Mechanical, Morphological and Wear Resistance of Natural Fiber / Glass Fiber-based Polymer Composites

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Natural fibers along with glass fibers were used as the reinforcement of an epoxy matrix for the betterment of mechanical and wear applications. The combination of overall wt% up to 20 resulted in 23.8 MPa of tensile strength compared to 15.5 MPa for untreated fibers. The wt% of areca fiber (AF) (20 wt%)/glass fibers (GF) (20 wt%) with 5% alkali treatment yielded a maximum tensile strength up to 62.6% in comparison to untreated fiber at lowest percentage of 10 wt%. The increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation. The alkali treated fibers, untreated fiber combinations achieved 33.8% and 26.8% improvement with impact properties. A decrease in the wear loss was shown with the increase in wt% of hybrid fiber incorporation from 20 to 40 wt%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influenced with applying higher loads. The frictional rate was highly increasing with increase in hybrid fiber wt% and also with higher loads applied. The SEM results for treated 20 wt% AF+20 wt% GF with hybrid fiber incorporation observed better results due to improved adhesion of fiber with matrix phase.

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INTRODUCTION

Natural fibers are getting vital attention in the current global condition due to their biodegradability, low cost, better mechanical properties, and lesser environmental threats. These natural fibers from various waste are used as the filler or reinforcement in enhancing the properties of thermoplastics and thermosetting plastic composites (Mittal *et al*. 2016; Patel and Parsania 2017; Khan *et al*. 2018; Rahman *et al*. 2019). This method will not only reduce the natural waste but also reduce the utilization of plastics, which is highly welcoming. Research and innovations are carried out in development of existing field of polymer composites for betterment in automobile, aerospace, medical implants, flame retardant, corrosion resistance, and other various applications (Sheykh *et al*. 2017; Muhammad *et al*. 2019; Oushabi 2019). The natural fibers were extracted from coconut shell, banana plant, sisal plant, pineapple leaf, kenaf, ramie, flax, *Aloe vera etc*. (Palanisamy *et al*. 2021; Almeshaal *et al*. 2022; Sumesh *et al*. 2023). Lignocellulosic fibers were incorporated with epoxy, polyethylene, polypropylene, polystyrene, and polyamide for enhancing the matrix properties. Synthetic fibers such as glass, carbon, kevlar fibers, *etc*., are used abundantly for high end application. The ecological problems such as global warming, and water and soil pollution reduce the usage of this (Nirmal *et al*. 2015; Chegdani *et al*. 2018; Senthilkumar *et al*. 2019; Todkar and Patil 2019).

The incorporation of hybrid natural fiber composites from sisal and coir enhanced the tensile, flexural, and impact strength of epoxy-based composites. Fiber weight percentage of 35 showed the better results (Sumesh and Kanthavel 2020; Ashraf *et al*. 2023). Hybrid fiber combination of glass and sisal with epoxy resin showed better results at overall wt% of 40 (Ramamoorthy *et al*. 2015; Junaedi *et al*. 2023). Hybrid natural fiber combination observed better mechanical properties due to better distribution of fibers in matrix with good adhesion of fiber with matrix phase (Arthanarieswaran *et al*. 2014; Karuppiah *et al*. 2022; Kar *et al*. 2023; Palanisamy *et al*. 2023b). It was observed that increasing the fiber percentage and adding nano clay particles to an epoxy/glass composite improved the tensile characteristics. The flexural strength of glass epoxy composites was also shown to be improved by adding nano clay to them (Jeyakumar *et al*. 2017; Basha *et al*. 2023). The hybrid natural fiber combination with banana and pineapple decreases its tensile, flexural property by overall incorporation of fiber at 50 wt% (Swolfs *et al*. 2014; Nopparut and Amornsakchai 2016; Palanisamy *et al*. 2024). Hybrid natural fibers using flax/glass/epoxy also enhanced the tribological behavior of the composites with low wear loss. In the dry sliding wear test using natural fiber composites, natural fiber combination and applied load factor has the highest significance in contributing to the wear properties (Chegdani *et al*. 2016; Johnson *et al*. 2019). Fiber addition more than the optimum range will inversely affect the mechanical and wear properties of epoxy-based composites (Singha and Thakur 2008; Nirmal *et al*. 2012; Shuhimi *et al*. 2016; Kumar *et al*. 2019). It was also observed that lignocellulosic fiber has its better application by adding the fibers in equal weight percentages (Satheesh Kumar *et al*. 2010; Liu *et al*. 2019; Nanda and Satapathy 2021; Hanan *et al*. 2023). The areca natural fibers up to 20 wt% observed better mechanical properties with epoxy-based composites (Johnson 2019). The surface treatment using NaOH had a significant contribution in adding to the tensile properties of areca/epoxy based polymer composites (Khan 2018).

The hydrophilic nature of the natural fibers is a bigger drawback that declines the properties of the polymer-based composites. Surface treatments such as NaOH, KOH, bleaching, and isocyanates reduce the water absorption property and enhance its applications. NaOH or alkali treatment is used in most with the natural fibers due to its effectiveness. Alkali treatment will remove the wax and dust particles from the fiber surfaces, which will enhance the adhesion with plastic composites (Santulli *et al*. 2023). The treatment also improves the cellulose richness in the fiber, thereby increasing the crystallinity in the combination (Gupta *et al*. 2016; Abdul Khalil *et al*. 2017; Maurya *et al*. 2017; Aslan *et al*. 2018; Oushabi 2019; Rajeshkumar 2021). The research work related to the combination of areca fiber, glass fiber with epoxy resin is lesser. In this work, mechanical, wear and morphological evaluations of areca fiber/glass fiber/epoxy resin matrix were discussed with the influence of multiple fibers, NaOH treatment.

EXPERIMENTAL

Materials

Areca is the natural fiber (Go green products, Tamilnadu, India) used in this work. S-glass fiber (Seenu and Co, Tamilnadu, India) was used as the synthetic fiber to improve the property of epoxy resin (LY556 grade) (Seenu and Co, Tamilnadu, India). Areca fiber had 0.7 to 0.8 g/cm^3 density, tensile strength of 147 to 322 MPa, and Young's modulus of 1.124 to 3.16 GPa. Hardener (HY951 grade) was added with epoxy resin at 1:10 ratio for proper mixing. Areca fiber and samples after fabrication are shown in Fig. 1. The S-glass fiber is a high strength glass fabric consisting of 4750 MPa of tensile strength, density of 2.49 g/cm^3. It has excellent abrasion resistance when used as a composite reinforcement material. All results were taken after the chemical composition testing of individual fibers. The natural fiber was treated with NaOH to reduce the water absorption and impurities present in the fiber. The NaOH pellets (0, 3, 5, and 8 wt%) were diluted in 1000 mL of distilled water, and natural fibers were soaked into it for 4 h at room temperature (Sivasubramanian *et al*. 2021).

Fig. 1. a) Areca fiber, b) areca fiber/glass fiber composite

Table 1. List of Hybrid Combinations

Composite Code	Treatment	Combination	Density (g/cm^3)
A1	5 wt% NaOH treated (T)	10 wt% AF/10 wt% GF	1.42
A2	Untreated (NT)	10 wt% AF/10 wt% GF	
B1	5 wt% NaOH treated (T)	15 wt% AF/15 wt% GF	1.54
B2	Untreated (NT)	15 wt% AF/15 wt% GF	
C1	5 wt% NaOH treated (T)	20 wt% AF/20 wt% GF	1.68
C2	Untreated (NT)	20 wt% AF/20 wt% GF	
D1	5 wt% NaOH treated (T)	25 wt% AF/25 wt% GF	1.64
D2	Untreated (NT)	25 wt% AF/25 wt% GF	
C3	5 wt% NaOH treated (T)	10 wt% AF/20 wt% GF	1.61
C4	5 wt% NaOH treated (T)	30 wt% AF/20 wt% GF	1.62
C5	5 wt% NaOH treated (T)	40 wt% AF/20 wt% GF	1.65
C6	3 wt% NaOH treated (T)	20 wt% AF/20 wt% GF	1.68
C7	8 wt% NaOH treated (T)	20 wt% AF/20 wt% GF	1.68
C8	Neat Epoxy Resin		1.16

After the required time, fibers were washed in distilled water to remove excess NaOH. Fibers were dried in sunlight for 48 h. To fully dry the fibers, they were heated in an oven for 3 h at 70 °C. The same procedure was followed in previous work (Sumesh and Kanthavel 2020). Finally, the dry fibers were cropped to a fiber length of 30 mm.

Fabrication

The areca and glass fibers were weighed using a weighing scale for different weight ratios of composition plate. A hand laying technique is used for the fabrication of composites with epoxy and hardener mixed at a 10:1 ratio. The required fibers were fixed in a square mould of 200×200×6 mm dimension. Epoxy resin along with hardener was poured into it and mixed well. A total of thirteen combinations with areca/glass fibers were used in this research with and without alkali treatment. The list of hybrid combinations is shown in Table 1.

Mechanical Testing

The universal testing machine (UTM) was used for finding tensile properties and flexural properties of epoxy-based composites. The tensile testing was calculated using ASTM D638-14 standard with gauge length 50 mm and crosshead speed of 5 mm/min (Sumesh and Kanthavel 2020). The test was performed using displacement control method. Similarly flexural and impact test followed ASTM D790-17, ASTM D256-10 standards (Karuppiah *et al*. 2020; Sumesh and Kanthavel 2020, 2022). Three-point bend testing was used for finding the flexural properties with span to depth ratio at 16:1 and crosshead speed of 2 mm/min. The impact test was used for finding the energy absorbed by the specimen with a notch width of 2.5 mm. All the results were plotted using Originpro 8.5 software.

Wear Testing

A pin on disc machine was used for detecting wear resistance and coefficient of friction for natural hybrid composites with ASTM G 99 standard. The EN 31 steel counter disc was used for this testing, polished with SiC abrasive paper of grade 1200, followed by areca composites with grade 800 polishing. Here in the experiment the applied load was changed from 10, to 15, to 20 N with constant sliding distance of 500 m and sliding speed 0.5 m/sec for finding the results.

SEM, XRF, and FTIR Testing

The SEM testing (Carl Zeiss EVO 18) was taken for finding the distribution of fibers in epoxy resin before and after performing the wear test. The influence of fiber distribution in matrix and applied load influence with combination will be detected here. Gold sputter coating was performed for passing electron beams through non-conducting samples (Palanisamy *et al*. 2023a). The SEM results were taken after the whole wear testing from 10 to 20 N applied load, by dipping in liquid nitrogen to get brittle sample and then breaking the composite sample. These broken samples were taken for SEM analysis. The tensile and impact testing setup is shown in Fig. 2. The X-ray fluorescence spectroscopy (XRF) testing was undertaken for finding the chemical composition in the composite sample. It is an S4 Bruker model machine having specifications of X ray tube collimators with 4 Kw Rh, 0.34 to 0.45°. The Fourier transform infrared testing was done using an NEXUX 6800-50 machine having spectral resolution 2 cm^{-1} and wave number ranging from 500 to 4000 cm^{-1} for detecting the functional groups evolved in areca fibers with surface treatment of NaOH.

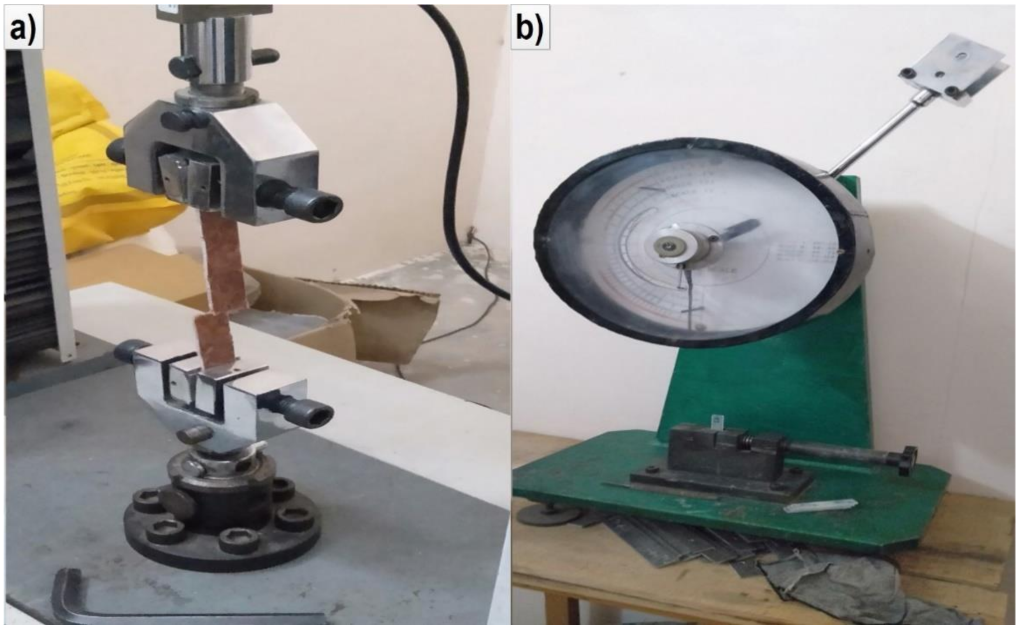

Fig. 2. a) Tensile testing, b) Impact testing Setup with hybrid natural fiber composites

RESULTS AND DISCUSSION

Tensile Testing

The tensile strength of the areca fiber/glass fiber/epoxy resin combination exhibited significant improvement in the strength with hybrid fiber incorporation and 5% alkali treatment (Fig. 3a). The initial combination of areca fiber (10 wt%)/glass fibers (10 wt%) observed 23.8 MPa of tensile strength compared to untreated fibers with 15.5 MPa. The overall wt% up to 40% with 5% alkali treatment showed maximum tensile strength up to 41.4 MPa. The same combination with untreated areca fibers showed a tensile strength of 27.3 MPa. The alkali treatment removes the wax and other waste from the natural fiber, which brings better compatibility with glass fiber/epoxy resin combination (Ramamoorthy *et al*. 2015). Tensile strength observed maximum properties at hybrid natural fiber combination at 40 wt% (Swolfs *et al*. 2014; Abdul Khalil *et al*. 2017). Increase in hybrid fiber incorporation improved the tensile strength from 15.5 to 27.3 MPa in untreated natural fibers. Increase in the fiber incorporation provided an even distribution of fibers in the epoxy resin matrix that enhances the tensile properties (Gupta *et al*. 2016; Aslan *et al*. 2018). Alkali treatment provided surface roughness to the fibers with less hydrophilic nature, which created good adhesion with an epoxy/hybrid fiber phase (Swolfs *et al*. 2014; Khan *et al*. 2021). Tensile modulus was enhanced with the increase in hybrid fiber incorporation of areca and glass fibers with overall wt% up to 50 (Fig. 3b). The tensile modulus is highly associated with the reinforcement addition (Todkar and Patil 2019). This property also showed decline in the value with the untreated natural fiber composites. Untreated fibers provided non homogenous distribution with high surface deformation, which can result in a decrease in the mechanical properties of epoxy-based composites (Nirmal *et al*. 2015). The tensile strength of epoxy resin was found to be 21.2 MPa, whereas most of the combinations showed better results than that.

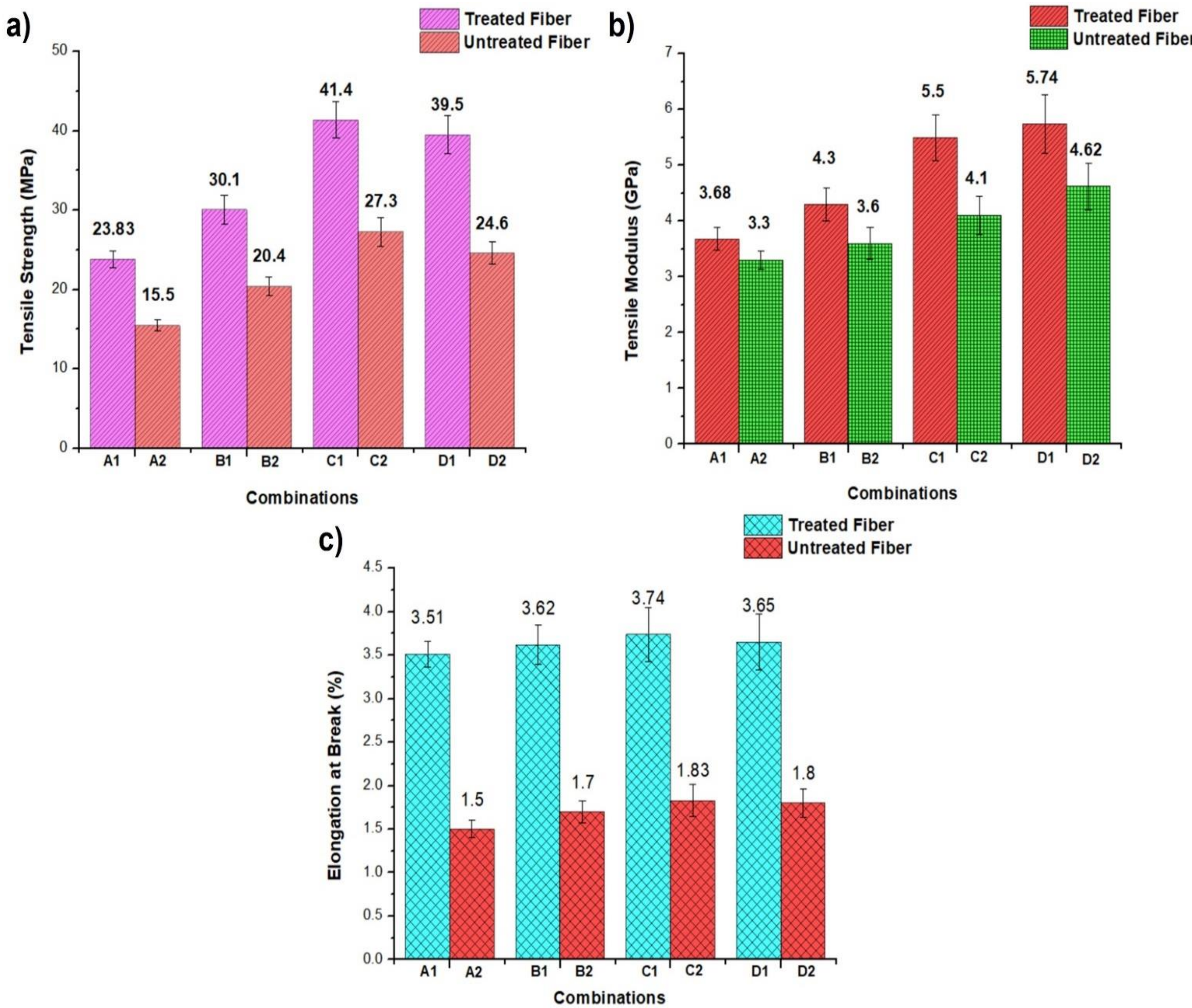

Fig. 3. a) Tensile Strength (TS), b) Tensile Modulus (TM) and c) Elongation at Break for Hybrid Epoxy based composites

Elongation at break did not change much with the increase in hybrid fiber incorporation with epoxy-based matrix (Fig. 3c). Similar to other results, non-treated fibers showed lower percentage values. The surface abnormalities in the untreated areca fiber combination resulted in low elongation at break.

Flexural Testing

The flexural strength of areca/glass fiber/epoxy resin combinations observed significant increase in the properties with fiber mixing (Fig. 4a). The lignocellulosic fibers with areca have cellulose, hemicellulose and lignin content that add to the mechanical properties of the composites (Maurya *et al*. 2017; Kurien *et al*. 2023). The alkali treatment with 5% NaOH created a barrier formation in the fibers which reduced water absorption properties of natural fibers (Sumesh and Kanthavel 2020; Rajeshkumar 2021). Glass fiber in combination with epoxy resin resulted in a significant improvement in the flexural strength of polymer composites (Ramamoorthy *et al*. 2015). The alkali-treated fibers at overall fiber wt% of 20 observed an increase from 38.9 to 52.4 MPa. This increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation (Swolfs *et al*. 2014; Khan *et al*. 2021). The treated (5%) natural fiber combinations observed maximum flexural strength of 74.6 MPa, in comparison to untreated natural fiber combination of 60.9 MPa. Fiber/matrix bonding, homogenous distribution of fiber these two factors must be better for enhancing the flexural strength of polymer composites (Sumesh and Kanthavel 2022). The flexural modulus observed significant improvement with alkali treatment and reinforcement incorporation in epoxy-based composites (Mittal *et al*. 2016). The maximum flexural modulus of 6.73 GPa was observed in alkali treated 25 wt% AF/25 wt% GF combination (Fig. 4b). The flexural strength of epoxy resin was found to be 44.8 MPa, whereas most of the combinations showed better results than that.

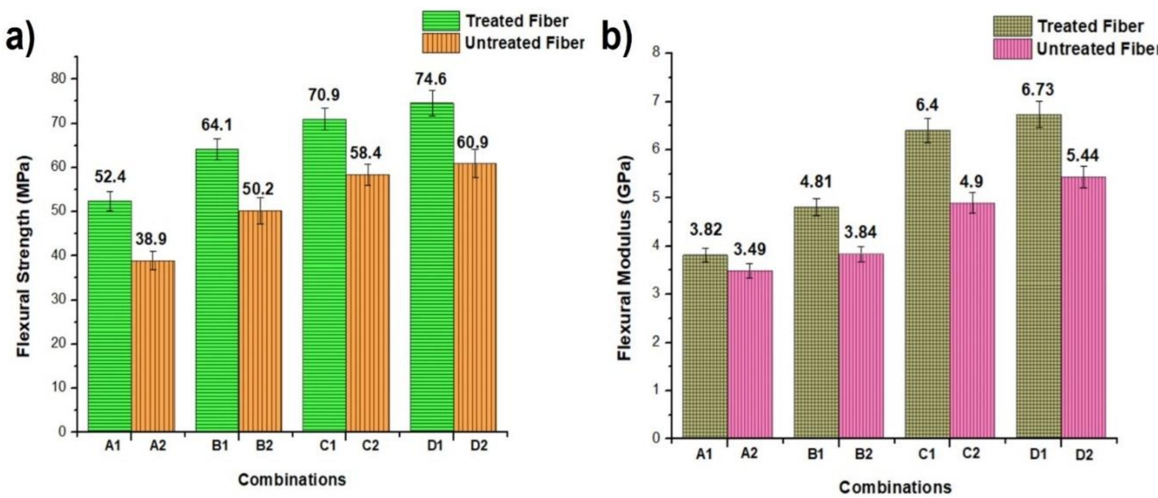

Fig. 4. a) Flexural Strength (FS), Flexural Modulus (FM) of Hybrid Natural Fiber Composites

Impact Testing and Hardness

The impact strength of epoxy matrix composites did not exhibit a high dependency on different factors in comparison to tensile and flexural strength (Fig. 5a). The impact strength results showed better improvement with the hybrid fiber mixing and alkali treatment with natural fibers (Rajeshkumar 2021; Goutham *et al*. 2023). The overall fiber incorporation from 20 to 40 wt% observed better properties. Higher fiber incorporation created high fiber debonding, fiber cracks, and similar surface deformations that declined the impact strength of the polymer composites (Sumesh and Kanthavel 2020; Karuppiah *et al*. 2022). The alkali treated fibers and the untreated fiber combinations observed 3.02 to 4.56 kJ/m^2 and 2.54 to 3.47 kJ/m^2 of impact properties, respectively. The hardness properties of epoxy-based composites increased with treatment and fiber incorporation (Fig. 5b). The maximum hardness was observed with 25 wt% AF/25 wt% GF/epoxy combination with alkali treated fibers. Hardness is highly influenced by the quality of bonding of fiber/matrix phase in epoxy-based composites (Ramamoorthy *et al*. 2015; Sumesh and Kanthavel 2022).

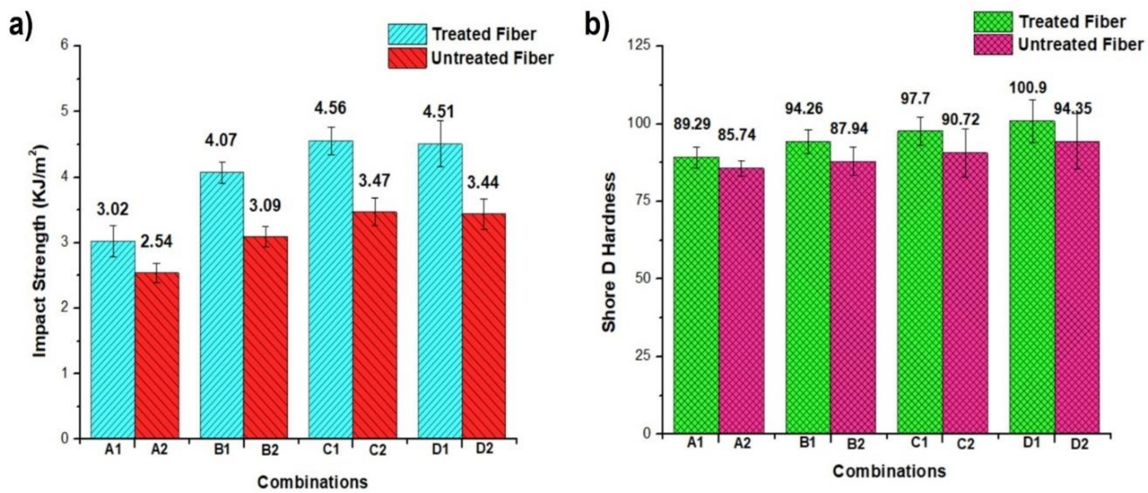

Fig. 5. a) Impact Strength, b) Shore D Hardness of natural fiber hybrid composites

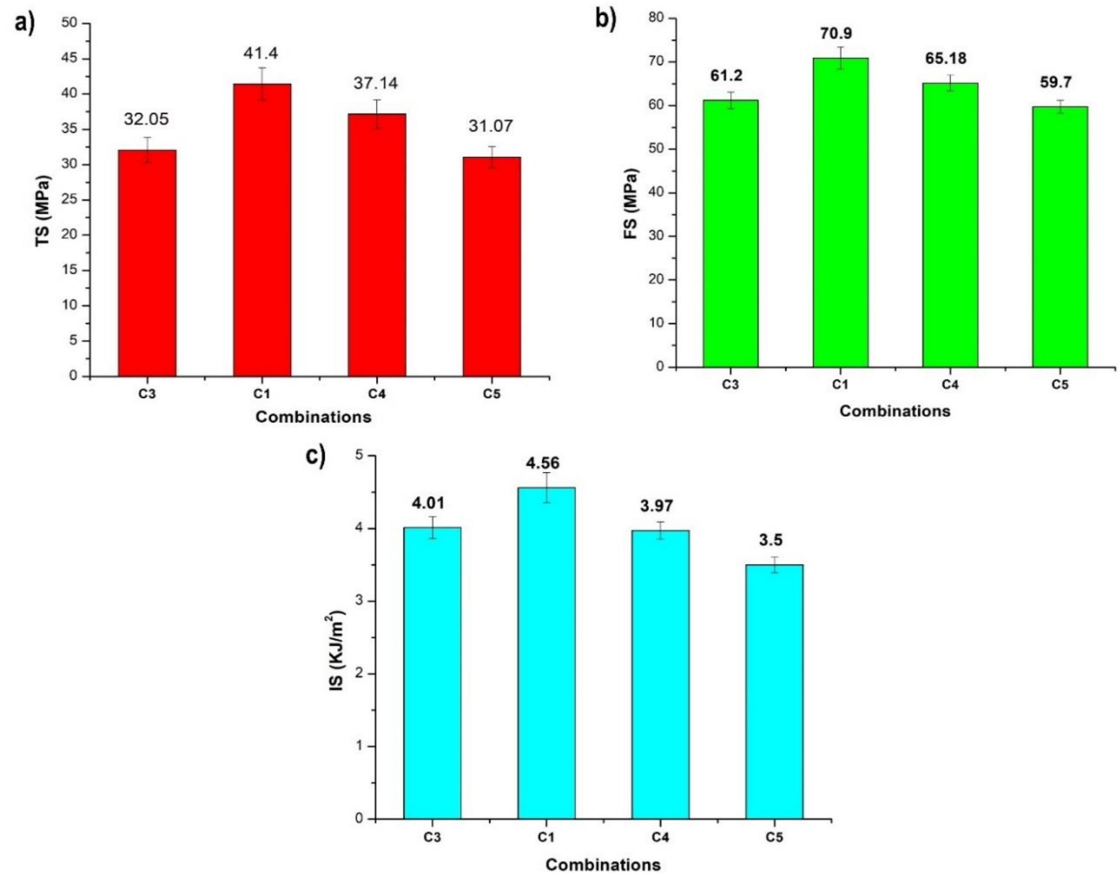

Fig. 6. a) Tensile Strength (TS), b) Flexural Strength (FS) and c) Impact Strength (IS) of natural fiber hybrid composites with different natural fiber percentage

Mechanical Results with Change in Natural Fiber addition and NaOH Treatment

It was observed from the previous step results that the combination 20 wt% AF/20 wt% GF exhibited overall better mechanical properties. This combination was tried with different natural fiber additions of 10, 20, 30, and 40 wt%. The maximum tensile strength with 41.1 MPa, flexural strength with 70.9 MPa, impact strength of 4.56 KJ/m^2 was observed with 20 wt% AF addition (Fig 6). Increase in the natural fiber incorporation beyond the optimum level resulted in a decline of the mechanical properties due to poor interfacial adhesion of filler and matrix phase (Rajeshkumar 2021).

The same 20 wt% AF/20 wt% GF combination with different chemical treatment using NaOH ranging from 0, 3, 5, and 8 wt% observed better tensile, flexural, and impact results at 5 wt% NaOH addition (Fig. 7). The surface treatment in natural fiber could act as a smooth carrier for improvement matrix/filler interaction (Sumesh and Kanthavel 2020).

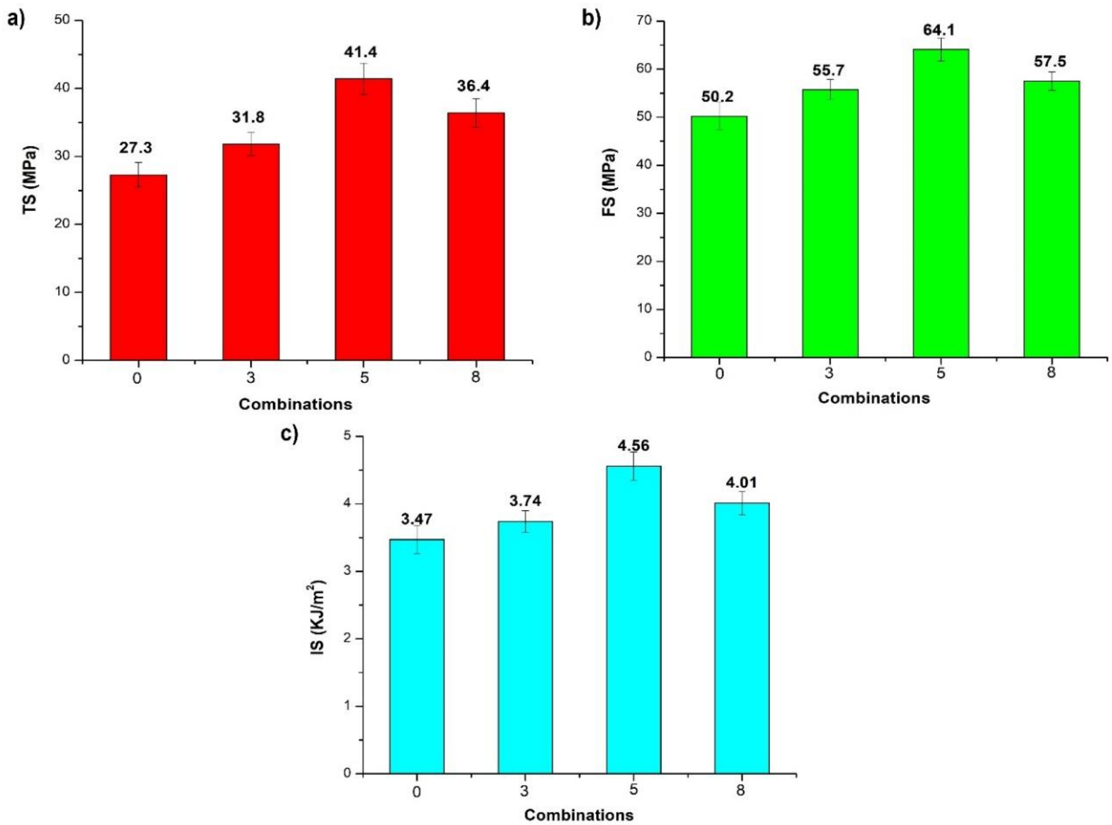

Fig. 7. a) Tensile Strength (TS), b) Flexural Strength (FS) and c) Impact Strength (IS) of natural fiber hybrid composites with different NaOH treatment

FTIR Results

The FTIR results for NaOH treatment in the areca fibers showed increased cellulose content (Fig. 8). The C-H asymmetric deformation and CH_2 symmetric cellulose bending in NaOH treated areca fibers showed a peak at 1370 cm^{-1} (Sumesh and Kanthavel 2022). This was not visible in untreated areca fibers. The surface treatment provided hydroxyl groups and created polar nature in the areca fibers. The peaks at 3277 and 3302 cm^{-1} for untreated and treated areca fibers corresponded to stretching vibrations in the natural fibers due to -CH and -OH groups (Todkar and Patil 2019). It can be seen that the peak at 5% NaOH treated natural fibers was properly visible (3302 cm^{-1}) in comparison to non-treated areca fibers (3277 cm^{-1}). The peaks at 1634 and 1642 cm^{-1} were attributed to bending mode for water absorption in the areca fibers. The peaks at 1022 and 1025 cm^{-1} were attributed to pyranose vibration in treated and untreated areca fibers (Sumesh and Kanthavel 2022).

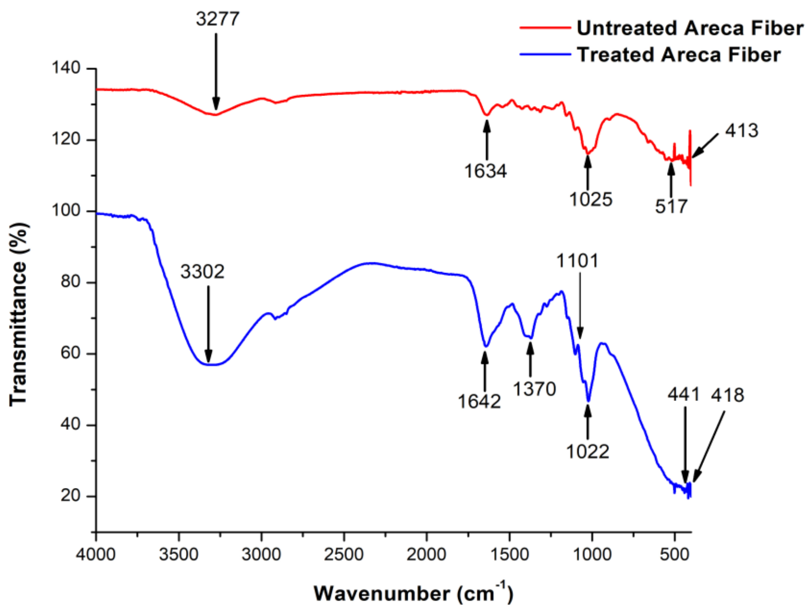

Fig. 8. FTIR results of treated and untreated areca fibers

Wear Testing

The dry sliding wear rate of hybrid natural fiber composites was carried out using pin on disc equipment with constant sliding distance of 500 m, sliding speed of 5 m/sec (Fig. 9a). Already in the authors' previous experiments, it was confirmed that surface treated fibers had significant improvement in the mechanical properties of the composites (Rajeshkumar 2021). Alkali-treated natural fibers were used in this combination. In the current application, the influence of different loads from 10 N to 20 N was applied with different combinations to find the wear loss of the specimen. The results observed decrease in the wear loss with the increase in wt.% of hybrid fiber incorporation from 20 to 40 wt.%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influenced with applying higher loads (Aslan *et al*. 2018). The irregularities in distribution of hybrid fiber incorporation at overall wt% of 50 led to the increase in wear loss of epoxy matrix composites. The increase in load from 10 to 20 N created high temperature area across the sample that will increase the wear loss with higher loads (Maurya *et al*. 2017). The better adhesion of fiber/matrix created a barrier layer that will protect the sample from higher wear rate (Rajeshkumar 2021).

The coefficient of friction (CoF) showed just the opposite of wear loss factor. The frictional rate was highly increasing with increase in hybrid fiber wt% and also with higher loads applied (Fig. 9b). The hybrid fiber combination possesses high hardness with increase in fiber wt% leading to high coefficient of friction (Kumar *et al*. 2019). Increase in the load created a high pressure with specimen and rotating disc, leading to high friction in the sample (Nanda and Satapathy 2021).

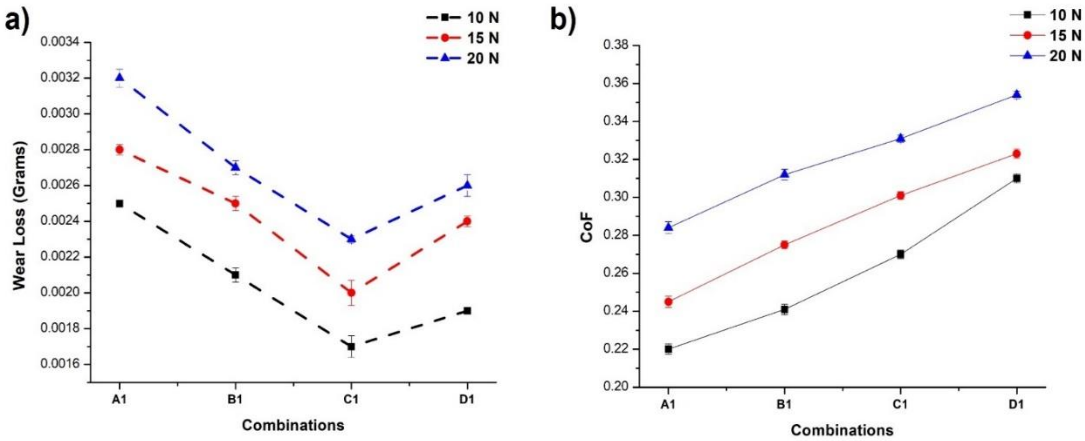

Fig. 9. a) Wear Loss, b) Coefficient of Friction (CoF) of Hybrid Natural Fiber Composites

SEM Analysis

The initial set of SEM analyses was taken before the wear testing of natural fiber samples (Fig 10). The images showed rough surfaces in the NaOH-treated natural fiber composites (Fig 10b) in comparison to untreated areca fiber combination. This roughness could have enhanced the compatibility of natural fiber/epoxy resin matrix (Rajeshkumar 2021). It is also visible that glass fiber, areca fiber at 20 wt% with the 5% NaOH treatment exhibited better interaction with fiber and resin. This contributed to the properties of polymer composites by adding to stress transferring capacity (Fig 10d) compared to untreated natural fiber with same fiber addition (Fig 10c).

The next set of combination SEM images were taken after wear testing. Figure 11 a) shows that untreated 10 wt% AF/10 wt% GF observed higher fiber breakages and matrix cracks in comparison to NaOH treated natural fibers (11 b). The same percentages of decline in the wear resistance of natural fiber epoxy-based composites were observed (Goutham *et al*. 2023; Arivendan *et al*. 2024). The combination with 20 wt% AF/20 wt% GF exhibited greater distribution of fibers in the matrix with better fiber/resin compatibility in NaOH treated natural fibers 11d than untreated fibers 11c. The sample with 25 wt.% AF/25 wt% GF (Fig. 12a, b) showed slight irregularities in the fiber distribution that declined the mechanical properties. The results were shown in Table 2, with almost 40% of SiO_2, which can be attributed to the presence of glass fibers. Other compounds including Al_2O_3, Fe_2O_3, CaO, and TiO_2 were in low amount and were attributed to components of the natural fibers. The other content with almost 50% was epoxy resin. Similar results with SiO_2, Al_2O_3, Fe_2O_3, CaO, TiO_2 were shown with natural fiber epoxy-based composites (Korneijenko *et al*. 2022).

Table 2. The XRF Results for 25 wt.% AF/25 wt.% GF/Epoxy Combination

Chemical Composition	Percentage
SiO_2	39.5
Al_2O_3	4.13
Fe_2O_3	1.2
CaO	1.1
P_2O_5	0.5
MgO	0.6

K_2O	0.3
$S0_3$	0.2
TiO_2	1.1
Cl	0.7
MnO	0.4
Na_2O	0.2
Others	50.07

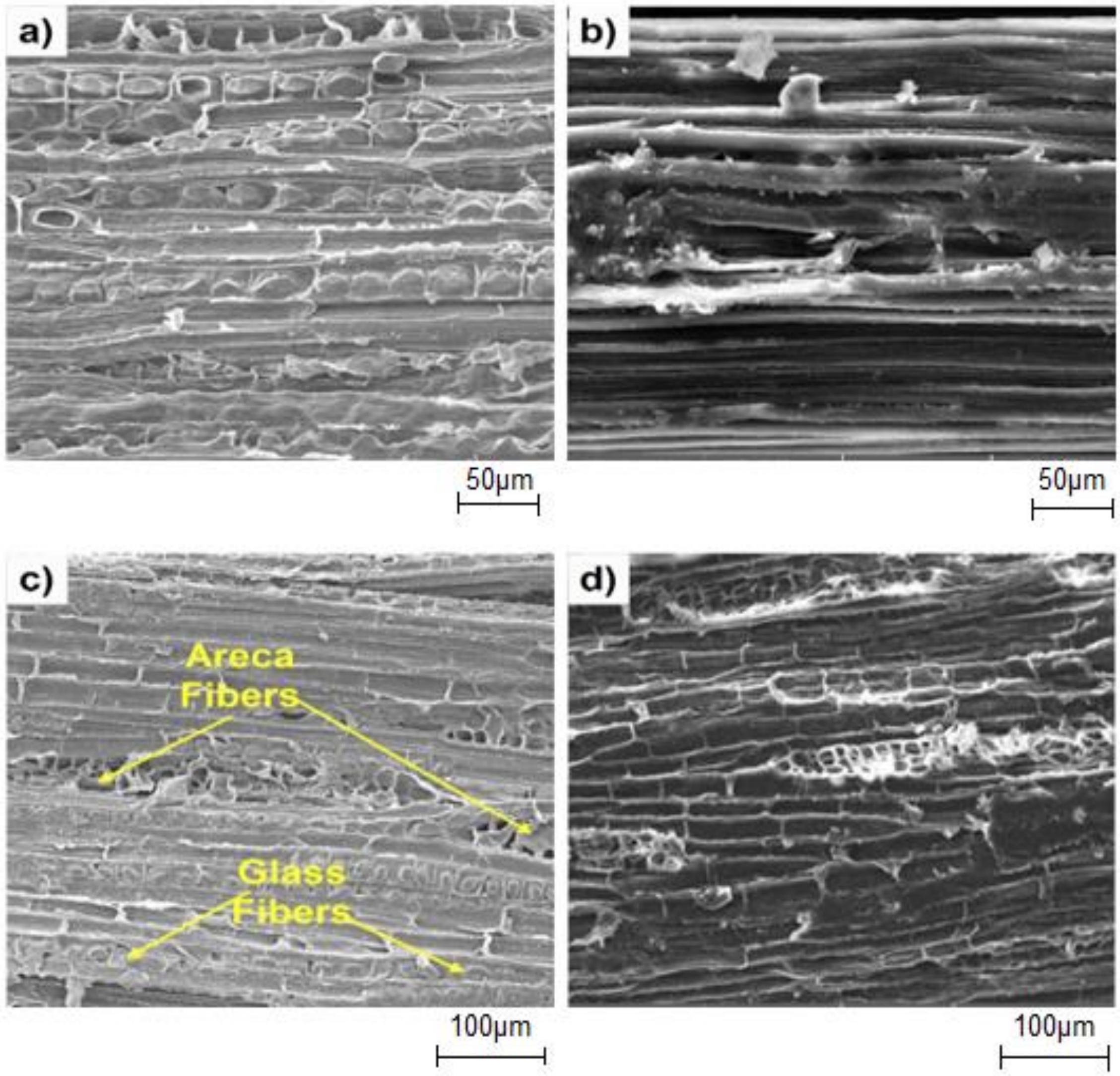

Fig. 10. SEM images before wear testing for a) untreated 10 wt% AF/10 wt% GF combination, b) 5% NaOH treated 10 wt% AF/10 wt% GF combination, c) untreated 20 wt% AF/20 wt% GF combination and d) 5% NaOH treated 20 wt% AF/20 wt% GF combination

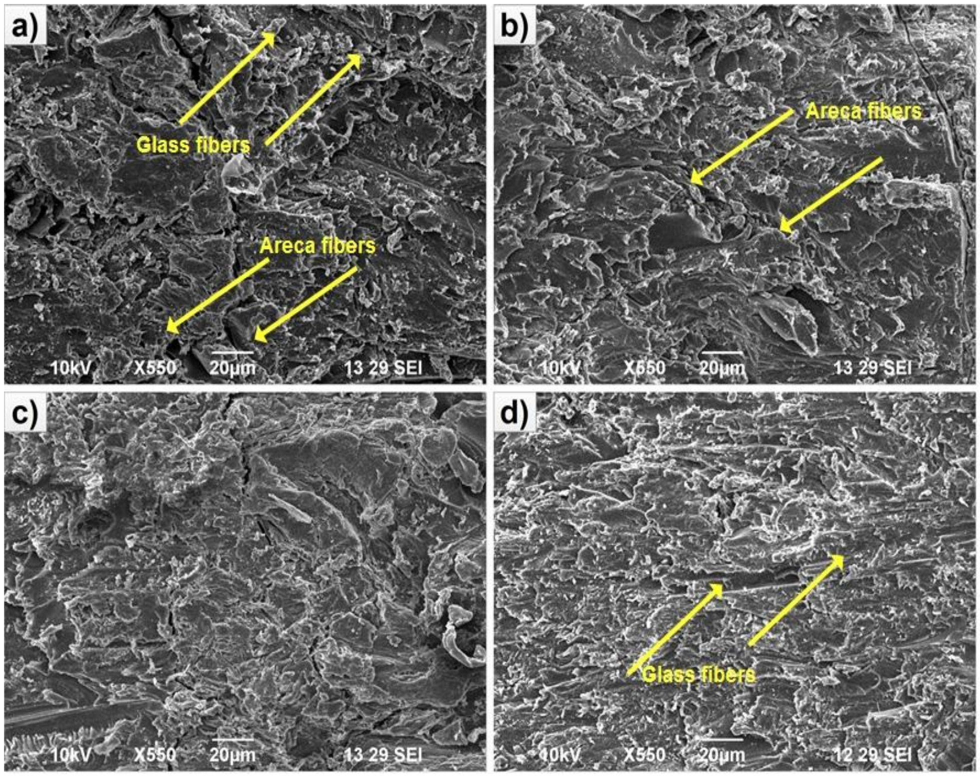

Fig. 11. SEM Images after wear testing for a) untreated 10 wt% AF/10 wt% GF combination, b) 5% NaOH treated 10 wt% AF/10 wt% GF combination, c) untreated 20 wt% AF/20 wt% GF combination, and d) 5% NaOH treated 20 wt% AF/20 wt% GF combination, all at 15 N load

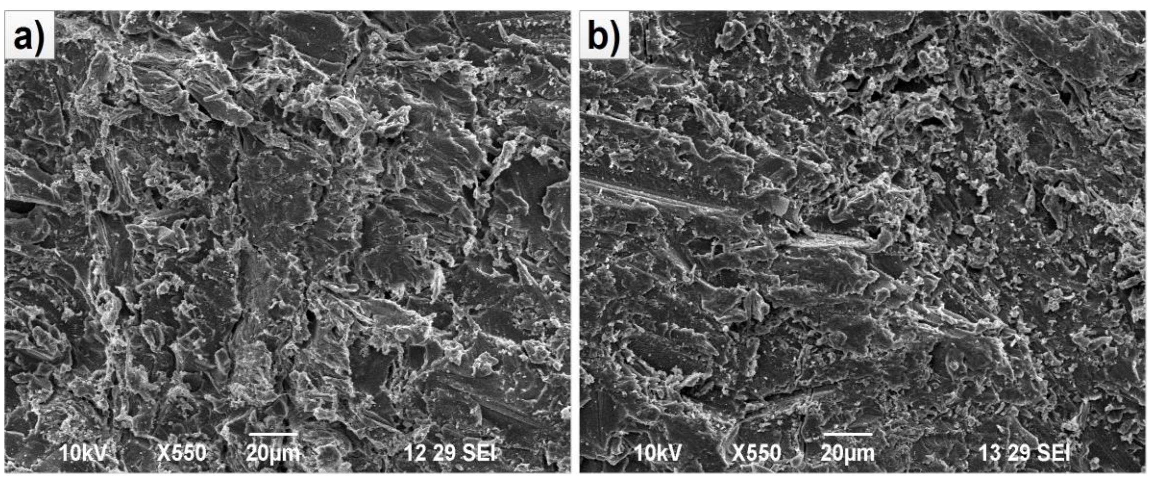

Fig. 12. SEM Images after wear testing for a) untreated 25 wt% AF/25 wt% GF combination and b) 5% NaOH treated 25 wt% AF/25 wt% GF combination at 10 N load

The SEM analysis after wear clearly showed the importance of hybrid fiber combination in enhancing the wear applications of the polymer composites. Figure 11a of D2 Treated 25 wt% AF/25 wt% observed high wear loss in the combination due to poor distribution of fiber causing fiber debonding and fiber breakages with lesser wear resistance. Figure 11b of D1 with Treated 25 wt% AF/25 wt% observed better wear resistance due to higher fiber incorporation with better fiber/matrix bonding.

CONCLUSIONS

1. The tensile strength of areca fiber /glass fiber/ epoxy resin combination observed significant improvement in the strength with hybrid fiber incorporation and alkali treatment. The combination of areca fiber (10 wt%)/glass fibers (10 wt%) observed 23.8 MPa of tensile properties compared to untreated fibers with 15.5 MPa.
2. The areca fiber (20 wt%)/glass fibers (20 wt%) with 5% alkali treatment exhibited maximum tensile strength up to 62.6% in comparison to untreated fiber combination with 10 wt%. Tensile modulus was enhanced with the increase in hybrid fiber incorporation of areca and glass fibers with overall wt% up to 50.
3. The alkali treated fibers at overall fiber wt% of 20 exhibited an increase in flexural strength from 38.9 to 52.4 MPa. This increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation.
4. Fiber/matrix bonding, in combination with homogenous distribution of fiber enhanced the flexural strength of polymer composites. The maximum flexural modulus of 6.73 GPa was observed in alkali treated 25 wt% AF/25 wt% GF.
5. The increase in wear resistance was shown with the increase in wt% of hybrid fiber incorporation from 20 to 40 wt%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influence with applying higher loads.
6. The irregularities in distribution of hybrid fiber incorporation at overall wt% of 50 leads to the increase in wear loss of epoxy matrix composites. The increase in load from 10 to 20 N created a high temperature area across the sample that will increase the wear loss with higher loads. The better adhesion of fiber/matrix created a barrier layer that will protect the sample from higher wear rate.
7. The frictional rate is increasing with increase in hybrid fiber wt% and also with higher loads applied. The hybrid fiber combination possesses high hardness with increase in fiber wt% leading to high coefficient of friction. Increase in the load created a high pressure with specimen and rotating disc leading to high friction in the sample.
8. The initial set of SEM analysis taken before the wear testing of natural fiber samples showed rough surfaces in the NaOH-treated natural fiber composites in comparison to untreated areca fiber combination. This roughness could have enhanced the compatibility of natural fiber/epoxy resin matrix. It is also visible that glass fiber, areca fiber at 20 wt% with the 5% NaOH treatment achieved better interaction with fiber and resin. This added to the properties of polymer composites by adding to stress transferring capacity comparing to untreated natural fiber with same fiber addition.
9. The SEM analysis after wear clearly showed the importance of hybrid fiber combination in enhancing the wear applications of the polymer composites. The treated 10 wt% AF+10 wt% GF observed high wear loss in the combination due to poor distribution of fiber, causing fiber debonding, fiber breakages with lesser wear resistance. The treated 20 wt% AF+20 wt% GF with 40 wt% of overall hybrid fiber incorporation achieved better results due to improved adhesion of fiber with matrix phase.

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Data Availability Statement

Data is available on request from the authors.

Declaration of Conflicting Interests

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REFERENCES CITED

Abdul Khalil, H. P. S., Masri, M., Saurabh, C. K., Fazita, M. R. N., Azniwati, A. A., Aprilia, N. A. S., Rosamah, E., and Dungani, R. (2017). "Incorporation of coconut shell based nanoparticles in kenaf/coconut fibres reinforced vinyl ester composites," *Materials Research Express* 4(3), article 35020. DOI: 10.1088/2053-1591/aa62ec

Almeshaal, M., Palanisamy, S., Murugesan, T. M., Palaniappan, M., and Santulli, C. (2022). "Physico-chemical characterization of Grewia Monticola Sond (GMS) fibers for prospective application in biocomposites," *Journal of Natural Fibers* 19(17), 15276-15290. DOI: 10.1080/15440478.2022.2123076

Arivendan, A., Sumesh, K. R., Chen, X. Q., Zhang, Y. F., Gao, W. H., Syamani, F. A., and Thangiah, W. J. J. (2024). "Combining the pineapple leaf fibre (PALF) and industrial ramie fibre to the epoxy matrix for high-strength light weight medium-density fibreboards," *Biomass Conversion and Biorefinery*. DOI: 10.1007/s13399-023-05243-0

Arthanarieswaran, V. P., Kumaravel, A., and Kathirselvam, M. (2014). "Evaluation of mechanical properties of banana and sisal fiber reinforced epoxy composites: Influence of glass fiber hybridization," *Materials & Design* 64, 194-202. DOI: 10.1016/j.matdes.2014.07.058

Ashraf, W., Ishak, M. R., Khan, T., Sebaey, T. A., Singh, B., and Alshahrani, H. (2023). "Study of impact performance of composite sandwich structure fabricated partially with natural fiber facesheet," *Polymer Composites*. DOI: 10.1002/pc.27999

Aslan, M., Tufan, M., and Küçükömeroğlu, T. (2018). "Tribological and mechanical performance of sisal-filled waste carbon and glass fibre hybrid composites," *Composites Part B: Engineering* 140, 241-249. DOI: 10.1016/j.compositesb.2017.12.039

Basha, M., Wagih, A., Khan, T., Lubineau, G., and Sebaey, T. A. (2023). "On the benefit of thin plies on flexural response of CFRP composites aged at elevated temperature," *Composites Part A: Applied Science and Manufacturing* 166, article 107393. DOI: 10.1016/j.compositesa.2022.107393

Chegdani, F., Mezghani, S., and El Mansori, M. (2016). "On the multiscale tribological signatures of the tool helix angle in profile milling of woven flax fiber composites," *Tribology International* 100, 132-140. DOI: 10.1016/j.triboint.2015.12.014

Chegdani, F., Wang, Z., El Mansori, M., and Bukkapatnam, S. T. S. (2018). "Multiscale tribo-mechanical analysis of natural fiber composites for manufacturing applications," *Tribology International* 122, 143-150. DOI: 10.1016/j.triboint.2018.02.030

Goutham, E. R. S., Hussain, S. S., Muthukumar, C., Krishnasamy, S., Kumar, T. S. M., Santulli, C., Palanisamy, S., Parameswaranpillai, J., and Jesuarockiam, N. (2023). "Drilling parameters and post-drilling residual tensile properties of natural-fiber-reinforced composites: A review," *Journal of Composites Science* 7(4), article 136. DOI: 10.3390/jcs7040136

Gupta, A., Singh, H., and Walia, R. S. (2016). "Hybrid filler composition optimization for tensile strength of jute fibre-reinforced polymer composite," *Bulletin of Materials Science* 39, 1223-1231. DOI: 10.1007/s12034-016-1248-1

Hanan, F., Khan, T., Jawaid, M., Sultan, M. T. H., Sebaey, T., Singh, B., and Sarmin, S. N. (2023). "Thermal characterization of epoxy bilayer hybrid composites reinforced with kenaf and oil palm fibers," *Polymer Composites* 44(1), 444-452. DOI: 10.1002/pc.27108

Jeyakumar, R., Sampath, P. S., Ramamoorthi, R., and Ramakrishnan, T. (2017). "Structural, morphological and mechanical behaviour of glass fibre reinforced epoxy nanoclay composites," *The International Journal of Advanced Manufacturing Technology* 93, 527-535. DOI: 10.1007/s00170-017-0565-x

Johnson, R. D. J., Arumugaprabu, V., and Ko, T. J. (2019). "Mechanical property, wear characteristics, machining and moisture absorption studies on vinyl ester composites– a review," *Silicon* 11, 2455-2470. DOI: 10.1007/s12633-018-9828-x

Junaedi, H., Khan, T., and Sebaey, T. A. (2023). "Characteristics of carbon-fiber-reinforced polymer face sheet and glass-fiber-reinforced rigid polyurethane foam sandwich structures under flexural and compression tests," *Materials* 16(14), 5101. DOI: 10.3390/ma16145101

Kar, A., Saikia, D., Palanisamy, S., Santulli, C., Fragassa, C., and Thomas, S. (2023). "Effect of alkali treatment under ambient and heated conditions on the physicochemical, structural, morphological, and thermal properties of *Calamus tenuis* cane fibers," *Fibers* 11(11), article 92. DOI: 10.3390/fib11110092

Karuppiah, G., Kuttalam, K. C., Ayrilmis, N., Nagarajan, R., Devi, M. P. I., Palanisamy, S., and Santulli, C. (2022). "Tribological analysis of jute/coir polyester composites filled with eggshell powder (ESP) or nanoclay (NC) using grey rational method," *Fibers* 10(7), article 60. DOI: 10.3390/fib10070060

Karuppiah, G., Kuttalam, K. C., and Palaniappan, M. (2020). "Multiobjective optimization of fabrication parameters of jute fiber / polyester composites with egg shell powder and nanoclay filler," *Molecules* 25(23), article 5579. DOI: 10.3390/molecules25235579

Khan, T., Hameed Sultan, M. T. Bin, and Ariffin, A. H. (2018). "The challenges of natural fiber in manufacturing, material selection, and technology application: A review," *Journal of Reinforced Plastics and Composites* 37(11), 770-779. DOI: 10.1177/0731684418756762

Khan, T., Sultan, M. T. H., Shah, A. U. M., Ariffin, A. H., and Jawaid, M. (2021). "The effects of stacking sequence on the tensile and flexural properties of kenaf/jute fibre hybrid composites," *Journal of Natural Fibers* 18(3), 452-463. DOI: 10.1080/15440478.2019.1629148

Korneijenko, K., Kejzlar, P., and Louda, P. (2022). "The influence of the material structure on the mechanical properties of geopolymer composites reinforced with short fibers obtained with additive technologies," *International Journal of Molecular*

Sciences 23(4), article 2023. DOI: 10.3390/ijms23042023
Sumesh, K. R., and Kanthavel, K. (2020). "Synergy of fiber content, Al_2O_3 nanopowder, NaOH treatment and compression pressure on free vibration and damping behavior of natural hybrid-based epoxy composites," *Polymer Bulletin* 77(3), 1581-1604. DOI: 10.1007/s00289-019-02823-x
Kumar, S., Patel, V. K., Mer, K. K. S., Gangil, B., Singh, T., and Fekete, G. (2019). "Himalayan natural fiber-reinforced epoxy composites: Effect of *Grewia optiva*/ *Bauhinia vahlii* fibers on physico-mechanical and dry sliding wear behavior," *Journal of Natural Fibers* 18(2), 192-202. DOI: 10.1080/15440478.2019.1612814
Kurien, R. A., Selvaraj, D. P., Sekar, M., Koshy, C. P., Paul, C., Palanisamy, S., Santulli, C., and Kumar, P. (2023). "A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites," *Cellulose* 30, 8643-8664. DOI: 10.1007/s10570-023-05441-z
Liu, Y., Lv, X., Bao, J., Xie, J., Tang, X., Che, J., Ma, Y., and Tong, J. (2019). "Characterization of silane treated and untreated natural cellulosic fibre from corn stalk waste as potential reinforcement in polymer composites," *Carbohydrate Polymers* 218, 179-187. DOI: 10.1016/j.carbpol.2019.04.088
Maurya, H. O., Jha, K., and Tyagi, Y. K. (2017). "Tribological behavior of short sisal fiber reinforced epoxy composite," *Polymers and Polymer Composites* 25(3), 215-220. DOI: 10.1177/096739111702500306
Mittal, V., Saini, R., and Sinha, S. (2016). "Natural fiber-mediated epoxy composites–a review," *Composites Part B: Engineering* 99, 425-435. DOI: 10.1016/j.compositesb.2016.06.051
Muhammad, A., Rahman, M. R., Hamdan, S., and Sanaullah, K. (2019). "Recent developments in bamboo fiber-based composites: A review," *Polymer Bulletin* 76, 2655-2682. DOI: 10.1007/s00289-018-2493-9
Nanda, B. P., and Satapathy, A. (2021). "An analysis of the sliding wear characteristics of epoxy-based hybrid composites using response surface method and neural computation," *Journal of Natural Fibers* 18(12), 2077-2091. DOI: 10.1080/15440478.2020.1722781
Nirmal, U., Hashim, J., and Ahmad, M. M. H. M. (2015). "A review on tribological performance of natural fibre polymeric composites," *Tribology International* 83, 77-104. DOI: 10.1016/j.triboint.2014.11.003
Nirmal, U., Hashim, J., and Low, K. O. (2012). "Adhesive wear and frictional performance of bamboo fibres reinforced epoxy composite," *Tribology International* 47, 122-133. DOI: 10.1016/j.triboint.2011.10.012
Nopparut, A., and Amornsakchai, T. (2016). "Influence of pineapple leaf fiber and it's surface treatment on molecular orientation in, and mechanical properties of, injection molded nylon composites," *Polymer Testing* 52, 141-149. DOI: 10.1016/j.polymertesting.2016.04.012
Oushabi, A. (2019). "The pull-out behavior of chemically treated lignocellulosic fibers/polymeric matrix interface (LF/PM): A review," *Composites Part B: Engineering* 174, article 107059. DOI: 10.1016/j.compositesb.2019.107059
Palanisamy, S., Kalimuthu, M., Nagarajan, R., Fernandes Marlet, J. M., and Santulli, C. (2023a). "Physical, chemical, and mechanical characterization of natural bark fibers (NBFs) reinforced polymer composites: A bibliographic review," *Fibers* 11(2), 13. DOI: 10.3390/fib11020013
Palanisamy, S., Kalimuthu, M., Santulli, C., Palaniappan, M., Nagarajan, R., and

Fragassa, C. (2023b). "Tailoring epoxy composites with *Acacia caesia* bark fibers: Evaluating the effects of fiber amount and length on material characteristics," *Fibers* 11(7), article 63. DOI: 10.3390/fib11070063

Palanisamy, S., Mayandi, K., Palaniappan, M., Alavudeen, A., Rajini, N., Vannucchi de Camargo, F., and Santulli, C. (2021). "Mechanical properties of *Phormium tenax* reinforced natural rubber composites," *Fibers* 9(2), article 11. DOI: 10.3390/fib9020011

Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., Ayrilmis, N., and Alavudeen, A. (2024). "Selection and processing of natural fibers and nanocellulose for biocomposite applications: A brief review," *BioResources* 19(1), 1789-1813. DOI: 10.15376/biores.19.1.Palanisamy

Patel, J. P., and Parsania, P. H. (2017). "Fabrication and comparative mechanical, electrical and water absorption characteristic properties of multifunctional epoxy resin of bisphenol-C and commercial epoxy-treated and-untreated jute fiber-reinforced composites," *Polymer Bulletin* 74, 485-504. DOI: 10.1007/s00289-016-1725-0

Rahman, M. R., Hamdan, S., Jayamani, E., Kakar, A., Bakri, M. K. Bin, and Yusof, F. A. B. M. (2019). "Tert-butyl catechol/alkaline-treated kenaf/jute polyethylene hybrid composites: Impact on physico-mechanical, thermal and morphological properties," *Polymer Bulletin* 76, 763-784. DOI: 10.1007/s00289-018-2404-0

Rajeshkumar, G. (2021). "A new study on tribological performance of phoenix Sp. fiber-reinforced epoxy composites," *Journal of Natural Fibers* 18(12), 2208-2219. DOI: 10.1080/15440478.2020.1724235

Ramamoorthy, S. K., Skrifvars, M., and Persson, A. (2015). "A review of natural fibers used in biocomposites: Plant, animal and regenerated cellulose fibers," *Polymer Reviews* 55(1), 107-162. DOI: 10.1080/15583724.2014.971124

Santulli, C., Palanisamy, S., and Dharmalingam, S. (2023). "Natural fibres-based bio-epoxy composites: Mechanical and thermal properties," in: *Epoxy-Based Biocomposites*, CRC Press, 163-176. DOI: 10.1201/9781003271017-8

Satheesh Kumar, M. N., Yaakob, Z., Mohan, N., Siddaramaiah, and Kumaresh Babu, S. P. (2010). "Mechanical and abrasive wear studies on biobased jatropha oil cake incorporated glass–epoxy composites," *Journal of the American Oil Chemists' Society* 87, 929-936. DOI: 10.1007/s11746-010-1575-0

Senthilkumar, K., Saba, N., Chandrasekar, M., Jawaid, M., Rajini, N., Alothman, O. Y., and Siengchin, S. (2019). "Evaluation of mechanical and free vibration properties of the pineapple leaf fibre reinforced polyester composites," *Construction and Building Materials* 195, 423-431. DOI: 10.1016/j.conbuildmat.2018.11.081

Sheykh, M. J., Tarmian, A., Doosthoseini, K., and Abdulkhani, A. (2017). "Wear resistance and friction coefficient of nano-SiO_2 and ash-filled HDPE/lignocellulosic fiber composites," *Polymer Bulletin* 74, 4537-4547. DOI: 10.1007/s00289-017-1975-5

Shuhimi, F. F., Abdollah, M. F. Bin, Kalam, M. A., Hassan, M., and Amiruddin, H. (2016). "Tribological characteristics comparison for oil palm fibre/epoxy and kenaf fibre/epoxy composites under dry sliding conditions," *Tribology International* 101, 247-254. DOI: 10.1016/j.triboint.2016.04.020

Singha, A. S., and Thakur, V. K. (2008). "Mechanical properties of natural fibre reinforced polymer composites," *Bulletin of Materials Science* 31(5), 791-799. DOI: 10.1007/s12034-008-0126-x

Sivasubramanian, P., Kalimuthu, M., Palaniappan, M., Alavudeen, A., Rajini, N., and

Santulli, C. (2021). "Effect of alkali treatment on the properties of *Acacia caesia* bark fibres," *Fibers* 9(8), article 49. DOI: 10.3390/fib9080049
Sumesh, K. R., Ajithram, A., Palanisamy, S., and Kavimani, V. (2023). "Mechanical properties of ramie/flax hybrid natural fiber composites under different conditions," *Biomass Conversion and Biorefinery* 1-12. DOI: 10.1007/s13399-023-04628-5
Sumesh, K. R., and Kanthavel, K. (2022). "Grey relational optimization for factors influencing tensile, flexural, and impact properties of hybrid sisal banana fiber epoxy composites," *Journal of Industrial Textiles* 51, 4441S-4459S. DOI: 10.1177/1528083720928501
Swolfs, Y., Gorbatikh, L., and Verpoest, I. (2014). "Fibre hybridisation in polymer composites: A review," *Composites Part A: Applied Science and Manufacturing* 67, 181-200. DOI: 10.1016/j.compositesa.2014.08.027
Todkar, S. S., and Patil, S. A. (2019). "Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites," *Composites Part B: Engineering* 174, article 106927. DOI: 10.1016/j.compositesb.2019.106927

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