be hampered by such interactions, which also increase the likelihood that weaknesses may occur in the substance [37].

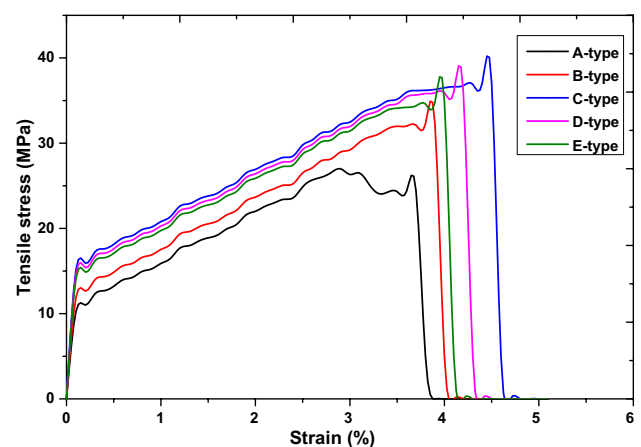


Fig. 4 Tensile stress-strain curve of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite

3.1.2 Flexural strength

The flexural strength and its modulus of hybridized organic fiber-based epoxy composites at varied silicon nanomaterials loadings is shown in Fig. 5. The results demonstrate unequivocally that the introduction of silicon nanoparticles increases the bending strength of the prepared composites. The flexural strength of the A-type materials without silicon nanoparticles was 47.26 MPa, which improved by 16% when 2 wt% silicon nanoparticles were added and stayed at 54.69 MPa. Bending behavior was estimated to be 61.25 MPa for C-type material, which is approximately 26% greater than A-type specimen. Furthermore, after loading with 4 wt% silicon nanoparticles, the flexural strength

begins to decrease, which could be due to greater filler-fiber interactions, and an increase in void content could produce a poor stress transfer process among fillers as well as fiber [38]. Somaiah et al. [35] encountered a similar consequence for strength properties for silicon nanoparticles packed in a sisal-Kevlar fiber-reinforced hybrid nanocomposite, in which the maximum flexural strength was witnessed for 4 wt% silicon nanoparticles and reduced with an additional rise in nanomaterial loading. Figure 6 shows the stress-strain curve of the flexural properties.

Strong linkages between SiO₂ nanoparticles and the matrix substance in the hybrid material can develop up to 4 wt.% of the time. This enhanced stress transfer and enhanced interaction at the filler-matrix interfaces lead to a more

Fig. 5 Flexural strength and modulus of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite

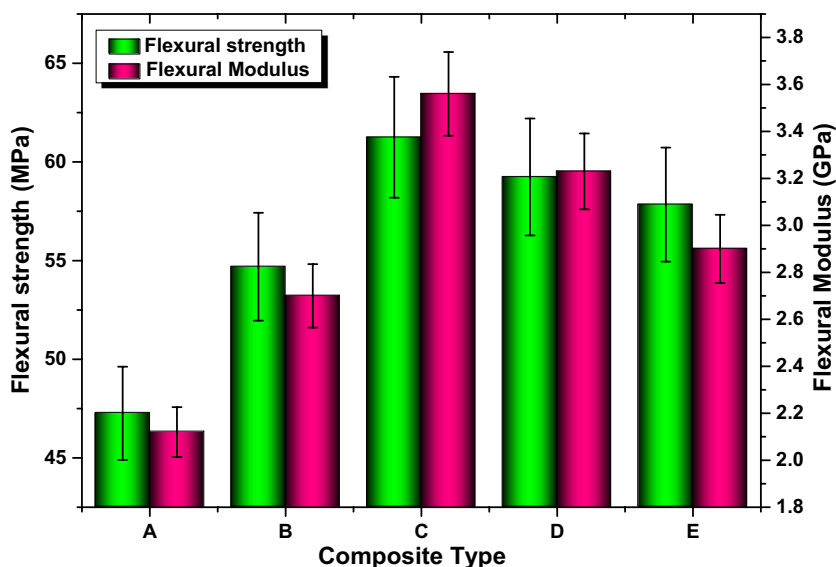
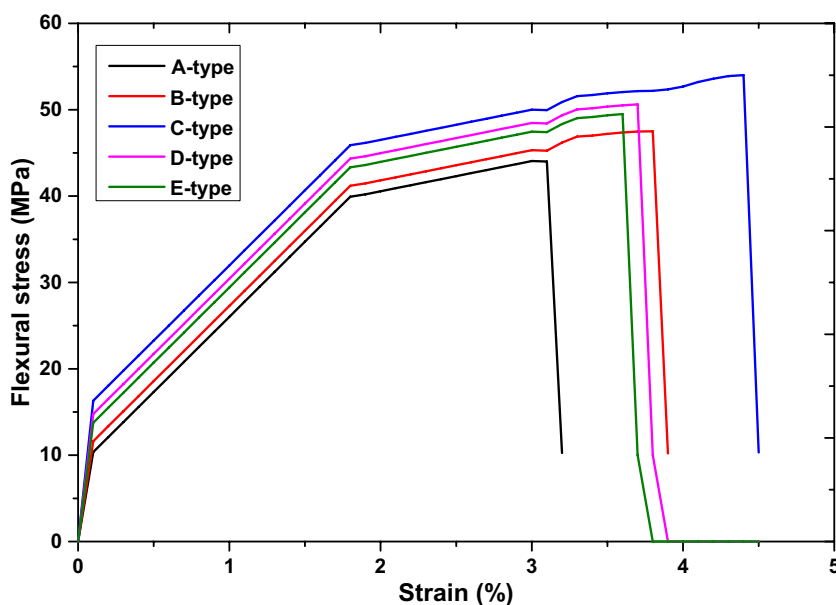


Fig. 6 Flexural stress-strain curve of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite



effective load-bearing ability and a greater flexural modulus. However, following the addition of 4 weight percent of SiO_2 , the aforementioned tendency was not maintained. This is due to the difficulty in ensuring a consistent distribution of the nanofillers at increasing levels [39]. Poor distribution can lead to poor adhesion among the filler and matrices, which would reduce the flexural modulus and restrict the ability for load transmission. The SiO_2 nanofiller's interaction with the matrix's substance is essential. The bonds that exist among the filler and matrices may become less advantageous over a specific concentration, resulting in less reinforcing effects and a reduction in flexural modulus. The particular causes of the decline in flexural modulus beyond 4 weight percent of SiO_2 nanofiller may differ based on the composition of the composite, the conditions under which it was processed, and other environmental variables [40].

3.1.3 Impact strength

Figure 7 depicts the impact force measurements of composite samples containing silicon nanoparticles. In general, adding silicon nanoparticles to the composites improved the impact strength of the hybridized organic fiber–reinforced epoxy composite substantially. It can be shown that composites with 4 wt% silicon nanoparticles introduced had a maximum impact force of 4.98 J, which is approximately three times greater than the minimum impact strength of an A-type combination. Nevertheless, for composites containing 4 wt% silicon nanoparticles, i.e., D and E-type, a drop of 10–33% was found. Velmurugan et al. [41] investigating the effect of silicon nanoparticles (0, 1.5, 3%, and 4.5 wt%) on the impact resistance of hemp-Kevlar fiber–reinforced blended nanostructure. The author discovered that impact

resistance continues to be greatest for 3 wt% nanomaterials packed polymer composites and decreases for lower silicon nanoparticles packed composite material.

Fiber-reinforced polymer mixtures are frequently associated with a large number of voids inherited from production faults. Such voids can act as maximum stress, hastening fracture development and spread. The inclusion of silicon nanomaterials aids in filling such spaces, which effectively inhibits the creation and spread of microcracks in hybrids. Nanomaterials can operate as interconnecting pins in the metaphase of matrix and reinforcement, improving interfacial bonding and leading to an increase in impact force [42]. Furthermore, silicon nanoparticles absorbed greater energies due to their increased proportion of surface to volume, which may account for the increase in impact strength. When the silicon particle deposition increases, the material becomes fragile, resulting in a decrease in impact strength, as shown empirically [43].

3.2 Physical properties

3.2.1 Density measurement

Figure 8(a) and (b) summarize the predicted and experimental densities with matching void percentages of the fabricated samples. The findings show that silicon nanomaterial reinforcing has a direct effect on density and void percentage. The theoretical and experimental densities of nanocomposites are 1.221–1.253 g/cm^3 and 1.211–1.24 g/cm^3 , respectively, and have been observed to rise with increasing silicon particle concentration. The increase in laminate density was attributable to the substitution of high-density silicon nanofillers for low-density epoxy matrix. Furthermore,

Fig. 7 Absorbed impact energy of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite

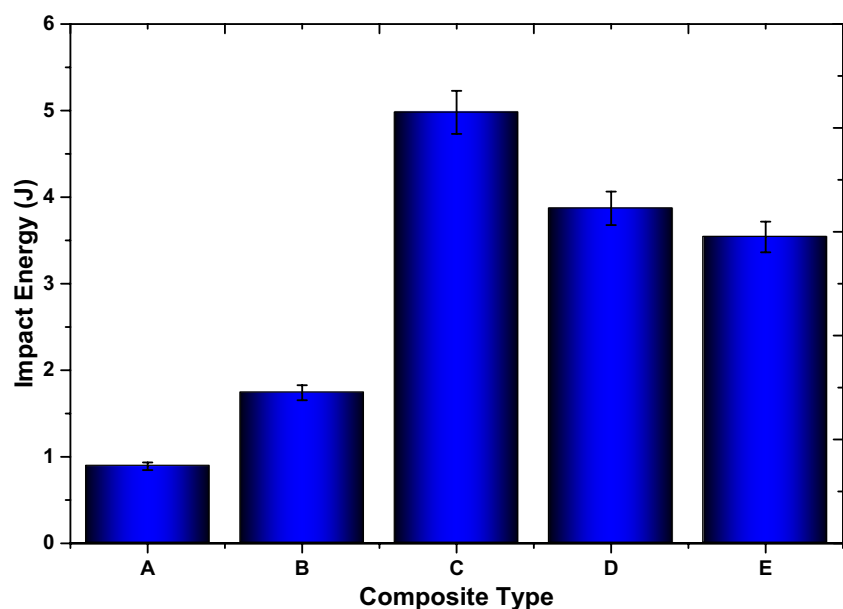
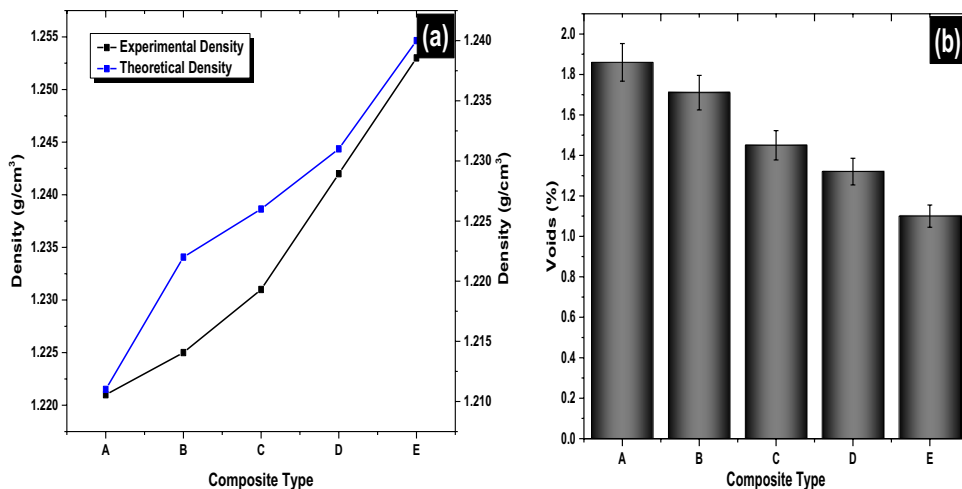


Fig. 8 Physical properties of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite. **a** Theoretical vs actual density; **b** void content



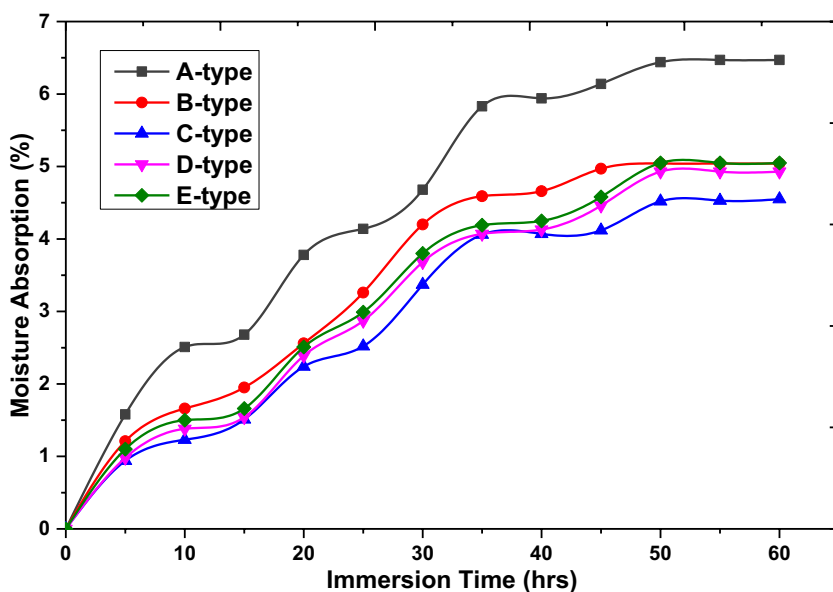
the void percentage reduces as the silicon nanomaterial concentration increases, owing to the good scattering of nano-fillers inside the epoxy coating [12, 44].

3.2.2 Moisture absorption behavior

Figure 9 depicts the correlation between percentage weight growth and the squared of the immersion period for PALF/Sisal-based hybrid composites with varying silicon contents by matrix weight at ambient temperature. The water uptake mechanism of such samples was discovered to satisfy the Fickian rule, which is defined as linear at the beginning of the water uptake curve as well as subsequently decelerating until it achieves saturation after a lengthy time frame. For the various soaking periods, the results reveal that introducing silicon nanomaterials to the

epoxy matrix resulted in reduced water uptake of hybrid fiber-reinforced epoxy composites compared to those without silicon. Silicon nanoparticles, which function as a barrier toward water in the epoxy matrix, are responsible for this [45]. These findings also show that when the amount of silicon nanoparticles increases, the initial moisture absorption rate and the maximum moisture content values decrease. This occurs as a result of the nanofiller’s efficient aspect ratio, which produced the tortuous route and strengthened the binding at the contact. The findings of this report’s analysis of water uptake characteristics match those that Velmurugan published for luffa/epoxy composites containing aluminum tetrahydrate [46]. Yet, specimens with much more than 4 weight percent of silicon absorbed more water compared to specimens with only 2 weight percent of silicon. This is due to greater voids

Fig. 9 Moisture absorption behavior of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite



forming in the changed matrices in the previous samples, as seen by the SEM picture in Fig. 13(c).

Furthermore, Fig. 13(d) demonstrates the presence of microscopic fractures at the interaction between fiber and matrix, which leads to water penetrating into the bulk matrix during the acclimation period. The emergence of these unavoidable fissures and voids inside the composite has been linked to the fabrication and densification processes. Unfilled (Type-A) hybrid composites exhibit poor hydrophilicity for varying soaking periods because of the hydrophilic properties of PALF and sisal fiber, which would be attributable to the hydroxyl groups found on the surface [47]. This also clarifies why the control samples' ability to hybridize continuously was greater than that of the hybridization specimens. By examining how well natural fibers absorb moisture, this phenomenon may be understood. Since that natural fiber has a large quantity of cellulose, the composites collect a considerable amount of water, which causes the fiber to inflate [48]. This sisal fiber and PALF inflation cause tiny fissures in the epoxy composite materials.

3.3 Wear characteristics

3.3.1 Wear behavior under load conditions

The load capacity was among the most essential operational factors for polymeric matrix sliding wear. Figure 10 depicts the volumetric wearing of hybrids as a result of average force at a constant sliding velocity (2 m/s) and distance (1000 m). Figure 10 shows that the volumetric degradation rises exponentially for all materials as the typical load increases. In contrast to A-type materials, the volumetric wearing tendency for silicon nanomaterial-filled composites

was minimal with increasing load condition. Wear rate was greatest in A-type hybrids and decreased as silicon particulate content increased in hybrid biocomposites. In fact, adding 4 wt% silicon nanoparticles decreases volumetric degradation by 8–13% even under typical loading conditions when compared to A-type hybrids. The presence of silicon nanofillers in the fiber matrix composition could be responsible for the lowered tendency in volumetric degradation. Because of the enhanced fragility of the nanocomposite, such rough nanomaterials improve wear resistance. Silicon nanoparticles can minimize stress on fibers and protect the matrices in the interface region against thermal and mechanical failures while sliding. Volumetric wear was discovered to rise with rising concentrations of nanofillers after displaying minimal wear at 4 wt% nanofillers. The lesser amount of silicon nanoparticles was firmly incorporated in the interphase of fiber and polymer matrices and formed transferring coatings on the material surface, resulting in less weight loss and thus a lower rate of wear. At higher concentrations, silicon particulate aggregation broadens the materials and countersurface distance, acting as separators [49]. This could also result in less adherence due to sliding friction, which leads to higher weight loss and volumetric degradation of the materials. Composite-damaged surfaces have also been investigated utilizing SEM to further comprehend the likely process of material damage.

Figure 11 depicts the worn interfaces of A and C-type composites exposed to varied load levels at a sliding velocity of 2 m/s. In the low loading situation (7 N), the worn surface of A-type composites (Fig. 11(a)) is reasonably flat, suggesting lesser wear caused by the progressive elimination of fractured fibers as a result of fiber thinning and fiber fracture. Kurdi et al. [50] discovered a comparable

Fig. 10 Volumetric wear rate of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite under various load conditions

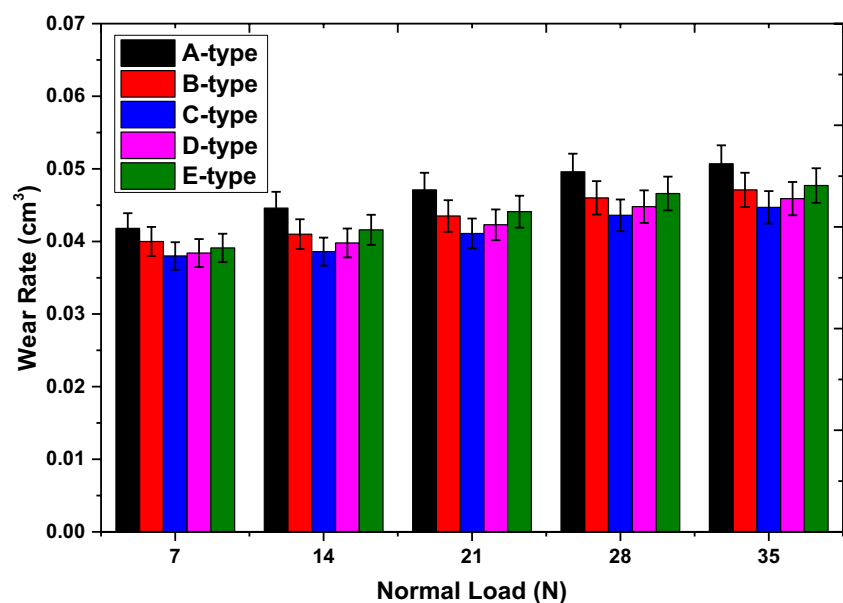
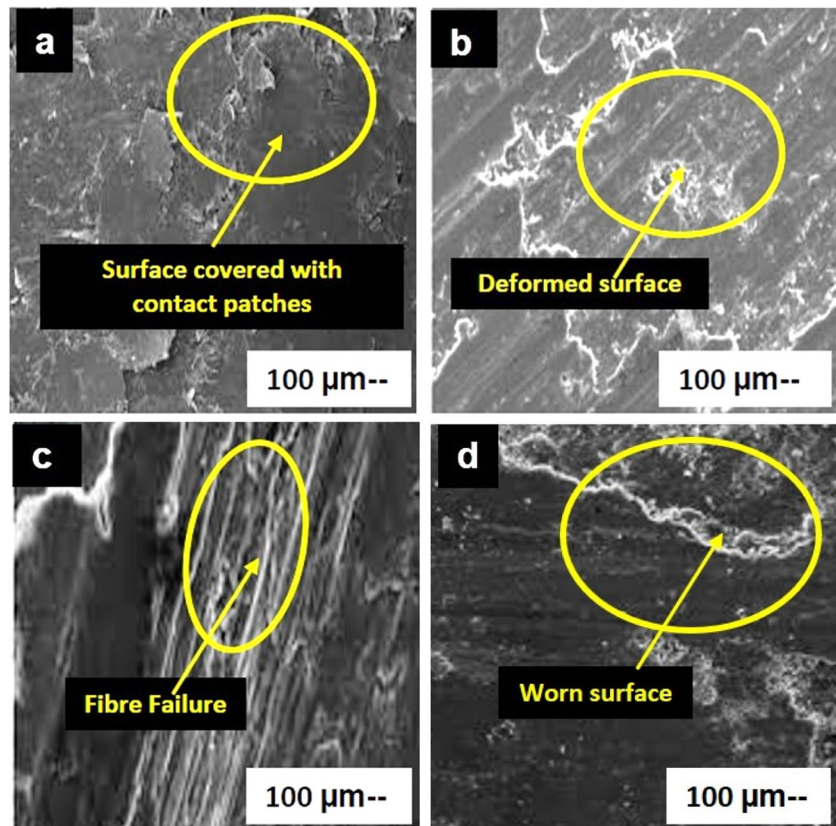


Fig. 11 Microstructural images of worn surface of **a** A-type under 7 N; **b** A-type under 35 N; **c** C-type under 7 N; **d** C-type under 35 N



wear behavior process in nano titanium oxide–filled carbon fiber–reinforced composites. Nevertheless, when the applied load increased (35 N, Fig. 11(b)), breakdown of the matrix–fiber interfacial area began, leading to its simple extraction. As a result, as shown in Fig. 11, the weight loss of a composite progressively increased due to severe fiber and epoxy substrate degradation. The deteriorated surfaces of a nanoparticles infused composites, on the other hand, were significantly different. The wear surface seems substantially better in contrast to A-type, as demonstrated in Fig. 11(c), and also at greater (35 N, Fig. 11(d)) stress conditions. The ingredients were gradually eliminated, and the inclusion of nanoparticles with fibers led to the aggregates’ improved damage tolerance.

3.3.2 Wear behavior under sliding speed conditions

Figure 12 depicts the influence of sliding velocity (1 m/s, 2 m/s, 3 m/s, 4 m/s, and 5 m/s) upon the volumetric wear of prepared composites under constant conditions of normal load (7 N) and followed by sliding distance (1000 m). Including all sliding velocities, A-type hybrids have the highest rate of wear, whereas C-type composites have the least. The wear rate of all combinations increases as the sliding velocity increases to 3 m/s and then begins to decrease progressively as the sliding speed climbs higher. The rate of

wear was noticed to decrease as silicon content increased, and then, after reaching the minimum values for C-type composites, wear started rising as silicon content increased further.

Regardless of constitution, the rate of wear maintains around 0.0356 cm^3 and 0.0412 cm^3 at lesser sliding velocities (2 m/s) and approximately 0.0449 cm^3 , 0.018 cm^3 at greater sliding velocities (4 m/s). At lesser sliding velocities (2 m/s), for instance, the rate of wear maintains 0.0369 cm^3 , 0.013 cm^3 for C-type material. Although the wear rate increased by 19% for materials required at higher sliding velocities (4 m/s), it stayed close to 0.0435 cm^3 and 0.005 cm^3 . Assessing the damaged surface of a blend confirmed this tendency in wear behavior. Figure 13 depicts the worn interfaces of C-type composites exposed to varying sliding velocities under fixed parameters of standard load as well as length. The composite surfaces showed some signs of smoothing at reduced sliding speeds (Fig. 13(a), (b)), indicating a decreased wear rate. Nevertheless, when the sliding velocity rose (Fig. 13(c), (d)), widespread fiber breakage and removal began due to the weakening of the epoxy caused by heat conduction. Materials (fibers and nanoparticles) are removed, creating wide grooves just on wear rate, leading to increased dimensional wear of the hybrids. Singh et al. [31] discovered a similar method for sliding wear in nano clay-based nanocomposites. Megahed

Fig. 12 Volumetric wear rate of different concentrations of nano silicon-filled PALF/sisal-based hybrid composite under various sliding velocity conditions

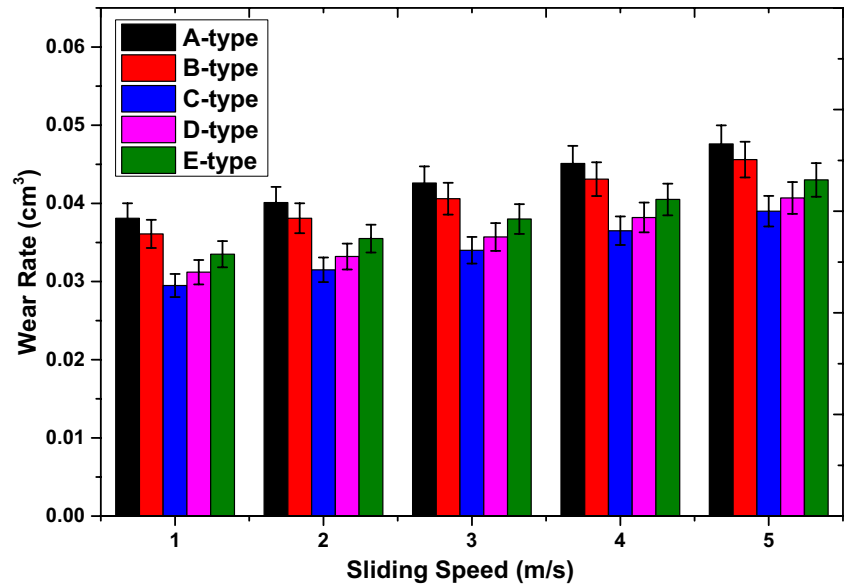
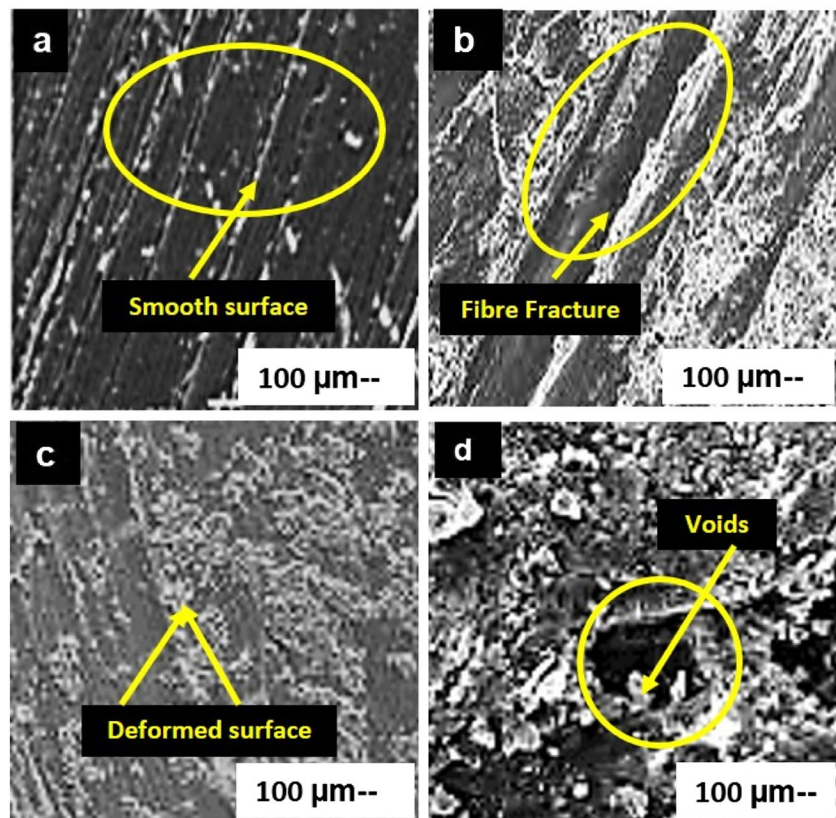


Fig. 13 Microstructural Images of worn surface of **a** A-type under 2 m/s; **b** A-type under 2 m/s; **c** C-type under 4 m/s; **d** C-type under 4 m/s



et al. [51] reported modest surface deformation leading to reduced wear under low strain situations when evaluating the worn interfaces of nanofillers added to glass fiber-reinforced composite material. The material distortion intensified as the load speed rose, leading to greater wear.

4 Future scope of the present research

1. Aging and durability studies: Future studies might concentrate on analyzing the durability and long-term aging

behavior of the hybrid PALF/sisal fiber–based polymeric nanocomposites that include silicon nanomaterials. In order to evaluate the composites' effectiveness and resilience over a long period of time, this would include exposing them to premature aging experiments using heat cycling, moisture contact, or UV irradiation.

2. **Multiscale modeling and simulation:** It is possible to use computational simulation and model-based approaches to comprehend the mechanical characteristics of nanocomposites at various dimensions. The reinforcing processes, interface conversations, and modes of failure of the composite substrate may all be better understood by multiscale modeling. This can help with the composites' design optimization and mechanical characteristic prediction prior to testing with experiments.
3. **Environmental impact assessment:** Future studies can examine the effects of silicon nanoparticle–containing hybrid PALF/sisal fiber–based nanocomposites on the ecosystem. To analyze the long-term sustainability and possible ecological issues related to the creation, usage, and removal of such nanocomposites, eco-toxicity research and life cycle analysis (LCA) may be used.
4. **Advanced fabrication techniques:** Research might look at cutting-edge manufacturing methods for creating blended PALF/sisal fiber–based polymer nanocomposites with better silicon nanoparticle orientation and distribution. To exert more influence over a material's morphology and characteristics, strategies like electrospinning, compounding, or three-dimensional printing might be investigated.
5. **Applications and industrial scalability:** Consequently, future studies might concentrate on investigating the useful uses of hybrid nanocomposites made of silicon nanoparticles and sisal fiber–based polymers. It is possible to look at the production process' scalability and the viability of using these substances in a variety of sectors, including construction, transportation, aviation, and packaging products.

The efficacy and prospective uses of silicon nanoparticle–reinforced PALF/sisal fiber–based polymeric hybrid nanocomposites may be better understood by tackling these research topics, which will improve the discipline of polymer composite materials.

5 Conclusions

The mechanical, wear, and physical attributes of PALF/sisal fiber–based polymeric hybrid nanocomposites have significantly improved because of the use of silicon nanomaterials. The durability, rigidity, and toughness of the material have improved as a result of the addition of

silicon nanoparticles, rendering them more appropriate for structural applications. Additionally, the incorporation of silicon nanoparticles has enhanced the tribological features of the nanocomposites, increasing their durability and resistance to frictional forces.

- In the current research, the presence of 4 wt.% of silicon nanoparticles has positively influenced the mechanical (i.e., 53.36 MPa tensile, 61.25 MPa flexural, and 4.98 J of impact energy) and physical properties (theoretical and experimental densities of nanocomposites are 1.221–1.253 g/cm³ and 1.211–1.24 g/cm³) of the nanocomposites. Overall, it has become clear that obtaining these improved qualities requires good silicon nanoparticle distribution and interactions throughout the polymer matrix.
- Furthermore, after loading with 4 wt% silicon nanoparticles, the composite strength begins to decrease, which could be due to greater filler-fiber interactions, and an increase in void content could produce a poor stress transfer process among fillers as well as fiber.
- The volumetric wear of the composites was sensitive to the normal load and found to increase with increased load, while the volumetric wear of the composites first increased with lower sliding speeds (2 m/s) and decreased gradually with further increases in sliding speeds. In fact, adding 4 wt.% silicon nanoparticles decreases volumetric degradation by 8–13% even under typical loading conditions when compared to A-type hybrids.
- The reduced tendency for volumetric deterioration may be caused by silicon nanofillers in the fiber matrix compositions. Regardless of constitution, the rate of wear maintains around 0.0356 cm³ and 0.0412 cm³ at lesser sliding velocities (2 m/s) and approximately 0.0449 cm³, 0.018 cm³ at greater sliding velocities (4 m/s). At lesser sliding velocities (2 m/s), for instance, the rate of wear maintains 0.0369 cm³ for C-type material. Although the wear rate increased by 19% for materials required at higher sliding velocities (4 m/s), it stayed close to 0.0435 cm³ and 0.005 cm³.

These results open up new avenues for the creation of novel materials with enhanced performance and long-term viability by highlighting the incredible potential of silicon nanoparticles as a strengthening component in PALF/sisal fiber–based polymeric hybrid nanocomposites. In order to maximize the usefulness of silicon nanoparticles in such hybrid materials, future research in this area should concentrate on further optimizing the nanoparticle loading and processing procedures.

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Author contribution Mayakannan S: conceptualization, writing an original draft, methodology.

Bensam Raj J: investigation, review.

Raja V L: testing and evaluation.

Nagaraj M: editing.

Data availability The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Yes. All permission granted.

Conflict of interest The authors declare no competing interests.

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