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Synthesis and mechanical characterization of epoxy bio-composites reinforced with *Kigelia Africana* (sausage) fruit fibers for biomedical applications

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Abstract

In recent days natural fibres are gaining lot of interest for the development of polymer composites as an alternative to conventional fibres such as carbon, glass, aramid, due to their low cost, relatively good mechanical characteristics, high specific strength, nonabrasive, eco-friendly, and biodegradability. In the present work, treated *Kigellia Africana* (sausage) fruit fibres are reinforced with epoxy resin, composites were fabricated and characterized for their structural, mechanical, wear, vibration characteristics. Mineral salts, dirt, inorganic residues, leftover fruit pulp, and waxy materials were all eliminated using hydrochloric acid (HCl) treatment. Following the bleaching of the treated material, its properties were assessed and characterized. After the alkali treatment and bleaching, a substantial level of lignin and hemicellulose were removed, resulting in a highly cellulosic fibre with improved characteristics. Results showed that the HCl-treated fiber composites with cenosphere demonstrated their viability for load-bearing applications with tensile strengths of 32.24 MPa (96% improvement) and flexural strengths of 50.28 MPa (39.8% increase). The structure and uniform distribution *Kigelia africana* fibers were responsible for a maximum hardness of 34 RHN (57% greater), whereas RSM analysis showed minimal wear at 25 N load, 3000 m sliding distance, and 0.5 m/s velocity.

Keywords *Kigellia Africana*, Alkali treatment, Tensile strength, Flexural strength, Hardness, Wear, Vibration and modal analysis, Biodegradability

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Introduction

A class of materials known as natural fibre reinforced composites (NFRC) combines natural fibers such as jute, flax, hemp, sisal, coir, or kenaf with a polymer matrix to create materials that are affordable, lightweight, and environmentally friendly. The potential of these composites to address environmental issues related to synthetic fiber-reinforced composites has attracted a lot of interest in recent years. Renewability, biodegradability, low density, and lower production energy usage are only a few benefits of natural fibres (Alam et al. 2021; Anand et al. 2024). These qualities are in line with international initiatives to create environmentally friendly materials that reduce carbon emissions. Because of the increased focus on sustainability and green materials, NFRC applications are spreading into industries like consumer goods, packaging, building, and automobiles. Automotive manufacturers are increasingly using NFRCs in interior components to meet environmental regulations, reduce vehicle weight, and improve fuel efficiency (Kumar et al. 2022).

Kigelia Africana, known as the “sausage tree”, is a medium-to-large ornamental tree widely grown in India. It features a spreading canopy, maroon-red bell-shaped blooms, glossy pinnate leaves, and distinctive gourd-like fruits up to 60 cm long and 10 kg in weight. Though inedible, the fruit and other parts of the tree have therapeutic properties, aiding in treatments for rheumatism, syphilis, ulcers, and lactation (Bello et al. 2016). Its extracts are also popular in cosmetics for anti-aging and skin-firming benefits. Additionally, the tree’s fruit fibers show promise for use in sustainable natural fiber composites. In general, sausage fibres are superior to fibres derived from a variety of unusual sources and share characteristics with cotton. Sausage fibres have better antibacterial and hydrophobic qualities, which may make them useful in functional polymer composites. *Kigelia Africana* is a medicinally significant plant, widely reported for its non-toxic, anti-inflammatory, antimicrobial, and wound-healing properties. Fibers extracted from its fruit are lignocellulosic in nature, biodegradable, and lightweight, making them attractive for biomedical-oriented bio-composite development when combined with epoxy matrices, can be used in non-load-bearing and semi-load-bearing orthotic and prosthetic components, such as prosthetic covers, braces, splints, and limb support shells. Due to their biodegradable and non-toxic nature, *Kigelia Africana* fibers are promising for temporary biomedical support structures, including positioning aids, temporary splints, and disposable biomedical fixtures. The epoxy matrix ensures mechanical integrity during service life while the natural fibers enhance sustainability (Ramakrishna et al. 2001; Sathishkumar et al. 2020). *Kigelia Africana* fiber epoxy composites are suitable for external biomedical device

housings, medical trays, instrument casings, rehabilitation aids, and mobility-assist components. These applications require moderate mechanical strength, lightweight nature, and structural reliability, which is effectively achieved using natural fiber epoxy composites (Faruk et al. 2012; Pickering et al. 2016).

In natural fibre reinforced polymer composites, the natural fibres which reinforces with polymer matrix strengthens the mechanical properties like tensile strength, flexural strength, and impact resistance, due to good fiber matrix adhesion. The mechanical characteristics of these natural fiber polymers composites are influenced by processing techniques, fiber length, orientation, and fiber-resin ratio, curing temperature etc. (Marichelvam et al. 2023). The mechanical and physical behavior of banana fiber-reinforced polymer (FRP) composites for different fiber proportions was investigated by Subramanya et al. (2020). The results showed that the tensile and flexural strength decreased as the fiber content in the matrix increased, and that further increases could result in decrements. There was also a decrease in the properties due to increased water absorption. Alagarsamy et al. (2015) investigated the tensile and impact strength of chicken feather and coir reinforced composites, results proved that presence of coconut coir fibre makes the composites to exhibit higher properties than the chicken feather. The mechanical characteristics of hybrid composites reinforced with Madar, Gongura, and Hibiscus cannabinus fibres and polyester resin were examined by Marichelvam et al. (2023). The composites showed a flexural modulus of 1548.588 GPa, a tensile strength of approximately 34.720 MPa, and a flexural strength of 77.957 MPa. The impact of fibre orientation and volume fraction on the tensile characteristics of NFRCs was investigated in-depth by Rana et al. (2022). The results showed that load-bearing capability is increased by uni-directional fibre orientation.

With a variety of chemical processing techniques that alter the natural fibres’ compatibility with the matrix, the disadvantages of natural fibres, including poor interfacial bonding and the appearance of hydrophilic qualities, can be addressed. Once chemical processing is applied, fully cured and cross-linked natural fibres are then formed. These fibres contribute to improved mechanical strength and thermal stability by reinforcing the polymeric matrix. Previous investigations have documented this (Lee et al. 2021; Sapuan et al. 2020). It may be possible to improve the compatibility between the natural fibres and the polymer binder by effectively eliminating surface contaminants and hydroxyl group components (Vijay et al. 2021). Archana et al. (2022) used naturally existing fibres from banana, ramie, jute, and sisal plants to create fiber-reinforced polymer (FRP) composites. Chemical treatment and non-chemical treatment were used to create two sets

of FRP composites. The manufactured FRP composites have been thoroughly characterised. The properties of fiber-reinforced composites treated with heat and chemicals showed satisfactory improvements in the properties.

Ilangovan et al. (2020) carried out the fruit's natural cellulose fibres were extracted using NaOH, bleached, and their characteristics were then described. The results showed that a considerable proportion of lignin and hemicellulose was lost during the bleaching and alkali treatment, resulting in a high percentage of cellulosic fibre (up to 71 percent). The degree of treatment affected the fibres' morphology, which ranged from rough to smooth as mild treatment increases surface roughness and excessive treatment smoothens the fiber due to over-removal of surface layers. Following treatment, there was an increase in thermal stability, hydrophobicity, and crystallinity.

Hemanth Kumar et al. (2021) examined the free vibration properties of woven plates of basalt fiber–vinyl ester–reinforced composite, with vinyl ester serving as the matrix and basalt fibre as reinforcement. These composite plates, which have varying basalt fibre compositions of 60, 50, and 45%, are made using the compression moulding technique. Using an impact hammer test with an aspect ratio of 0.83, the natural frequencies and mode shapes for these laminates were identified. Nagaraja Ganesh et al. (2025) used an unsaturated polymer resin based on isophthalic acid as the matrix and different weight percentages (5, 15, 25, 35, and 45) of these fibres, composite samples were created. With 35 weight percent fibre loading, the best tensile, flexural, and impact strengths were 17.6 ± 0.72 MPa, 50.2 ± 0.15 MPa, and 1.18 ± 0.21 J, respectively. The samples' wear experiments revealed a specific wear rate of $0.024 \text{ mm}^3/\text{Nm}$ and a coefficient of friction of $0.52 \text{ mm}^3/\text{Nm}$, respectively. The fibres demonstrated appropriate matrix interfacial adhesion. Karuppiyah et al. (2020) studied composites with jute fiber mat as reinforcement and eggshell powder (ESP) and montmorillonite nanoclay (NC) as fillers, results show that fiber GSM and eggshell powder content are significant variables that improve mechanical strength, while the nanoclay appears less important. Palanisamy et al. (2022) tested four types of fibres: untreated and treated with sodium hydroxide (NaOH) at concentrations of 5, 10, and 15% for a whole day at room temperature. The sample treated with 10% NaOH had the best performance in the tensile tests, with an average tensile strength of $16.2 (\pm 5.63)$ N and an ultimate elongation of $4.6 (\pm 1.0)$ %. Tensile strength, flexural strength, interlaminar shear strength (ILSS), impact strength, hardness, and water absorption were assessed by Aruchamy et al. (2025) for the composites made with different proportions of Palmyra Palm leaflet and Coconut Sheath Leaf fibres. The composite containing 20% Palmyra Palm Leaflet and 10%

Coconut Sheath Leaf had the best mechanical performance, with the maximum tensile strength of 42.22 MPa, flexural strength of 94.35 MPa, interlaminar shear strength of 7.52 MPa, and impact strength of 5.98 MPa.

Santulli et al. (2022) studied an agro-industrial by-product, pineapple leaf fibers composite, applications in industries including construction and automotive. The gap between suggested applications and actual execution is examined in this study, which notes that industrialization still faces obstacles. Optimized fiber architecture, the creation of novel matrix systems, hybrid composites, and focusing on high value-added applications are some potential strategies to get around these restrictions.

Through available literature, it is noticed that, the majority of the research concentrate on widely used natural fibre reinforced composites including banana, flax, sisal, jute, and coir fibres as reinforcement. The extraction, processing, and composite performance of *Kigelia Africana* fruit fibres, especially in epoxy matrices, are the subject of very little research. *Kigelia Africana* fruit is well-known in the medical field, but limited research has been conducted on using its fibers for engineering applications. The present research addresses the lack of studies on *Kigelia Africana* fruit fiber–reinforced epoxy composites and their mechanical, tribological and dynamic behavior. The unique contribution lies in introducing a novel natural fiber source, applying systematic chemical treatment, and providing a comprehensive evaluation of mechanical, wear, and vibration characteristics relevant to biomedical and automotive applications.

Materials and methods

Matrix material

Epoxy L-12: Epoxy is thermo set resin material used in the fabrication of composites, when used with its compatibility hardener. It undergoes chemical reaction to form a strong bonding material. When it is mixed with its compatibility hardener K-6, it imparts good bonding strength, load bearing capacity, resistance to deformation and impact resistance. Table 1 lists the properties of epoxy as provided by the supplier, Sai Impex, located in Bangalore, Karnataka, India.

Kigelia Africana fruit fiber-reinforcement material

Kigelia Africana (sausage) fruits (Fig. 1), weighing roughly 4–5 kg each, were gathered on the side of the

Table 1 Properties of Lapox 12

Properties	Unit	Values
Appearance	-	Clear, Viscous liquid
Minimum time for curing	min	15–30 min at 100 °C
Viscosity	m Pas	9000–12000 at 25 °C
Specific gravity	-	1.1–1.2 at 25 °C



Fig. 1 *Kigelia Africana* fruit

road close to our institute's campus, Bengaluru, Karnataka. Hybrid Fine Chemicals in Bangalore, Karnataka, provided the chemicals needed for the experiment.

Fiber extraction and bleaching

In the present study, approximately 30 fruit samples with very hard, woody shells were collected, making the extraction process painstaking, allowed to dry in the sun for three days, and then crushed manually. A natural water retting method was used to remove fibres from *Kigelia Africana* fruit. After being submerged in clean water at room temperature (27 ± 3 °C), the fruits were let to rest for about 21–24 days. Because the water was kept

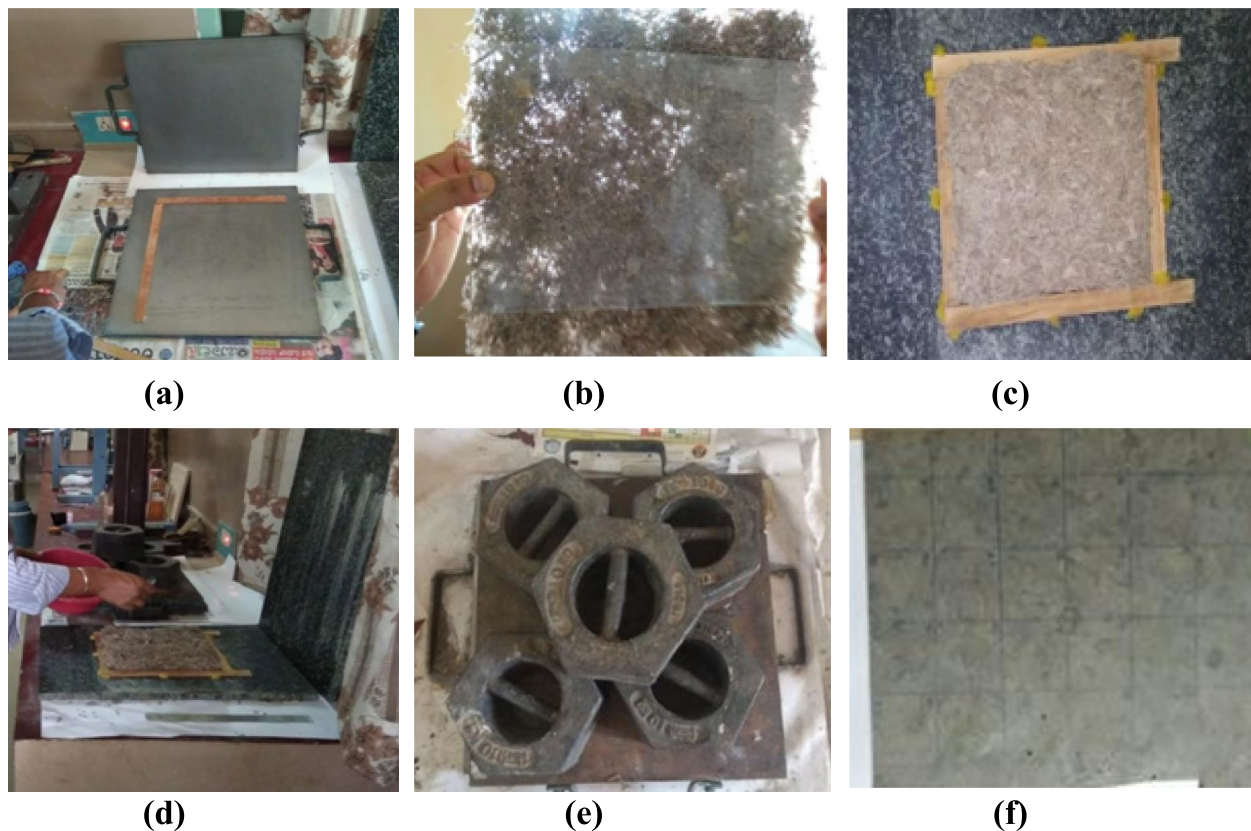


Fig. 2 **a** *Kigelia Africana* fruit, **b** fruits dried in sunlight for 3 days, **c** then fruits are crushed, **d** fruits are soaked in water for 3 weeks, **e** water retting process, **f** chemical treatment to remove of lignin and cellulose, **g** dried fibres

**Fig. 3** Evaluation of fiber properties

in an open container, pectins and other binding elements surrounding the fibres could be broken down more easily by natural microbial activity. Every four to five days, the retting water was changed to avoid over fermentation and the production of odours. Fibre separation was accomplished by naturally occurring bacteria and water-borne enzymes without the need of additional microbial cultures. After retting was finished, the loosened fibres were manually separated, properly cleaned with distilled water to get rid of any remaining organic matter, and then sun-dried for 48 h. They were then exposed to an HCl solution at 100 °C for 90 min. The ratio of untreated fibre to alkali was kept constant at 1:5. Following medical care, the liquid that contained lignin, hemicelluloses,

and other extractives was decanted and thrown away. After being chemically removed, the fibres were extensively cleaned until their pH was neutral. After soaking in a 10% acetic acid solution for ten minutes, the fibres with a neutral pH were washed. The fibres were then stored for additional characterisation after being dried for three hours at 110 °C in a hot air oven. 7% sodium chlorite was used to further bleach the alkali-treated fibres for one hour at 80 °C. The ratio of fibre to sodium chlorite was kept constant at 1:5. The fibres were bleached and then repeatedly cleaned with de-ionized water. To neutralise the alkali, the fibres were subsequently submerged in 5% acetic acid. After three hours of drying at 110 °C, the bleached fibres were being chopped to an average length

**Fig. 4** Composites preparation (a) mould preparation (b) arranging fibres (c) fibre stacking in mould (d) alternate layers of resin and fibre stack placed (e) known weight is placed on it (f) prepared composite after curing

of 5 ± 1 mm for composite construction. This fibre length was chosen to minimise fibre entanglement during hand lay-up processes and to guarantee uniform dispersion inside the epoxy matrix for additional examination. Figure 2 shows the procedure followed in fibres processing.

Fiber characterization

In accordance with ASTM D 3822–14, the fibre tensile strength was evaluated using a Universal Tensile Tester at Central Silk Board in Bengaluru. The gauge length was fixed at 25.4 mm and the cross-head speed was set at 10 mm/min. For characterisation, three distinct samples were used, and the average value was taken into account. Scanning electron microscope was used to analyse the fibres' morphology. After that, the coated samples were examined at a 15 kV operating voltage. In order to create prospective bioproducts, extracted fibres were utilised as matrix reinforcements Fig. 3.

Fibres have undergone testing and the results are as follows, average tenacity- 6.2 gf/tex, breaking load- 2562 gf, elongation- 10.2%, moisture- 0.47% and density- 0.45 to 0.5 g/cc.

Material formulation and preparation of laminates

After preparation of fibers we produced laminates by using hand lay-up technique for testing and analysis. The procedure followed to produce laminates is as follows: (a) selection of surface: flat and leveled surface plate is chosen (b) cleaning of surface plate: there will be presence of dust and dirt on surface plate which may affect the laminates, so that we use sand paper and surface plate cleaner to remove dust and dirt from the surface (c) die making: wooden die is prepared as per the required dimension ($20 \times 20 \times 3$ mm), as it helps in easy removal of laminates and the dies cannot be reused (d) packing fibers: weigh the fibers and take required amount of fiber, chop the fibers into small length and ram the fibers to pack tightly. Check for the gaps and cover if there is any gap. Keep the packed fibers inside the die neatly and tightly (e) preparation of matrix material: resin L-12 and hardener K-9 mixed with 10:1 proportion and the solution thoroughly mixed until resin viscosity gets decreased (f) combining resin and matrix material: pour the resin solution uniformly all over the fiber packed bed and distribute to each and every corner by ramming with plate (Proportions: 30 wt.% fiber, 10 wt.% cenosphere and 60 wt.% resin) (g) drying: close the upper surface plate and put on some weights on it for proper moulding and let it dry for 3–4 h at room temperature. In order to generate isotropic mechanical behaviour appropriate for biomedical components subjected to multidirectional loads and to imitate realistic processing circumstances, random

orientation was selected. In the present investigation, cenospheres are incorporated as a secondary reinforcement to enhance the mechanical and functional performance of the composite system. The hollow structure of cenospheres significantly reduces the overall density of the composite, making the material suitable for lightweight biomedical applications such as prosthetic components and non-load-bearing implants; they contribute to improve compressive strength, stiffness, and impact resistance by acting as micro-load-bearing elements and restricting crack propagation within the epoxy matrix. Due to their spherical geometry, cenospheres act as crack arresters, dissipating energy under mechanical loading and improving fracture toughness. Several researchers have reported that cenospheres content in the range of 5–15 wt. % leads to significant improvements in compressive strength, stiffness, and impact resistance of epoxy composites, while higher loadings cause particle agglomeration and deterioration of mechanical properties due to stress concentration and poor interfacial bonding (Santulli et al. 2022; Rohatgi and Guo 1998; Satapathy and Patnaik 2004). At approximately 10 wt. %, uniform dispersion of cenospheres within the epoxy matrix is achieved, ensuring effective stress transfer and enhanced mechanical performance (Ranjbaran 2011). Additionally, studies have shown that increasing cenospheres beyond 10–12 wt. % results in a significant increase in resin viscosity, leading to poor fiber wetting and processing difficulties, particularly in natural fiber-reinforced composites (Basavaraju et al. 2024). Therefore, 10 wt. % cenospheres provides an optimal compromise between weight reduction and structural integrity, which is essential for biomedical composite applications requiring consistent and reliable performance (Ran et al. 2023). Figure 4 gives stage by stage procedure of composite preparation. In the present investigation, four different laminates have been produced by extracting fibers from *Kigelia Africana* fruit were used as the reinforcing phase in the epoxy matrix material, as described in Table 2.

Table 2 Material formulation for composites and their designation

Specimen No	Fibre treatment	Cenosphere filler	Designation
1	water treated	Without Cenosphere (0 wt. %)	WT30wt%S0wt%C
2	water treated	10 wt. % Cenosphere	WT30wt%S10wt%C
3	HCl treated	Without Cenosphere (0 wt. %)	HCIT30wt%S0wt%C
4	HCl treated	10 wt. % Cenosphere	HCIT30wt%S10wt%C

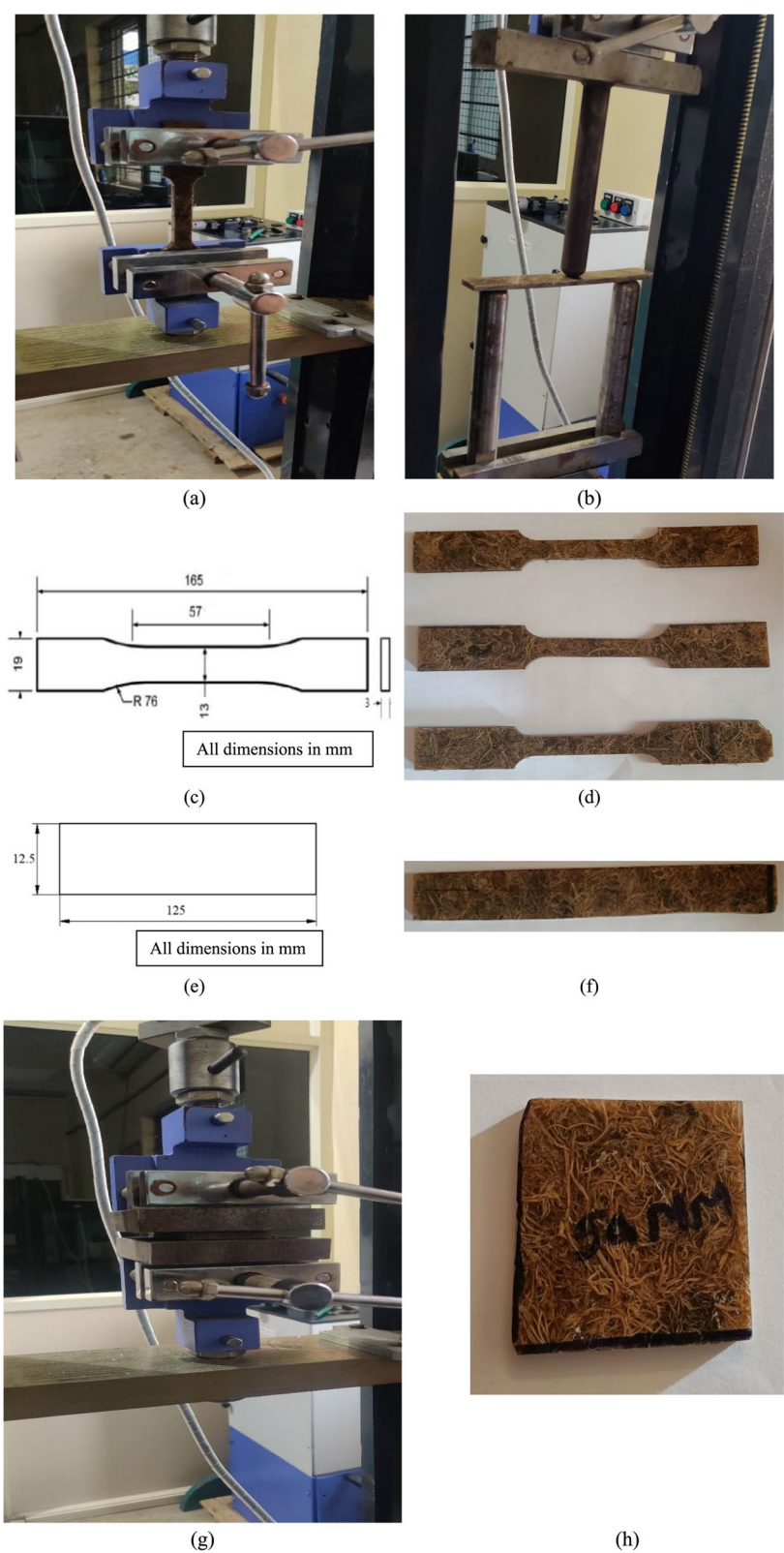
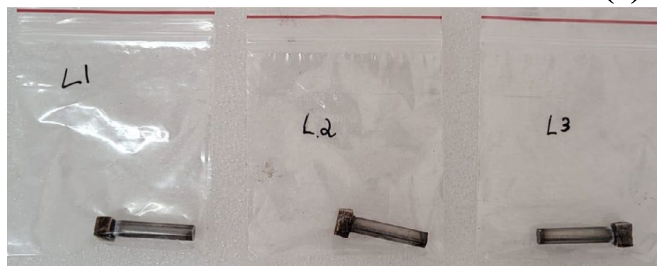


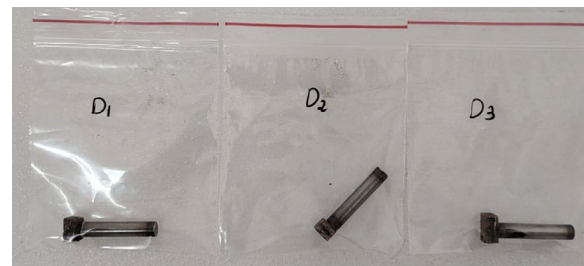
Fig. 5 **a** Tensile test apparatus **b** Flexural test apparatus **c** ASTM D638 standard tensile test specimen dimensions **d** tensile test specimen **e** flexural test specimen dimensions **f** flexural test specimen **g** compression test setup **h** compression test specimen



(a)



(b)



(c)



(d)

Fig. 6 a Pin on disc tribometer, b Specimens under varying loads, c Specimens under varying track distance covered, d Specimens under varying velocities

Material characterization

For each test, three specimens are prepared in agreement with ASTM standards, and the average of their results is recorded and presented.

The samples of tensile test are prepared as per ASTM D3039 standard. The tensile load is applied to the specimen at constant strain rate of 2 mm/min; the system calculates ultimate strength, ultimate load, and

displacement. The tensile test is carried out on an Instron make 6800 series 10 kN UTM at SJC Institute of Technology, Chickballpur, Karnataka, India. Figures 5a shows UTM and 6c & d shows tensile test specimen with all dimensions.

The bending test, conducted according to ASTM D-790, generates both tensile and compressive stresses on the test specimen, which develops shear stress along



Fig. 7 Vibration and modal analysis

the span of the specimen. To prevent specimen failure the shear stress must be minimized. This is achieved by regulating the L/d ratio, which is the ratio of the outer span length to the specimen height. The flexural test is performed using three-point bending attachments on an Instron 6800 series 10 kN universal testing machine (UTM) at SJC Institute of Technology, Chickballpur,

Karnataka, India. Figures 5b shows apparatus and 6e & f depicts the bending test specimen, which has dimensions of 125 mm in length, 12.5 mm in width, and 5 mm in thickness.

The response of a material to compressive forces applied to a test specimen is evaluated using the compression strength test, following ASTM D-695 standards. This test determines the material's strength and stiffness under crushing loads. The test was performed at SJC Institute of Technology, Chickballpur, Karnataka, India, using an Instron 6800 series 10 kN testing machine with specialized fixtures to apply compressive pressure to the specimen. A Fig. 5g & h illustrates the compression test specimen.

The wear test evaluates the durability and performance of a material under simulated application conditions,

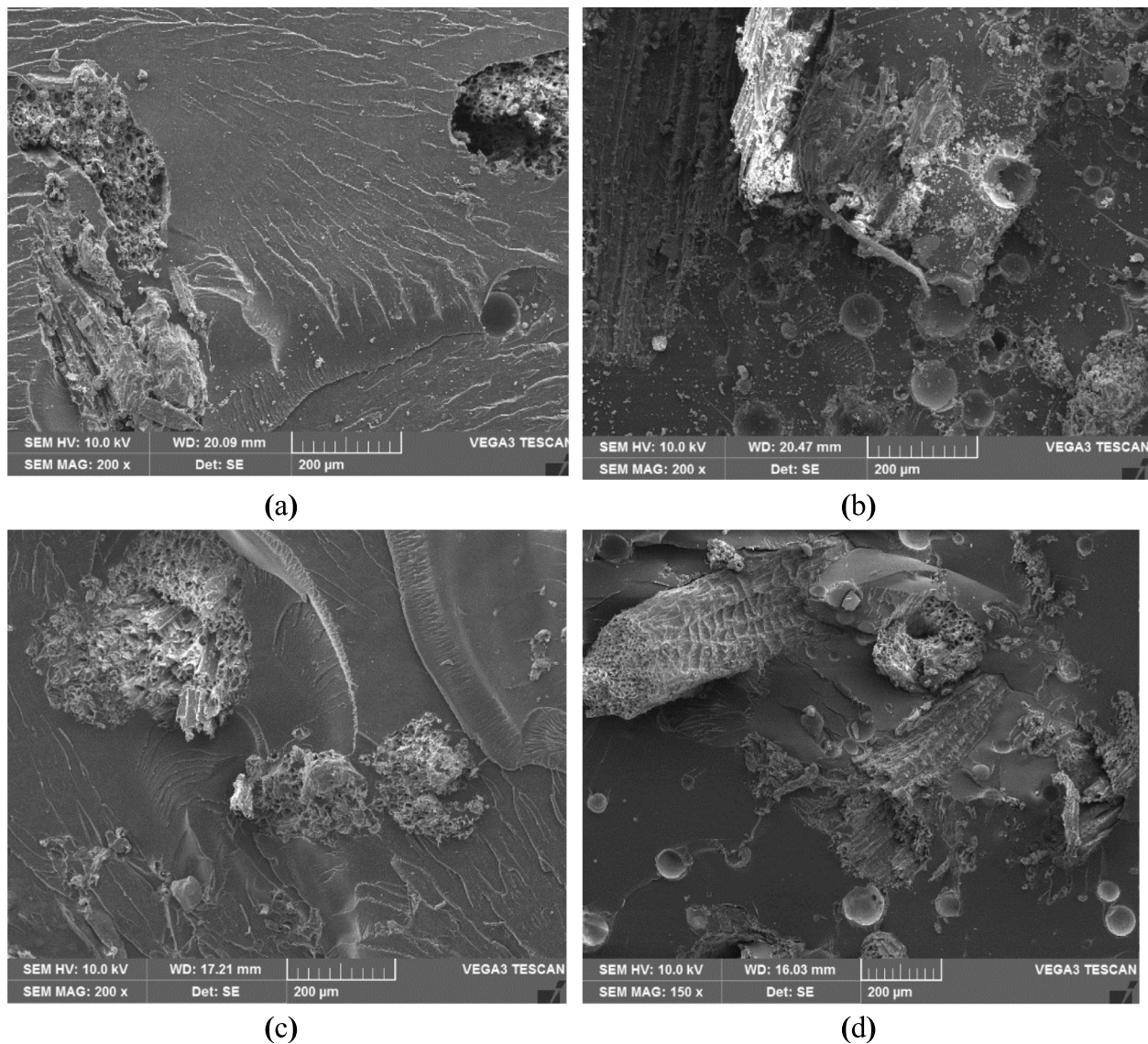


Fig. 8 Surface morphology of **a** WT30wt%S0wt%C **b** WT30wt%S10wt%C **c** HCIT30wt%S0wt%C **d** HCIT30wt%S10wt%C

following standard ASTM G99 for pin-on-disc testing, shown in Fig. 6. Specimens are prepared with precise dimensions and surface finishes as per the requirements. The specimen is mounted on a pin-on-disc test machine and interacts with a counterface material. Test parameters, including normal load, distance, and speed are selected based on Taguchi's L9 orthogonal array. Wear is quantified by measuring the mass loss after specified time duration.

Modal and vibration analyses are essential for ensuring structural safety, reliability, and performance. They identify key vibration characteristics like natural frequencies, mode shapes and damping ratios, which are crucial for maintaining structural integrity. By addressing excessive vibrations that can cause fatigue, noise, or failure, these analyses enhance performance, optimize design, and reduce maintenance costs. Vibrational analysis test rig is used to analyse, at SJC Institute of Technology, Chickballpur, Karnataka, India, shown in Fig. 7.

Results and discussion

All The test specimens were prepared according to ASTM standards. All The specimens were kept in insulating covers to avoid moisture absorption. A minimum of three samples for each material system are tested, and the average values are recorded and tabulated.

Morphological studies of composite

The surface morphology of water-treated and HCl-treated fibers was analyzed using SEM to assess the effect of chemical treatment in reducing hydrophilicity and eliminating contaminants. The longitudinal surfaces of water-treated fibres are shown in SEM images in Fig. 8a & b. The pictures suggest that the parallel set of fibres had microfibrils and a cylindrical form. Additionally, SEM pictures revealed that the fibre surface was covered with oils, waxes, and grime. Wax, oils, and other contaminants were also removed by the HCl treatment, as shown in Fig. 8c & d. Additionally, the water treatment created some surface damage and rendered the fiber's surface rough, which may have contributed to the lowering of the composite's strength. However, when the composites were made using HCl-treated fibres as reinforcement, there were not many fibre defects that could have improved performance. Similar research work was carried out by Vijay et al. (2021). The present study's future scope includes developing epoxy composites with fibres, analysing their properties in accordance with ASTM, and using the best-performing composite to create a lightweight, application focused solution.

Evaluation of tensile strength of composite

The tensile strength specimens were developed using ASTM D638 standards. The prepared specimens were

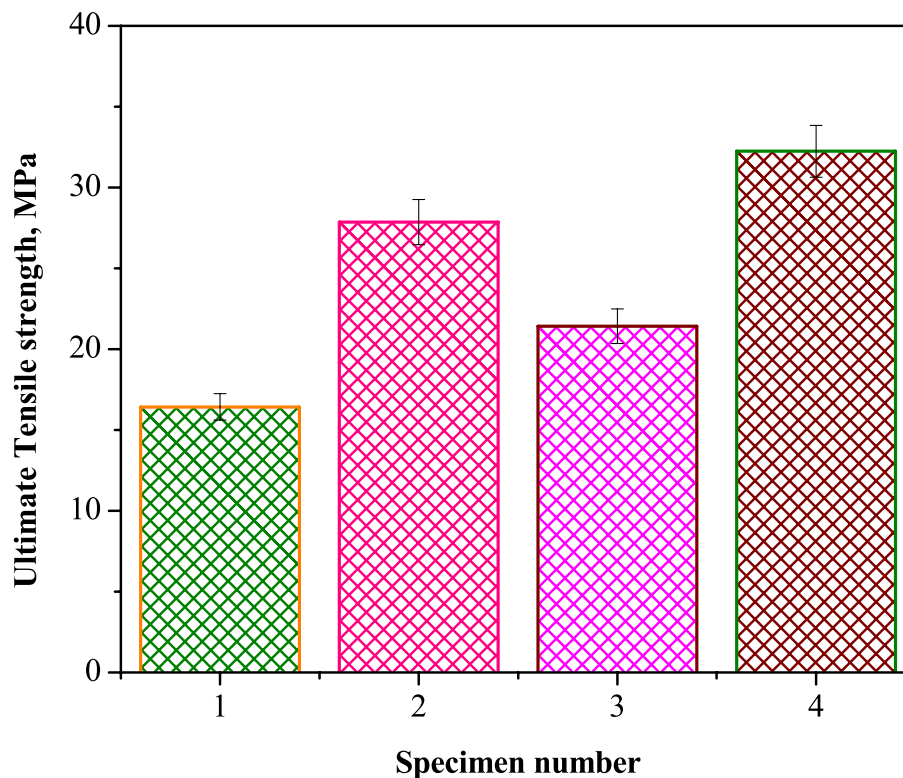


Fig. 9 Plot of UTS for different specimens to optimize composition

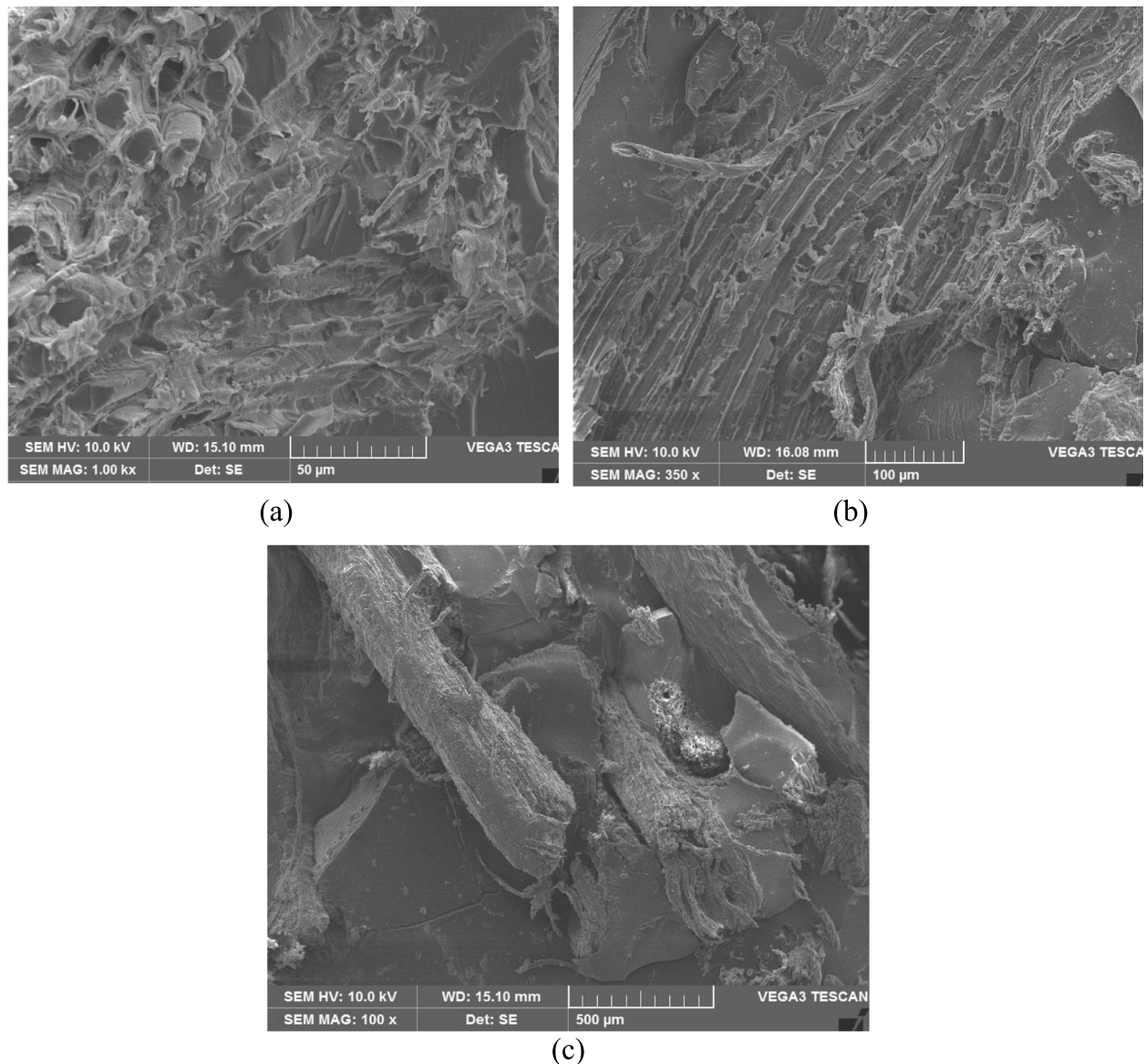


Fig. 10 Morphology of fractured surface of tensile tested samples under different magnifications

tested in universal testing machine Fig. 9 showed the ultimate tensile strength behavior of Sausage fruit fibers reinforced composites.

Crucially, if the right chemical is applied in the right concentration, the surface interlocking characteristics will improve, resulting in mechanical rigidity. Comparable results were observed in fibres treated with HCl, where the higher cellulose content are responsible for a higher strength value and a lower strain rate than in other specimens. Although the water-treated fibres were weaker because of the increased cellulose removal, which destroyed the structure and contents seen in the Fig. 10, the strain was lower than that of the water-treated fibres because of the removal of hemicellulose and lignin.

In the case of the HCl treated fibers, the ultimate tensile strength results were slightly higher than treated fibers as shown in Fig. 9. This is because higher concentrations of non-cellulose ingredients result in a higher strain rate. This behavior was consistent with the literature (Vinod et al. 2019). The variation of tensile strength for water treated and HCl treated with and without inclusion of cenosphere of sausage fruit fibers epoxy composites is given in table and shown in figure. From the table the tensile strength of water and HCl treated with and without cenosphere was found to be 16.43, 27.86 and 21.42, 32.24 MPa respectively and also the maximum tensile strength is observed for the HCl treated with cenosphere composite was found to be 32.34 MPa. From the results it will be concluded that chemical treatments can improve

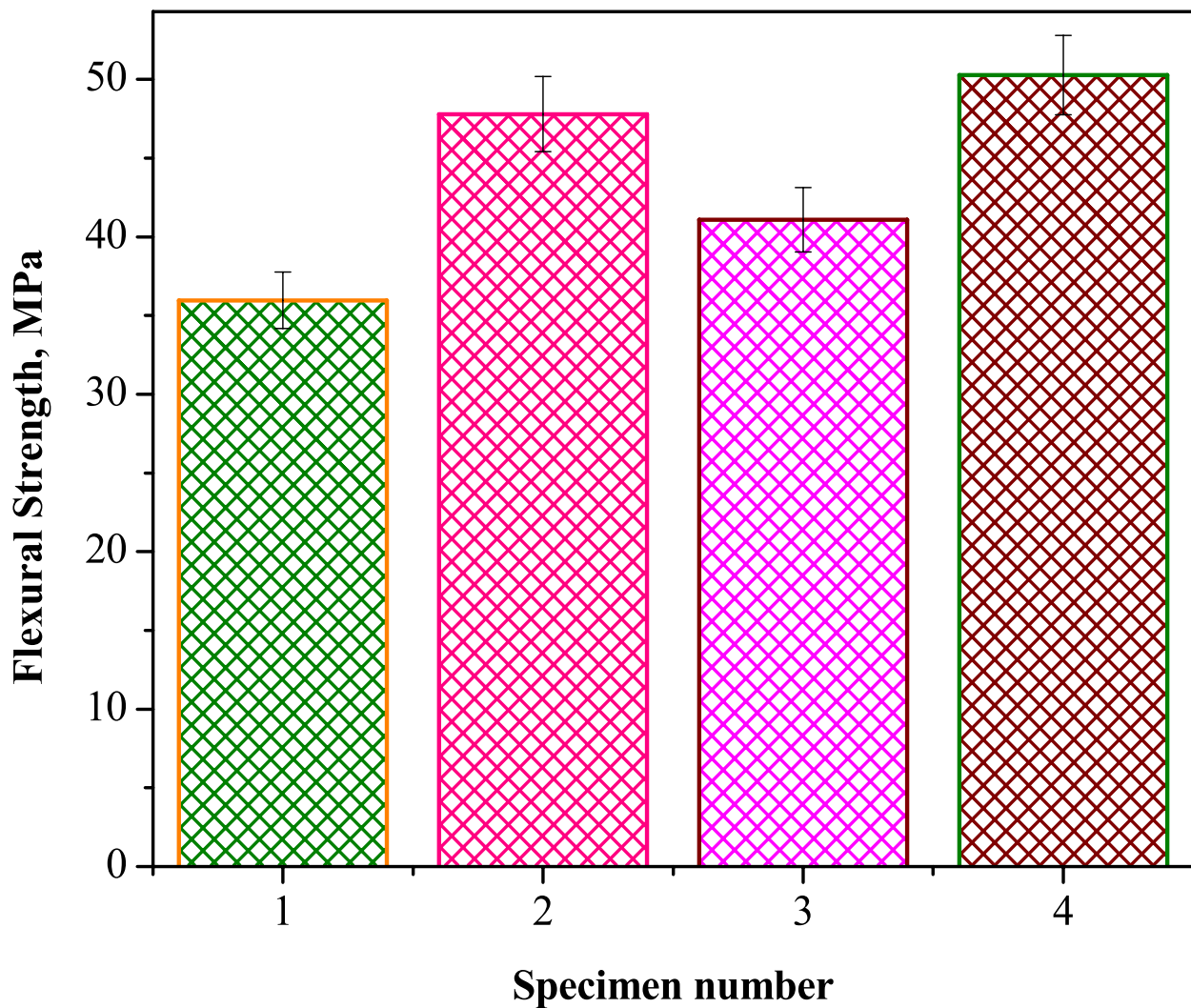


Fig. 11 Plot of flexural strength for different specimens to optimize composition

the fiber's chemical properties, which helps it bond with the matrix and enhances the properties of the composites by 10 to 15%. The results obtained are in line with the investigation carried out by Dalbehera et al. (2016), Vijay et al. (2021) and Singh (2025).

The increase in mechanical strength of the *Kigelia Africana* fiber-reinforced epoxy composites is attributed to the high cellulose content and microfibrillar structure of the fibers, combined with chemical treatment that removes surface impurities and non-cellulosic constituents. HCl and bleaching treatments improve fiber surface roughness, cellulose exposure, and interfacial adhesion, enabling efficient load transfer and enhanced resistance to crack propagation.

In order to assess the fiber-matrix interfacial adhesion and comprehend the fiber-matrix failure processes, the morphology of the broken surfaces of tensile fractured samples was examined using micrographs obtained from scanning electron microscope (SEM). Figure 10 show that incorporating spherical cenosphere into the matrix

matrix of sausage fruit fiber-reinforced composites facilitates tensile load transmission along the cenosphere's spherical surface. The result is to improve the composite's tensile characteristics and decrease the propagation of fractures along the matrix material, which is in line with the outcomes of Hegde et al. (2024).

Evaluation of bending strength of composite

The bending test specimens are prepared according to ASTM D 790 and the dimensions of specimens are $125 \times 24.5 \times 5$ mm.

The three-point bending test on the sausage fruit fiber-reinforced composites, with and without cenosphere, was investigated. The variation in flexural strength is presented in Fig. 11 Incorporating sausage fruit fibers into the epoxy resin significantly enhances the composite's strength. According to the data, the flexural strength of water-treated and HCl-treated fiber composites is 35.96 MPa and 41.08 MPa, respectively. When combined

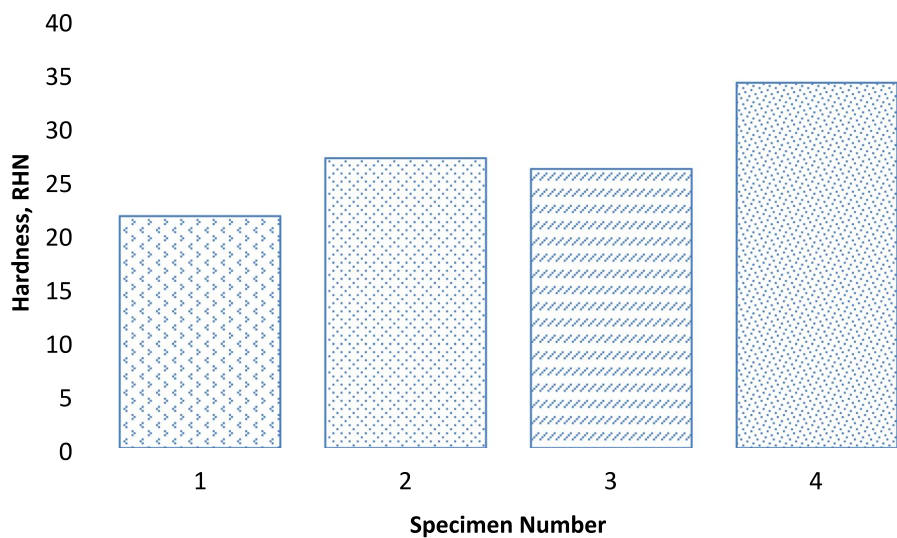


Fig. 12 Hardness plot for specimens

with cenosphere particles, these values increase to 47.79 MPa and 50.28 MPa. The highest flexural strength of 50.28 MPa was recorded for the HCl-treated fiber composite with cenosphere particles. The capacity of cenosphere fillers to absorb compressive stresses is responsible for the samples’ increased flexural strength and modulus. Compressive stresses during bending tests may be transferred straight to the cenosphere surfaces due to the strong adhesion between the epoxy and

cenosphere. A large amount of the bending stress is absorbed by the porous cenosphere particles, improving the samples’ flexural characteristics. Additionally, when 10 wt% cenosphere was added to the hybrid composite, minimal stretching and bending of sausage fruit fibers were observed without breaking, as shown in Fig. 11. This further supports the improvement in hybrid composite strength due to cenosphere addition. Similar findings have been reported by other researchers,

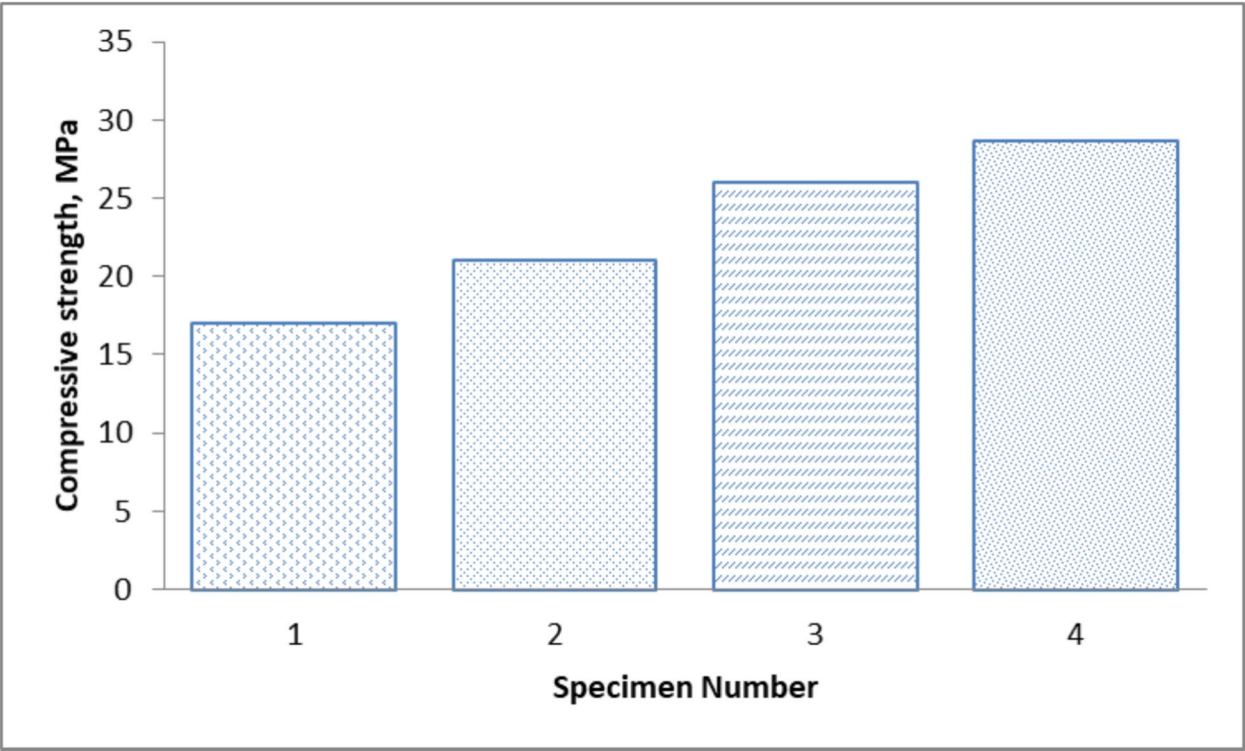


Fig. 13 Compressive strength plot for specimens

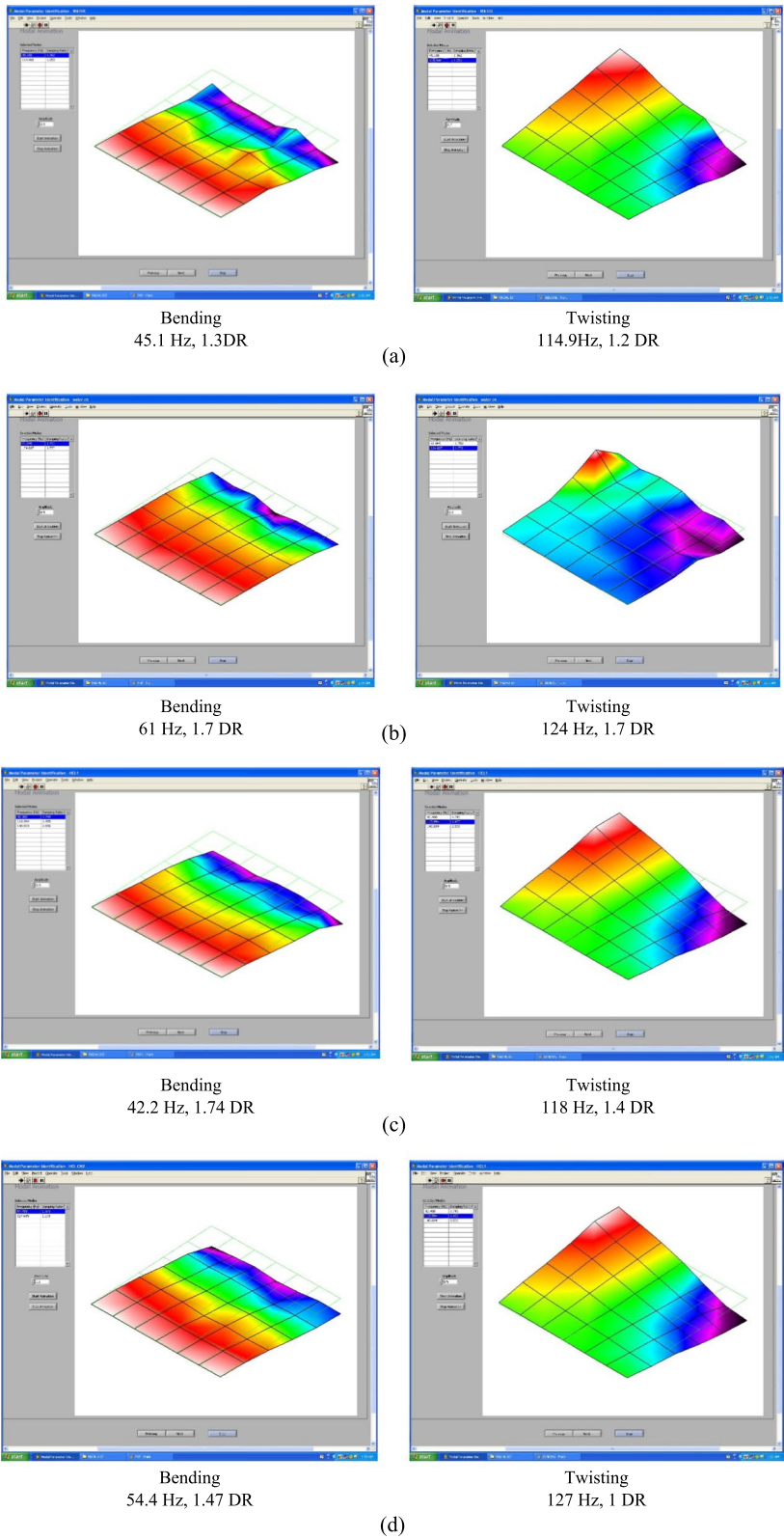


Fig. 14 **a** Water treated without cenosphere **b** Water treated with cenosphere **c** HCl treated without cenosphere **d** HCl treated with cenosphere

Table 3 Design matrix showing parameters and their levels

Parameters		Unit	Level I	Level II	Level III
Sliding distance	SD	m	1000	2000	3000
Load	P	N	25	50	75
Sliding velocity	SV	m/s	0.5	1.0	1.5

aligning with this study's results (Satapathy and Patnaik 2004).

Evaluation of hardness of composite

The ability of a surface to withstand abrasion or indentation from mechanical forces is known as its hardness. Greater wear resistance and a lower friction coefficient are indicated by higher hardness levels. The Rockwell test method, as per ASTM E-18 standards were conducted on the specimens.

From the test, the hardness of the water treated fiber and HCl treated fiber composite is found to be 21.6 and 26 whereas the hardness of water treated fiber and HCl treated fiber with cenosphere particles were found to be 27 and 34, respectively. From the Fig. 12 the maximum hardness of 34 RHN was observed for composite of HCl treated fiber with cenosphere particles. The hardness of the samples increased with the addition of cenosphere, attributed to the reduced void content. The 10% cenosphere sample exhibited the lowest void percentage. The hardness values improved as void content decreased, indicating a uniform distribution of cenosphere particles within the epoxy matrix (Santulli et al. 2022). It is evident that small size cenosphere was contributed to a lower value of density (Rohatgi and Guo 1998) and hence the hardness is increased to a greater extent as shown in Fig. 12.

Evaluation of compressive strength of composite

The results indicate that fibers significantly enhance compressive strength, consistent with the improvements observed in tensile and flexural tests. Specifically, incorporating fibers into the matrix increased compressive strength by 68.8%. Figure 13 presents the compressive strength plot for the tested specimens.

Evaluation of vibration and modal analysis

A useful technique for determining a structure's dynamic properties is modal analysis. At its resonance frequency, every structure vibrates with large amplitude. Every part of a machine must meet its design specifications in order to avoid an unreported failure. By forecasting the dynamic behavior of the structure under various operating conditions, the modal analysis technique can do this. For applications where components are subjected to dynamic loads, cyclic stresses, or operating vibrations, particularly in biomedical assistive devices, prosthetic support structures, and lightweight structural components, such analysis is crucial. The vibrational analysis test rig shown in Fig. 7, is used to carryout dynamic analysis to find the critical frequencies and modes are extracted from Lab View+ software. The dimensions of a square laminate with $200 \times 200 \times 5$ mm width and length are prepared for the test. From the results, it was observed that the natural frequencies under bending and twisting modes of the water treated composites without and with cenosphere were 45.1 and 114.9 Hz, and 61 and 124 Hz, respectively. Also, for the HCl treated composites without and with cenosphere, bending and twisting natural frequencies were found to be 42.2 and 118 Hz and 54.4 and 127 Hz, respectively. It was reported that the structural stiffness required maintaining stability also generally increases with increase in frequency, which was found under HCl treated with the incorporation of cenosphere which leads to increased stiffness and improved load-bearing capability of the composite material. The increase in natural frequencies observed in fiber-reinforced specimens is attributed to improved elastic modulus and enhanced fiber matrix bonding resulting from chemical treatment of *Kigelia Africana* fibers. Chemical treatments improve stress transfer and raise elastic modulus by exposing cellulose fibrils and removing surface contaminants. When compared to water treated composite, this increase in stiffness causes higher natural frequencies. In the present study, the increase in damping ratio observed in fiber and cenosphere-reinforced epoxy composites can be

Table 4 Specific wear rate for predefined input wear process parameters

Wear test parameters							Specific wear rate *10 ⁻⁴ mm ³ /N-m
Trail No	Coded values			Actual values			
	SD	P	SV	SD	P	SV	
1	-1	-1	-1	1000	25	0.5	5.87×10 ⁻⁴
2	0	-1	-1	1000	50	1.0	7.76×10 ⁻⁶
3	+1	-1	-1	1000	75	1.5	3.02×10 ⁻⁴
4	-1	-1	0	2000	25	0.5	2.71×10 ⁻⁴
5	0	-1	0	2000	50	1.0	2.524×10 ⁻⁵
6	+1	-1	0	2000	75	1.5	2.92×10 ⁻⁴
7	-1	-1	+1	3000	25	0.5	1.36×10 ⁻⁴
8	0	-1	+1	3000	50	1.0	4.415×10 ⁻⁴
9	+1	-1	+1	3000	75	1.5	2.76×10 ⁻⁴

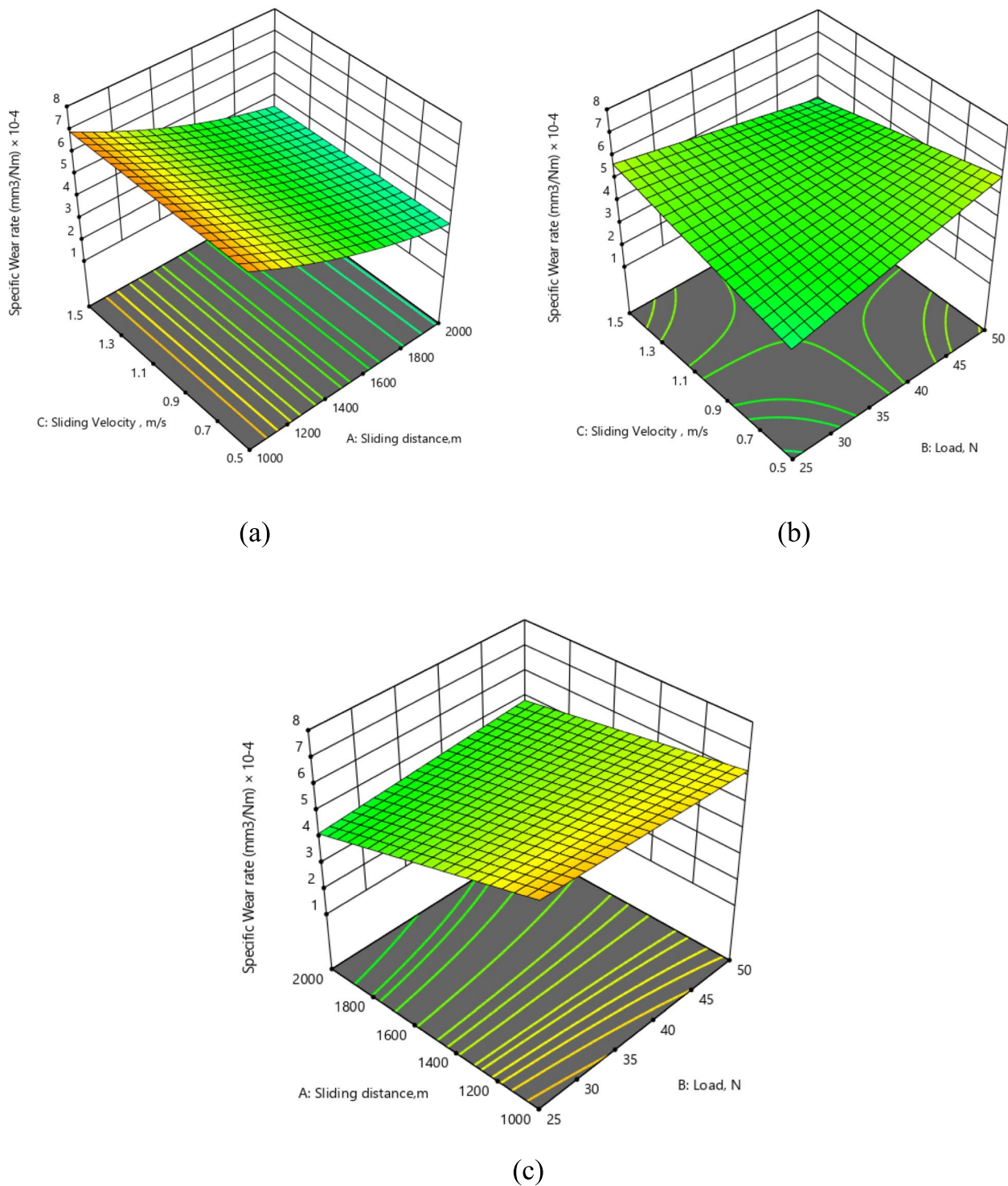


Fig. 15 Interaction effect of specific wear rate, sliding distance and load

attributed to enhance energy dissipation mechanisms, including micro sliding at the fiber matrix interface, viscoelastic behavior of the epoxy, and stress wave scattering caused by the presence of hollow cenospheres. These

mechanisms interrupt vibration transmission and reduce resonance amplitude, thereby improving damping performance. Figure 14 demonstrates twisting and bending modes for all the specimens.

Evaluation of wear characteristics

A pin-on-disk wear test was conducted on the composite samples. The rotating disk was set to 275 rpm with a diameter of 100 mm for a specified duration. The load, sliding velocity, and sliding distance were determined based on the L9 orthogonal array shown in Tables 3 and 4.

The wear rate of the samples was calculated as a function of weight loss at a predetermined sliding distance and velocity on a Pin on disk wear test apparatus.

The above Fig. 15 describes the response surface for the specific wear rate (SWR) as a function of wear parameters, including sliding velocity, load, and sliding distance. Increasing the applied load causes the pin to rub more firmly on the steel plate, which raises the SWR. The SWR of composites is also influenced by the percentage of reinforcement; reinforcement in the matrix reduces wear rate by acting as a barrier. The interaction effect of sliding velocity and sliding distance on SWR is shown in Fig. 15a. Higher sliding velocities have a major effect on SWR at lower sliding distances. A crucial factor in the wear process is sliding velocity; lower sliding velocities result in lower SWR, which progressively rises with increasing velocity. The effect of load and sliding velocity on SWR (mm^3/Nm) is depicted in Fig. 15b. SWR steadily grows as the load does. The wear rate is mostly determined by the combined effects of sliding velocity and load. The effect of sliding distance and load on SWR is shown in Fig. 15c. SWR decreases with lower loads and then sharply rises with greater loads. When the reinforcing layer is visible during sliding, it serves as a barrier, lowering the wear rate by minimizing the area of contact between the two surfaces. At higher loads, the SWR of composites increases sharply but decreases with the inclusion of fibers. The increase in specific wear rate of *Kigellia Africana* fiber reinforced epoxy composites is primarily attributed to fiber matrix interfacial debonding, fiber fracture, and third body abrasion caused by detached fiber debris. While the fibers contribute to load sharing, their lower abrasion resistance and increased surface roughness lead to enhanced material removal under sliding conditions.

Conclusions

This study demonstrates the potential of *Kigelia Africana*, as effective eco-friendly reinforcement in composite materials. The following conclusions were reached after a thorough evaluation:

1. The composites exhibited maximum tensile strength of 32.24 MPa for HCl treated fibers with cenosphere, also an enhancement of tensile strength was found to be 96% due to improved interfacial bonding with the polymer matrix.
2. From the flexural test, it is observed that a maximum bending strength of 50.28 MPa with the inclusion of cenosphere under HCl treated conditions, which is nearly 39.8% enhancement without inclusion of cenosphere. Hence it is revealed that the laminates possess good flexural strength and stiffness, suitable for load bearing applications.
3. The laminates demonstrated satisfactory hardness values, attributed to the rigid structure of *Kigelia Africana* fibers. Fiber volume fraction and uniform distribution significantly influenced the hardness of 34 RHN; it is about 57% higher as compared to other combinations.
4. According to vibrational study, the laminates have strong damping qualities, which make them appropriate for applications where vibration control is essential. Improved energy absorption and vibration attenuation were made possible by the natural fibres.
5. The Response Surface Methodology (RSM) analysis's findings showed that the reduction in specific wear rate at a load of 25 N, a sliding distance of 3000 m, and sliding velocity of 0.5 m/s.
6. Finally it can be concluded that, the fibers from *Kigelia Africana* fruit can be used to make composite materials which are applicable for low load carrying capacity in many fields.

Authors' contributions

Conceptualization, B.E.R, A.B.M.A; Writing—Review and Editing, C.A, R.P; Methodology, A.R, A.S; Formal analysis, Y.D.J, A.A.H.K;

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Data availability

The data that supports the findings of this study are available within the article.

Declarations

Competing interests

The authors declare no competing interests.

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