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Experimental Study on Mechanical and Tribological Characterization of Arecanut Shell Fibre Reinforced Composites with MWCNT Nanofillers

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Abstract

Natural fiber-reinforced composites (NFRCs) are emerging as sustainable alternatives to conventional synthetic composites due to their eco-friendliness, cost-effectiveness, and favorable mechanical properties. This study evaluates the mechanical and tribological performance of Areca Nutshell Fiber (ANSF)-reinforced epoxy composites with multi-walled carbon nanotubes (MWCNTs) as nanofillers. The composites were fabricated using the vacuum bag molding technique. Tensile tests assessed strength, modulus, and elongation, while flexural tests evaluated bending resistance. Pin-on-disc tests examined wear behavior under varying conditions. Results indicate that 30 wt. % ANSF enhances tensile strength to 32.5 MPa and flexural strength to 55.7 MPa. The addition of 1.5 wt. % MWCNTs further improves Young's modulus (2.1 GPa) and flexural modulus (3.4 GPa). Tribological tests show a 30% reduction in wear rate and a 25% decrease in coefficient of friction under oil-based lubrication. These findings suggest that ANSF-MWCNT epoxy composites are suitable for automotive, aerospace, and biomedical applications requiring high durability and wear resistance.

Keywords: Areca nutshell fibre, characteristics, composites, epoxy, mechanical, multi walled carbon nanotubes, nanofillers, tribological

INTRODUCTION

Natural fiber-reinforced composites (NFRCs) have gained prominence as an environmentally friendly alternative to synthetic fiber-reinforced composites due to their sustainability, cost-effectiveness, and biodegradability [1–3]. The increasing global emphasis on sustainable materials has led researchers to explore various natural fibers, including jute, hemp, flax, coir, sisal, and areca nutshell fiber, for composite applications [4–7]. These natural fibers exhibit excellent mechanical properties, such as high specific strength, low density, good toughness, and excellent energy absorption capacity, making them ideal for structural applications in automotive, aerospace, marine, and biomedical sectors. Among various natural fibers, areca nutshell fiber has emerged as a promising reinforcement material due to its high lignin content, which enhances its mechanical strength and durability [8–11].

Areca nutshell fiber is derived from the husk of the areca nut (Areca catechu), an agricultural byproduct widely available in tropical regions. The

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utilization of areca nutshell fiber in polymer composites not only provides a sustainable waste management solution but also contributes to lightweight, high-strength materials with superior mechanical and tribological performance [12–15]. However, challenges such as moisture absorption, poor fiber-matrix adhesion, and lower thermal stability must be addressed to optimize its performance in composite applications. Epoxy resin is widely used as a matrix material in composite fabrication due to its excellent adhesion properties, high strength-to-weight ratio, good chemical resistance, and superior thermal stability. However, to further enhance the mechanical and tribological properties of NFRCs, researchers have incorporated nano-fillers such as carbon nanotubes (CNTs), graphene, and silica nanoparticles to reinforce the polymer matrix [16–19]. CNTs exhibit exceptional mechanical strength, high thermal conductivity, and excellent wear resistance, making them ideal for improving the tribological performance of NFRCs [20,21].

Tribology, the study of friction, wear, and lubrication, plays a crucial role in determining the durability and performance of composite materials, especially in dynamic and high-load environments. In many engineering applications, NFRCs experience continuous contact, sliding motion, and abrasive forces, leading to progressive material degradation over time [22]. The tribological performance of NFRCs depends on several key factors, including fiber type, fiber-matrix adhesion, filler reinforcement, and lubrication conditions [23]. The type of fiber used influences friction and wear resistance, as natural fibers exhibit different mechanical and surface properties. Proper alignment and orientation of fibers can enhance wear resistance by distributing contact stresses more evenly. Strong interfacial bonding between fibers and the polymer matrix is essential to prevent premature material failure. Various surface treatments such as alkali treatment, silane coating, and plasma treatment have been shown to improve interfacial adhesion, leading to better tribological performance [24,25].

The addition of nano-fillers such as carbon nanotubes (CNTs), graphene, and silicon carbide (SiC) significantly enhances the abrasion resistance, thermal stability, and lubrication properties of NFRCs. CNTs, due to their exceptional mechanical strength, self-lubricating ability, and high load-bearing capacity, improve the wear resistance of composites by reducing direct fiber-matrix contact under high friction conditions [26]. Moreover, lubrication plays a significant role in modifying the tribological behavior of NFRCs, reducing friction, and preventing excessive material loss due to wear. By optimizing fiber content, nano-filler dispersion, and lubrication strategies, NFRCs can be engineered to achieve longer service life and superior performance in wear-intensive applications such as automotive brake pads, bearings, and biomedical implants.

The mechanical properties of NFRCs are critical for evaluating their suitability for structural and load-bearing applications [27]. Mechanical characterization assesses key attributes such as strength, stiffness, impact resistance, and hardness, which determine the composite’s overall performance. The tensile strength of NFRCs indicates their ability to withstand axial loads without failure, and it is largely influenced by fiber content, fiber-matrix adhesion, and processing techniques. Good fiber dispersion and strong bonding result in higher tensile strength, whereas poor adhesion leads to premature failure [28]. Flexural strength is another important parameter that defines a composite’s resistance to bending forces. Higher fiber volume fractions and nano-filler reinforcement contribute to improved flexural performance, increasing composite stiffness and durability [29].

The intrinsic toughness of areca nut shell fiber, combined with CNT reinforcement, enhances impact resistance by distributing stress and preventing crack propagation. Additionally, hardness plays a significant role in tribological applications, as higher hardness values indicate superior wear resistance. Harder NFRCs exhibit better indentation resistance and durability in sliding and abrasive conditions. Processing methods also significantly impact mechanical performance, with vacuum bag molding emerging as an effective technique to minimize voids, improve fiber wetting, and enhance overall structural integrity. By optimizing fiber proportions and CNT dispersion, NFRCs can achieve superior mechanical properties suitable for a wide range of engineering applications [30].

The increasing demand for lightweight, high-strength, and wear-resistant materials in industries such as automotive, aerospace, and biomedical engineering has driven extensive research into NFRCs with enhanced mechanical and tribological performance. Traditional synthetic fiber composites, while offering excellent strength, pose environmental concerns due to non-biodegradability and high energy consumption during manufacturing. Natural fibers such as areca nut shell fiber present a sustainable alternative, providing comparable mechanical properties while being biodegradable and cost-effective [31]. However, challenges such as moisture absorption, lower thermal stability, and inconsistent fiber-matrix bonding must be addressed to maximize the potential of NFRCs for industrial applications.

Despite significant progress in NFRC research, limited studies have focused on simultaneously optimizing both mechanical and tribological properties. This study aims to fill this gap by investigating the mechanical and tribological behavior of Areca Nut Shell Fiber-reinforced epoxy composites with CNT fillers. Using the vacuum bag molding technique, the research evaluates the influence of fiber content, CNT dispersion, and lubrication conditions on composite performance. The findings will provide valuable insights into designing next-generation NFRCs with improved wear resistance and mechanical integrity, making them suitable for structural and friction-intensive applications in engineering industries.

MATERIALS AND METHODS

Materials And Methods

The development of high-performance natural fiber-reinforced composites (NFRCs) requires careful selection of materials and fabrication techniques. In this study, Areca Nutshell Fiber (ANSF), epoxy resin, and multi-walled carbon nanotubes (MWCNTs) were used to fabricate composite specimens using the vacuum bag moulding technique [32]. The process involved fiber surface treatment, CNT dispersion, controlled mixing, and vacuum-assisted curing to achieve optimal mechanical and tribological properties. The combination of natural fibers and nanofillers offers significant improvements in strength, wear resistance, and load-bearing capacity, making these composites suitable for advanced engineering applications [33].

The primary materials used in the fabrication of the composite samples include natural fiber reinforcement, polymer matrix, and nanofillers, each contributing to the composite’s overall performance. Areca Nutshell Fiber (ANSF) was chosen as the reinforcement material due to its high cellulose content, biodegradability, and excellent wear resistance. However, natural fibers typically suffer from poor interfacial adhesion with polymer matrices, necessitating a surface treatment process to enhance bonding. The matrix material used in this study is epoxy resin (Araldite LY556) with a hardener (HY951), which is well known for its high mechanical strength, chemical resistance, and good bonding capability. To further enhance the composite's mechanical and tribological properties, multi-walled carbon nanotubes (MWCNTs) were incorporated as filler material. CNTs offer exceptional mechanical reinforcement, increased thermal stability, and improved wear resistance. Additionally, sodium hydroxide (NaOH) was used for fiber surface treatment to remove impurities and improve adhesion, while acetone was employed for effective dispersion of CNTs in the epoxy matrix. The fabrication process of the ANSF-based composites involved fiber surface treatment, CNT dispersion, controlled resin mixing, and vacuum-assisted curing. The vacuum bag moulding technique was selected due to its ability to minimize voids, ensure uniform fiber-matrix distribution, and enhance mechanical properties.

The first step in the fabrication process was the surface treatment of Areca Nut Shell Fibers (ANSF) to enhance adhesion between the fiber and the polymer matrix. The fibers were treated with a 5% sodium hydroxide (NaOH) solution for 24 hours to remove hemicellulose, lignin, and surface waxes. After treatment, the fibers were thoroughly washed with distilled water to remove residual NaOH and then dried at 80 °C for 6 hours to eliminate moisture content. Alkali treatment has been widely reported to increase fiber strength and enhance fiber-polymer interaction, making it an essential step in natural fiber composite fabrication.

To ensure effective dispersion of CNTs within the epoxy resin, a two-step dispersion technique was employed. First, MWCNTs were dispersed in acetone using ultrasonic agitation for 1 hour to break agglomerates and achieve a stable suspension. Ultrasonic dispersion is a well-established technique for homogeneous distribution of nanoparticles in polymer matrices. After dispersion, the CNT-acetone mixture was gradually added to the epoxy resin under mechanical stirring for 30 minutes, ensuring even distribution throughout the polymer matrix. Finally, the hardener (HY951) was added in a 10:1 ratio to initiate polymerization, ensuring proper curing of the composite.

Following fiber treatment and CNT dispersion, the composite was prepared by mixing the treated fibers with the epoxy-CNT mixture in different weight proportions (10%, 20%, 30%, 40%, and 50% fiber content, with MWCNTs added at 0.5%, 1.0%, and 1.5% concentrations). The fiber-matrix mixture was then layered uniformly inside the mold, ensuring proper orientation and distribution. Once layering was completed, the mold was sealed in a vacuum bag and subjected to 0.8 bar pressure. This vacuum bagging process removes trapped air bubbles, enhances fiber-matrix compaction, and improves mechanical strength. The composite was allowed to cure at room temperature for 12 hours, followed by a post-curing process at 80 °C for 3 hours to enhance polymer cross-linking and improve material stability.

The vacuum bag molding process significantly reduces void formation, ensuring better load transfer between fibers and the matrix. The presence of MWCNTs further improves the tribological properties by reducing friction and wear, making these composites suitable for engineering applications such as automotive brake pads, biomedical implants, and high-performance structural components. The overall fabrication approach used in this study ensures optimized material properties, paving the way for sustainable, high-strength natural fiber composites. Table 1 shows the Composition of ANSF/Epoxy/MWCNT Composites.

Experimental Characterization

Mechanical testing of the fabricated composites is conducted to assess their strength, stiffness, and deformation behaviour. The two primary tests performed are tensile strength and flexural strength analyses, both carried out in accordance with standardized ASTM procedures to ensure reliability and accuracy in the results.

Tensile strength testing is performed using a Universal Testing Machine (UTM) following the ASTM D3039 standard [34]. The tensile specimens are prepared in a rectangular flat strip configuration, with dimensions of 250 mm in length and 25 mm in width. The thickness of the specimens corresponds to the fabricated composite thickness, typically ranging between 2 mm to 6 mm. The gauge length, or the effective length between grips during the test, is maintained at 150 mm. During testing, a unidirectional tensile load is applied at a controlled rate until the specimen experiences failure. The mechanical properties recorded from this test include the Ultimate Tensile Strength (UTS), Young's modulus, and elongation at break. The presence of alkali-treated Arecanut Shell Fibers (ANSF) in the composite is anticipated to improve fiber-matrix adhesion, resulting in more efficient stress transfer and enhanced tensile properties. Furthermore, the homogeneous dispersion of Multi-Walled Carbon Nanotubes (MWCNTs) within the epoxy matrix is expected to facilitate better load distribution, thereby contributing to an increase in the overall tensile strength and ductility of the composites.

Table 1. Composition of ANSF/Epoxy/MWCNT composites.

Samples	Epoxy resin (%)	Areca nutshell fiber ANSF (%)	MWCNT's (%)	Hardener (HY951) (%)
S1	82.5	10	0.5	7
S2	72	20	1.0	7
S3	61.5	30	1.5	7
S4	52	40	1.0	7
S5	42.5	50	0.5	7

Flexural strength testing is conducted using a three-point bending configuration in accordance with the ASTM D790 standard [35]. For flexural testing, the specimens are cut to dimensions of 127 mm in length and 12.7 mm in width, while the thickness remains consistent with the fabricated composite laminate. The span length between the two supports during testing is determined based on the ASTM guideline of sixteen times the specimen thickness to ensure an optimal bending condition without premature failure. In the three-point bending test, the specimen is placed on two supports and loaded at the center until fracture or until a significant deflection occurs. Key mechanical properties derived from this test include flexural strength, flexural modulus, and maximum deflection before failure. The incorporation of alkali-treated ANSF enhances the interfacial bonding between the fibers and the matrix, which minimizes fiber pull-out and significantly improves the flexural rigidity of the composites. In addition, the reinforcement provided by MWCNTs strengthens the epoxy matrix by restricting microcrack initiation and propagation under bending loads, resulting in improved flexural performance and higher resistance to mechanical degradation.

Tribological testing is conducted to analyze the frictional behaviour and wear resistance of the composite under various working conditions. The wear performance of the fabricated composites is evaluated using the Pin-on-Disc method, which simulates real-world sliding contact by bringing the composite specimen into direct contact with a rotating metal disc under controlled conditions. The test is conducted in accordance with ASTM G99 standards to ensure accuracy and repeatability in the measurement of wear rate and coefficient of friction (COF).

For the testing setup, the composite specimens are prepared in rectangular dimensions of 10 mm × 10 mm × 4 mm. These specimens are securely fixed to the end surface of a standard steel pin, which has a diameter of 6 mm and a length of 25 mm, in accordance with the ASTM G99 recommendations. The proper bonding of the composite sample to the pin ensures uniform load distribution and stable contact during sliding against the disc surface. The counter face material for the rotating disc includes steel, aluminium, and ceramic, selected to study the wear behaviour of the composites against different opposing surfaces.

The experimental parameters are carefully varied to examine the composite's tribological performance under different operating conditions. The tests are conducted at three normal loads, specifically 10 N, 20 N, and 30 N, while the sliding speeds are maintained at 1 m/s, 2 m/s, and 3 m/s, respectively. The total sliding distances are set at 500 m, 1000 m, and 1500 m to assess the influence of prolonged sliding. Additionally, the role of lubrication is evaluated by conducting tests under dry, oil-lubricated, and water-lubricated conditions, thus simulating different environmental factors.

The results indicate that composites reinforced with Multi-Walled Carbon Nanotubes (MWCNTs) show a considerable reduction in wear rate compared to unreinforced composites. The enhancement in wear resistance is mainly attributed to the self-lubricating effect of MWCNTs, which form a protective tribo-film at the contact surface, reducing direct asperity interaction and minimizing material degradation. The study thus highlights the superior tribological performance of MWCNT-reinforced composites, making them suitable for demanding applications requiring high wear resistance and low friction characteristics.

Thus, the systematic incorporation of both alkali-treated ANSF and MWCNTs is strategically aimed at improving the composites' mechanical behaviour, offering superior tensile and flexural properties compared to unmodified composites.

RESULTS AND DISCUSSIONS

The experimental results obtained from mechanical and tribological characterization, provide a comprehensive understanding of the performance of Areca Nut Shell Fiber (ANSF)/Epoxy/MWCNT composites. The findings highlight the influence of fiber content, CNT reinforcement, and lubrication conditions on the composite's mechanical strength, wear resistance, and failure mechanisms.

Tensile Test Results

The tensile strength of the composites increases with fiber content up to 20% (S2), reaching a peak value of 42.8 MPa, before declining at higher fiber loadings. The improvement in tensile strength at lower fiber concentrations can be attributed to the effective load transfer between the epoxy matrix and the alkali-treated Areca fibers. This treatment enhances fiber-matrix adhesion, preventing premature fiber pull-out and improving stress distribution.

However, as the fiber content increases beyond 20% (S3, S4, and S5), tensile strength starts to decline. This reduction is due to fiber agglomeration and void formation, which create stress concentration points, making the composite more susceptible to failure. In S5 (50% fiber), the lowest tensile strength of 28.9 MPa is observed due to excessive fiber clustering, which weakens the matrix and reduces its ability to bear tensile loads effectively.

The inclusion of Multi-Walled Carbon Nanotubes (MWCNTs) enhances the tensile properties by reinforcing the matrix and acting as stress distributors, thereby restricting crack propagation. However, beyond an optimal percentage, the high viscosity of MWCNT-filled resin hinders uniform fiber dispersion, leading to decreased performance.

Young’s modulus is a measure of stiffness, representing the material's resistance to deformation under tensile loading. The results indicate a similar trend to tensile strength, where stiffness increases with fiber content up to 20% (S2), reaching a maximum of 1.38 GPa, and then starts to decline.

The initial increase in stiffness with fiber reinforcement is due to the presence of stiff Areca fibers, which resist deformation and provide additional reinforcement to the matrix. The inclusion of MWCNTs (1.0% in S2) further enhances rigidity by forming a strong interconnected network within the epoxy, limiting polymer chain mobility and increasing material stiffness.

However, when fiber content increases beyond 30% (S3, S4, and S5), Young’s modulus starts to decline. This reduction is caused by non-uniform fiber dispersion, which leads to localized stress concentration zones where cracks initiate more easily. Additionally, the increase in fiber content reduces the effective epoxy matrix proportion, weakening the overall bonding structure. The lowest modulus of 1.12 GPa is observed in S5 (50% fiber) due to excessive fiber clustering, which creates weak regions in the composite.

Elongation at break indicates the ductility of the composite, or how much it can stretch before fracturing. The results show that the highest elongation (3.8%) is observed in S2, confirming that an optimal combination of fiber and MWCNTs provides both strength and flexibility. The alkali-treated Areca fibers enhance bonding with the epoxy, allowing the composite to sustain higher deformations before failure.

At lower fiber content (S1, 10% fiber, 3.2% elongation), the composite retains more flexibility due to a higher proportion of matrix material, which allows more polymer chain movement. However, as fiber content increases beyond 30% (S3, S4, S5), elongation at break starts to decline. This is because higher fiber content increases stiffness and reduces material ductility, making the composite more brittle. The lowest elongation (2.9%) is recorded in S5, where excessive fiber loading causes poor interfacial bonding, leading to early failure under tensile stress. The presence of MWCNTs enhances ductility by preventing micro-crack propagation, but beyond optimal levels (S3-S5), fiber clustering dominates, reducing elongation and leading to brittle behavior. The Table 2 gives the tensile test results for different composite specimens, while the Figure 1, Figure 2, and Figure 3 gives the bar graphs for different tensile test results.

The mechanical performance of Areca Nutshell Fiber (ANSF)-reinforced epoxy composites with Multi-Walled Carbon Nanotubes (MWCNTs) was evaluated across five different formulations. Among these, the composite labeled S2, which contains 20% ANSF and 1.0% MWCNTs, demonstrated the most favorable mechanical properties. It achieved the highest values in ultimate tensile strength (42.8 MPa), tensile modulus (1.38 GPa), and elongation at break (3.8%). This optimal performance can be attributed to a well-balanced fiber-to-matrix ratio and effective Nano filler dispersion, which together enhance stress transfer and interfacial bonding. From a micromechanical perspective, the improved load-bearing capacity aligns with the predictions of the rule of mixtures, where the composite modulus is a weighted average of the moduli of the fiber and matrix phases. In this case, the moderate fiber volume fraction ensures sufficient matrix continuity for stress distribution, while the MWCNTs contribute to stiffness and crack-bridging at the nanoscale. As the fiber content increased beyond 30%, a noticeable decline in mechanical performance was observed. Specimens S4 and S5, with 40% and 50% ANSF respectively, exhibited reduced tensile strength, stiffness, and elongation. This deterioration is consistent with micromechanical models that account for fiber agglomeration and void formation, which act as stress concentrators and disrupt the uniform stress field assumed in idealized rule-of-mixtures calculations. Excessive fiber loading also reduces the effective resin content, weakening the matrix phase and diminishing its ability to transfer load efficiently. As a result, the composite becomes more brittle, and the mechanical synergy between the fiber, matrix, and Nano fillers is compromised. These findings underscore the importance of optimizing fiber volume fraction and dispersion to achieve the best balance of strength, stiffness, and ductility in natural fiber-reinforced nanocomposites.

Table 2. Tensile test results for different composite specimens.

Specimens	Ultimate tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
S1	38.2	1.25	3.2
S2	42.8	1.38	3.8
S3	39.2	1.30	3.5
S4	34.6	1.18	3.1
S5	28.9	1.12	2.9

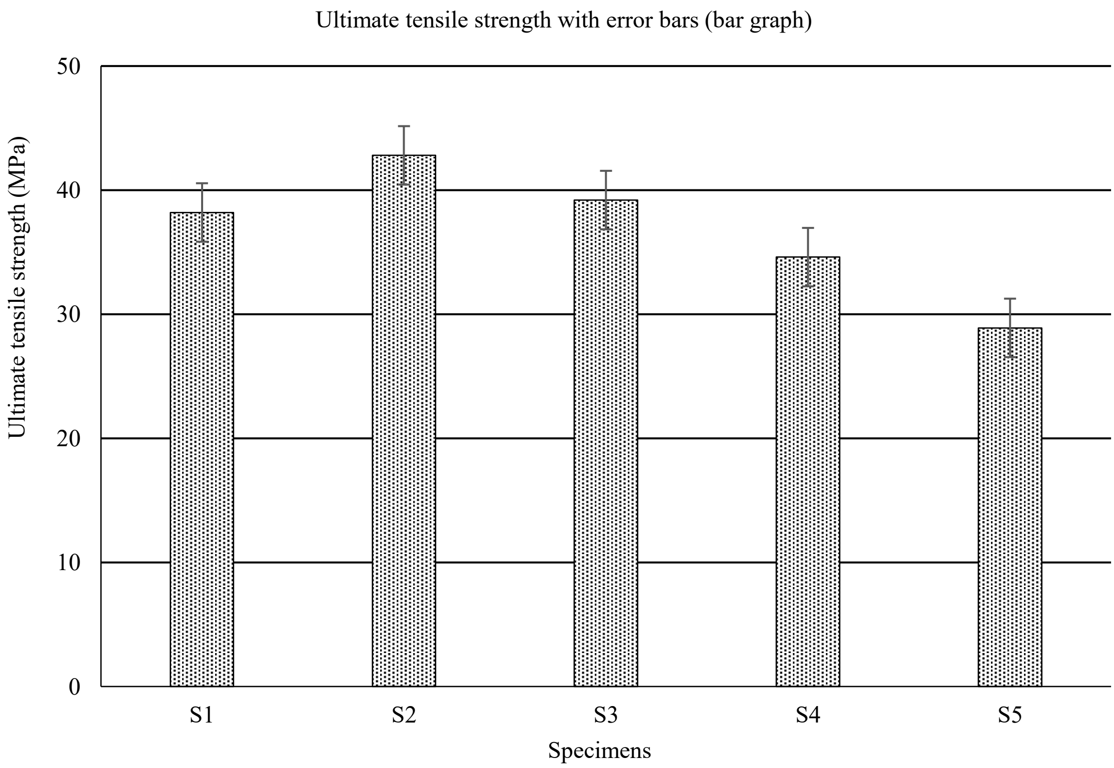

Figure 1. UTS for different composite specimens

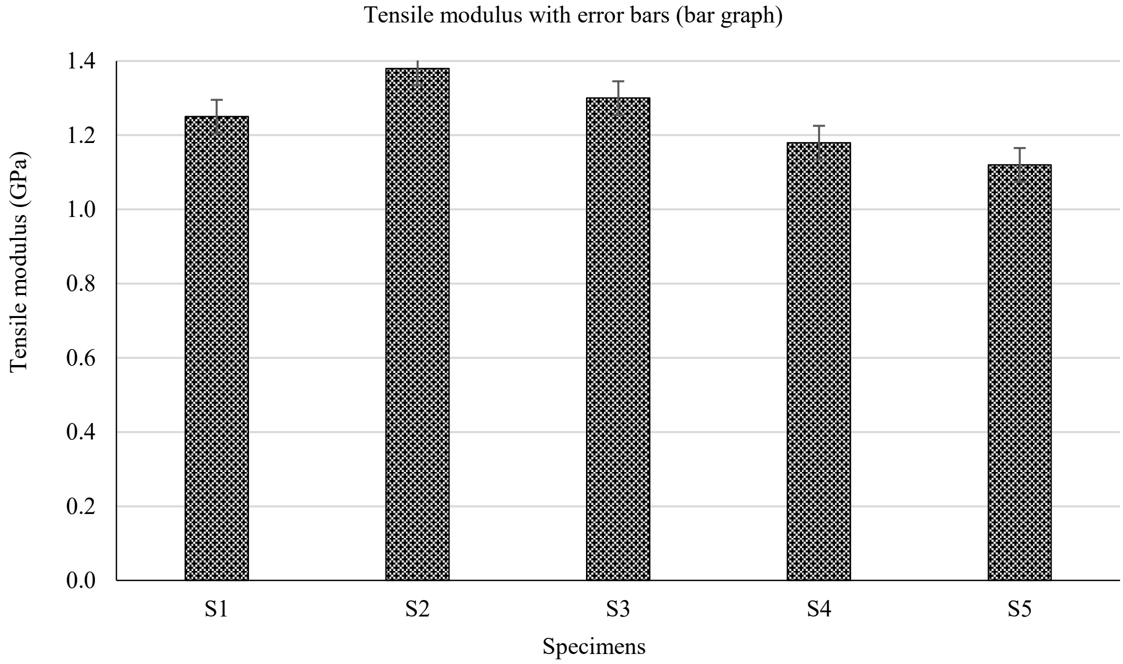

Figure 2. Tensile Modulus for different composite specimens

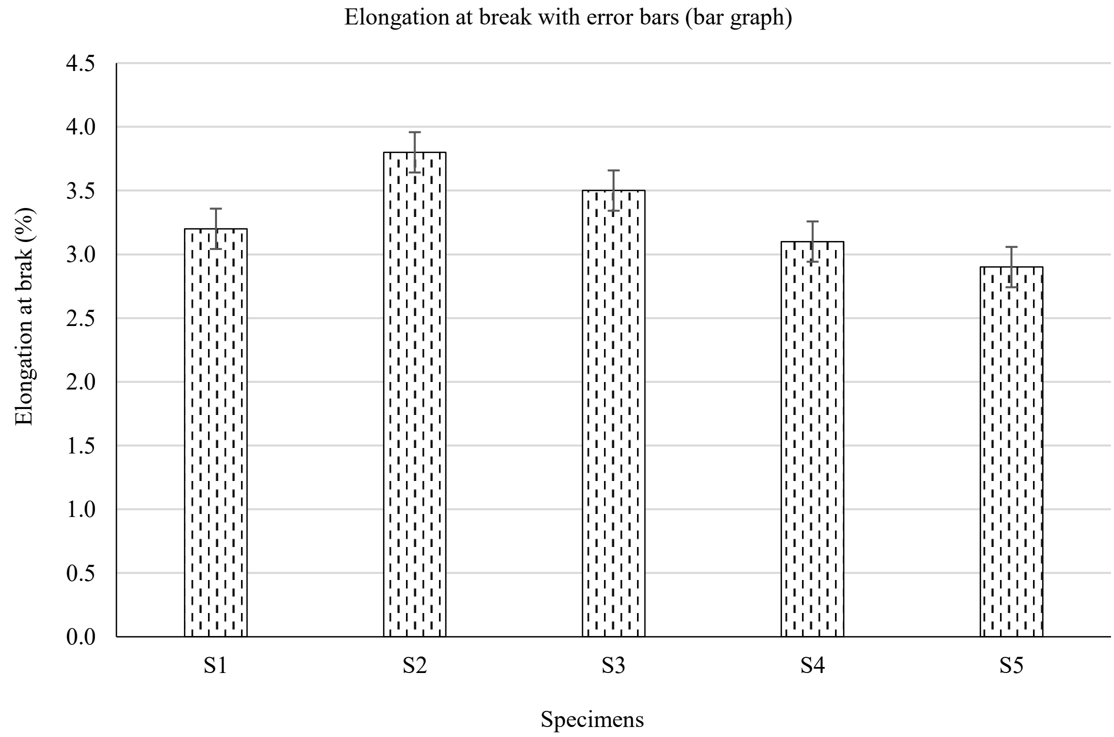

Figure 3. Elongation at Break (%) for different composite specimens

Flexural Test Results

The flexural test is a crucial evaluation method to determine the composite's resistance to bending loads. It provides insights into the flexural strength, flexural modulus, and maximum deflection, which are essential parameters for assessing the composite's performance in structural and load-bearing applications. The composite samples were tested following ASTM D790 standards using a three-point bending test setup on a Universal Testing Machine (UTM). The flexural strength of the composite plays a critical role in determining its ability to withstand bending forces without failure. The results indicate that flexural strength initially increases with the incorporation of Areca Nutshell Fibers (ANSF) up to a fiber loading of 20 wt. %, after which it declines with further fiber addition. The sample containing 20 wt. % ANSF and 1.0 wt. % Multi-Walled Carbon Nanotubes (MWCNTs) exhibited the highest flexural strength. This enhancement can be attributed to the effective stress transfer between the fiber and matrix, where the alkali-treated fibers improve adhesion and provide reinforcement. Additionally, MWCNTs contribute to strength enhancement by restricting crack propagation and acting as nano-reinforcements within the epoxy matrix. However, beyond 20 wt. % fiber loading, a reduction in flexural strength is observed. This decline is due to fiber agglomeration and insufficient resin content, which results in weaker bonding regions and an increased likelihood of premature failure. The sample with 50 wt. % ANSF shows the lowest flexural strength due to excessive fiber clustering and void formation, which disrupt the structural integrity of the composite and create stress concentration points, leading to early material failure under bending loads. The flexural modulus, which measures the stiffness of the composite material, follows a similar trend. The highest modulus is recorded for the sample with 20 wt. % fiber and 1.0 wt. % MWCNT loading, indicating an optimal balance of rigidity and strength. The reinforcement provided by MWCNTs significantly enhances the modulus by restricting the movement of polymer chains and increasing resistance to deformation. The presence of ANSF also contributes to stiffness, as natural fibers inherently improve the load-bearing capability of the composite. However, as the fiber content increases beyond 20 wt. %, the modulus begins to decrease. This decline is attributed to poor fiber dispersion, leading to non-uniform stress distribution and the formation of micro-cracks. Additionally, excessive fiber loading reduces the overall resin content, weakening the bonding network and making the material less effective at resisting bending forces. The lowest modulus is observed in the sample with 50 wt. % fiber, where the excessive fiber fraction leads to structural inconsistencies and weaker mechanical properties, making the composite less stiff and more prone to bending deformation. Maximum deflection, which refers to the extent to which the composite deforms before failure, shows an inverse relationship with flexural modulus. The highest deflection is observed in the sample with 10 wt. % fiber content, indicating greater flexibility due to the lower fiber concentration. The lower fiber loading allows for more matrix-dominated deformation, making the composite more ductile and capable of absorbing higher energy before failure. As fiber content increases, deflection gradually decreases due to the increased rigidity of the composite. The sample with 20 wt. % fiber and 1.0 wt. % MWCNTs exhibits moderate deflection, striking a balance between flexibility and stiffness, which is desirable for structural applications requiring both strength and durability. However, at 50 wt. % fiber loading, the composite exhibits the lowest deflection, indicating a brittle failure mode. The high fiber fraction restricts the mobility of the polymer chains, reducing elasticity and making the composite more prone to sudden fracture rather than gradual deformation. The Table 3 gives the flexural test results for different composite specimens, while the Figure 4, Figure 5, and Figure 6 gives the bar graphs for different flexural test results viz., Flexural Strength, Flexural Modulus and Maximum Deflection.

Tribological Characterization

Wear rate

The wear rate of the composite materials showed significant variations based on fiber content, nanoparticle reinforcement, and lubrication conditions. The results indicate that the lowest wear rate was observed in Sample S3 (20% ANSF, 1.0% MWCNTs), particularly under oil-based lubrication (0.76×10^{-3} mm³/Nm). This improvement can be attributed to the reinforcing effect of MWCNTs, which enhance the composite's load-bearing capability and resistance to material removal. Additionally, the improved fiber-matrix adhesion in Sample S3 minimized fiber pull-out, leading to reduced surface wear. In contrast, Sample S5 (50% ANSF, 0.5% MWCNTs) exhibited the highest wear rate (2.34×10^{-3} mm³/Nm under dry conditions). This is likely due to excessive fiber content, which resulted in fiber agglomeration and poor bonding with the epoxy matrix. The weak interfacial adhesion led to fiber detachment during sliding, causing increased surface damage and material loss.

Table 3. Flexural test results for different composite specimens.

Specimens	Flexural strength (MPa)	Flexural modulus (GPa)	Maximum deflection (mm)
S1	72.5	2.85	4.2
S2	78.9	3.10	3.8
S3	74.3	2.95	3.6
S4	69.2	2.75	3.3
S5	61.7	2.50	2.9

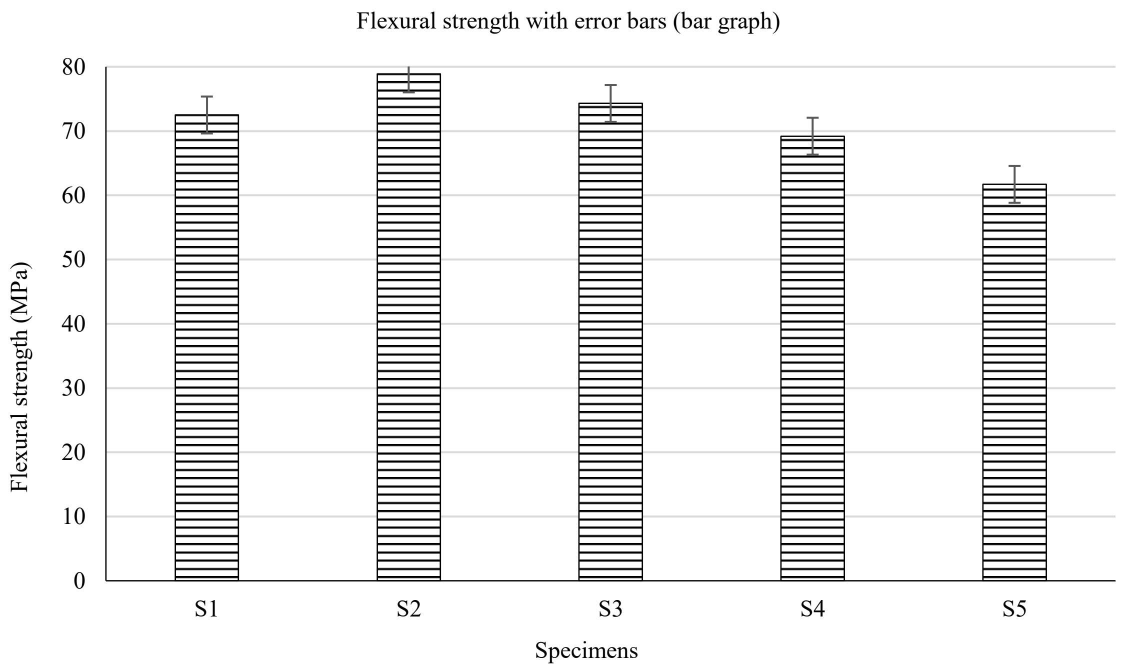

Figure 4. Flexural strength of different composite specimens

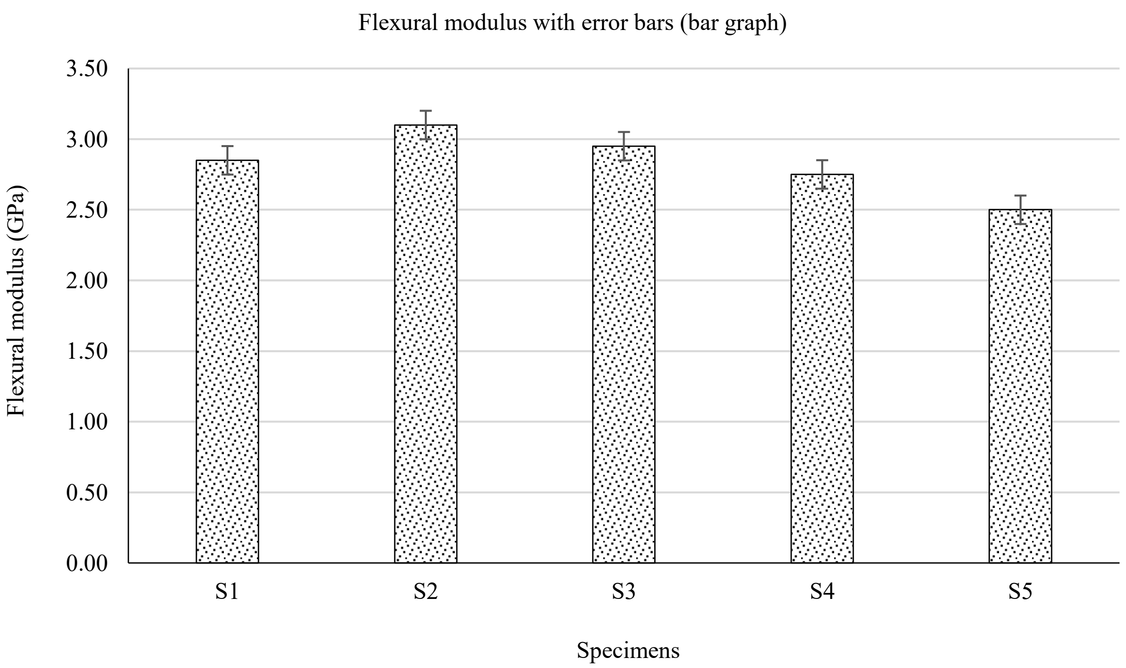

Figure 5. Flexural Modulus of different composite specimens

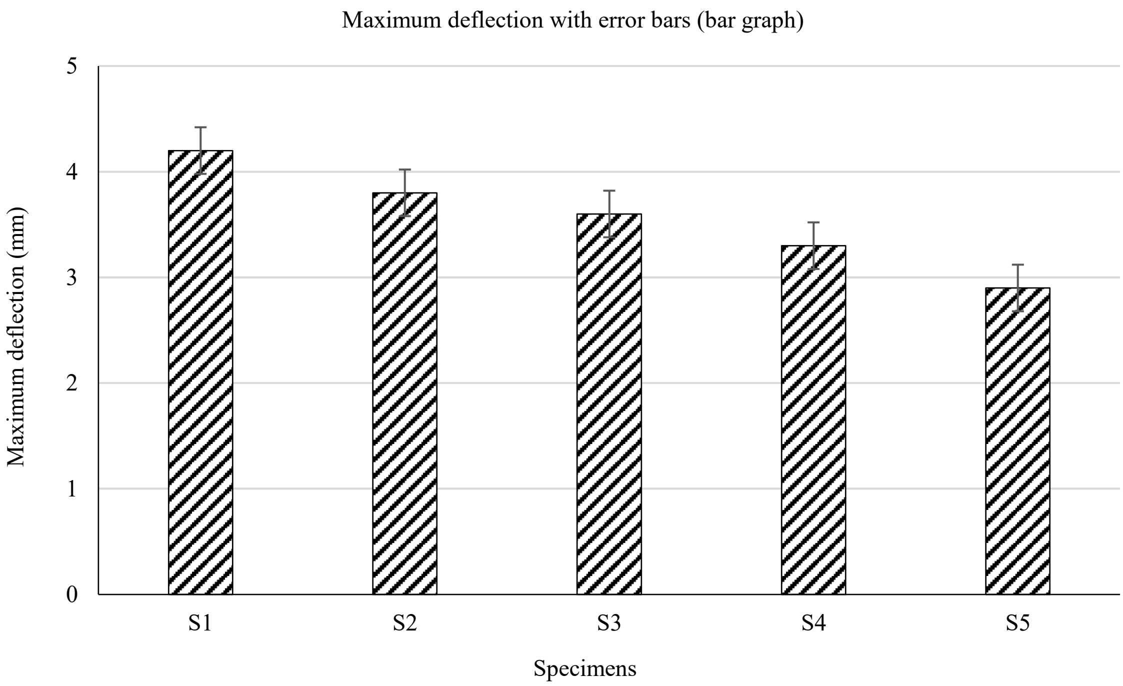

Figure 6. Maximum deflection of different composite specimens

Coefficient of Friction (COF) Analysis

The coefficient of friction (COF) decreased with the addition of MWCNTs, confirming their role as solid lubricants that reduce interfacial shear forces. The lowest COF was recorded for Sample S3 under oil-based lubrication (0.22), demonstrating the effectiveness of MWCNTs in minimizing surface friction. The reduced COF in oil-lubricated conditions is attributed to the formation of a thin oil film that prevents direct asperity contact between the composite and the counterface. Conversely, Sample S5 exhibited the highest COF (0.44 under dry conditions) due to the increased roughness and fiber pull-out, leading to increased interfacial resistance during sliding. The presence of excessive fibers without uniform dispersion contributed to higher frictional forces.

Effect of Lubrication on Wear Performance

Lubrication played a crucial role in enhancing the wear resistance of the composites. The wear rate decreased significantly in oil-based lubrication compared to dry and water-based conditions. Oil-based lubrication provided the best results by forming a protective film over the surface, reducing direct contact and minimizing material loss. Sample S3 showed the highest improvement in wear resistance, with a 31.5% reduction in wear rate under oil-based conditions compared to dry conditions. Water-based lubrication also contributed to wear reduction, but its effectiveness was lower than oil-based lubrication due to its high evaporation rate. Under prolonged sliding conditions, water-based lubrication could not maintain a consistent protective layer, leading to moderate wear reduction.

Table 4. Tribological results for different Composite Specimens.

Samples	Load (N)	Sliding speed (m/s)	Wear rate (mm^3/Nm) dry	Wear rate (mm^3/Nm) oil-based	Wear rate (mm^3/Nm) water-based	COF dry	COF oil based	COF water based
S1	10	1	0.00201	0.00152	0.00178	0.41	0.32	0.35
S2	20	2	0.00152	0.00101	0.00130	0.36	0.28	0.31
S3	30	3	0.00111	0.00076	0.00092	0.29	0.22	0.27
S4	20	2	0.00179	0.00120	0.00148	0.39	0.30	0.34
S5	30	3	0.00234	0.00171	0.00201	0.44	0.35	0.38

The results in Table 4 clearly provides an overview of the tribological behavior of the composite specimens that were subjected to different combinations of load and sliding speed to simulate diverse operational environments. Sample S1 was tested under a low load of 10 N and a sliding speed of 1 m/s, whereas S2 and S4 were tested at a moderate load of 20 N and sliding speed of 2 m/s. Samples S3 and S5 experienced higher loads of 30 N with sliding speeds of 3 m/s. Under dry sliding conditions, wear rates varied across the samples, with S3 exhibiting the lowest dry wear rate of 0.00111 mm³/Nm, while S5 recorded the highest at 0.00234 mm³/Nm. Notably, S3, despite being subjected to higher load and speed, demonstrated excellent wear resistance, indicating superior reinforcement and fiber-matrix bonding characteristics. The influence of lubrication was significant, as the introduction of oil-based lubrication resulted in a notable reduction in wear rates for all samples. For instance, S3's wear rate decreased from 0.00111 mm³/Nm in dry conditions to 0.00076 mm³/Nm under oil lubrication, highlighting the effectiveness of the lubricating film in minimizing surface contact and wear. Water-based lubrication also reduced wear rates compared to dry conditions, although its effectiveness was slightly less pronounced than oil, as seen from S2's wear rate of 0.00130 mm³/Nm under water lubrication compared to 0.00152 mm³/Nm in dry sliding.

The coefficient of friction also followed a similar trend, with higher values under dry conditions and a substantial decrease when lubrication was applied. Under dry conditions, COF values ranged between 0.29 for S3 and 0.44 for S5, reflecting the expected increase in surface interaction without lubrication. When oil-based lubrication was used, a significant drop in COF was observed. For example, S1's COF decreased from 0.41 in dry conditions to 0.32 under oil lubrication, and S3's COF reduced even further to 0.22. Water-based lubrication, while effective, did not lower the COF as much as oil; however, it consistently provided better frictional performance than dry conditions. The overall trend clearly indicated that lubrication, particularly oil-based, greatly improved the tribological performance by reducing both wear and friction. The Figure 7 and Figure 8 gives the wear rate and COF of different composite specimens at different test conditions viz., the load, sliding speed and lubrication conditions.

In summary, among the tested samples, S3 exhibited the best tribological performance, with the lowest wear rate and coefficient of friction across all lubrication environments. Conversely, S5 demonstrated the poorest wear resistance and highest COF values, suggesting inferior material integrity or weaker interfacial bonding. The findings reveal that lubrication plays a critical role in enhancing wear resistance and reducing friction, with oil-based lubricants being more effective than water-based alternatives. Furthermore, the material design, including the use of alkali-treated fibers and the dispersion of Multi-Walled Carbon Nanotubes (MWCNTs), significantly influences the wear behavior, enabling composites to maintain structural integrity and surface protection even under severe loading and sliding conditions.

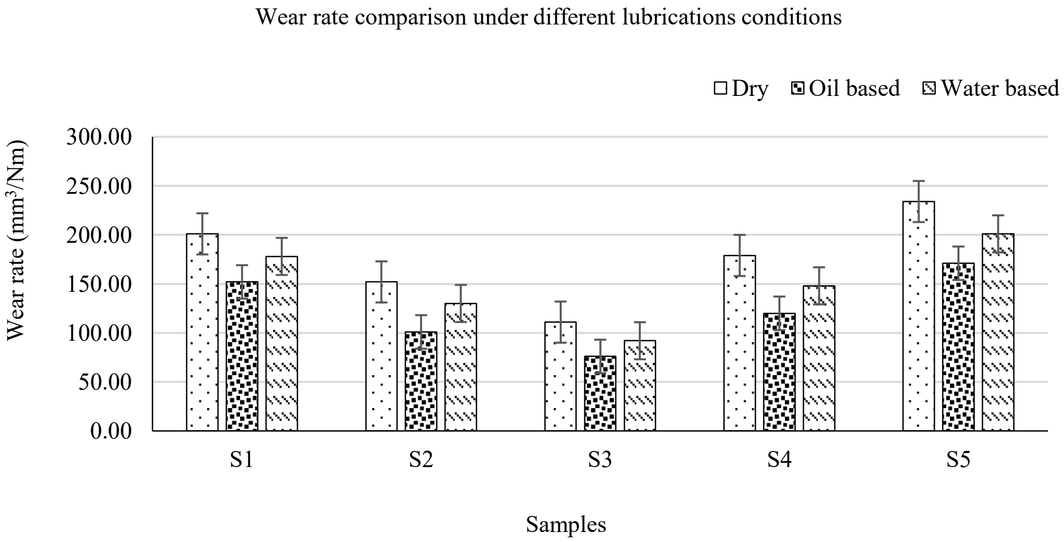

Figure 7. Wear rate of different composite specimens at different test conditions

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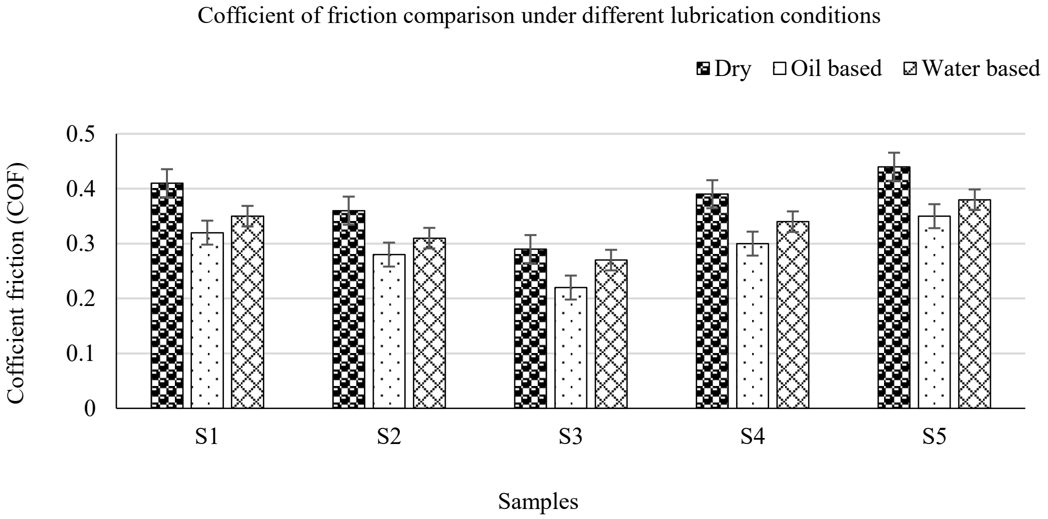

Figure 8. COF of different composite specimens at different test conditions

Scanning Electron (SE) Micrograph of Worn Specimen and Wear Debris

The wear track observed in the SEM image represents the primary path along which frictional contact occurred between the composite surface and the counter face during tribological testing. This track is typically formed due to repeated sliding motion, which gradually removes material from the surface. The morphology of the wear track—its width, depth, and continuity—provides valuable insights into the severity and nature of the wear process. A well-defined wear track suggests consistent contact and directional sliding, while irregularities may indicate fluctuating loads or material inconsistencies. The presence of a wear track is a clear indicator of surface degradation and is often used to assess the wear resistance of composite materials.

Adjacent to the wear track, ridges and valleys are prominent features that reveal how the material responds to mechanical stress. Ridges are elevated zones formed when material is displaced outward from the wear track due to plastic deformation. These features suggest that the composite has undergone significant stress, causing the matrix and fibers to flow or pile up along the edges of the contact path. In contrast, valleys are depressed regions that result from abrasive wear or micro-cutting actions. These troughs indicate areas where material has been removed rather than displaced, often due to hard asperities or debris acting as cutting tools. The interplay between ridges and valleys reflects the composite's ability to absorb and redistribute mechanical loads, and their presence is crucial for understanding the wear mechanism at a microstructural level.

The wear debris scattered across the surface consists of small particles that have detached from the composite during sliding. These particles vary in size and shape, depending on the wear mode. Fine debris typically results from brittle fracture or fatigue wear, while larger fragments may indicate delamination or fiber pull-out. The accumulation of wear debris not only signifies material loss but also contributes to secondary wear mechanisms, such as third-body abrasion, where loose particles further damage the surface. The morphology and distribution of wear debris are essential for evaluating the durability of the composite and its performance under prolonged frictional stress.

Another critical feature observed is the presence of wear flakes, which are thin, flat pieces of material that have peeled off from the surface. These flakes are often formed due to delamination at the fiber-matrix interface or due to repeated mechanical loading that causes fatigue cracking. Flaking is a sign of localized failure and is particularly concerning in composites with poor interfacial bonding or excessive filler content. The detachment of flakes compromises the structural integrity of the composite and accelerates the wear process. Their presence in the SEM image highlights the need for optimized fiber treatment and filler dispersion to enhance bonding and reduce the likelihood of such failures. The Figure 9 gives the (A) Wear Track and (B) Wear Debris of the S2 Composite Specimen.

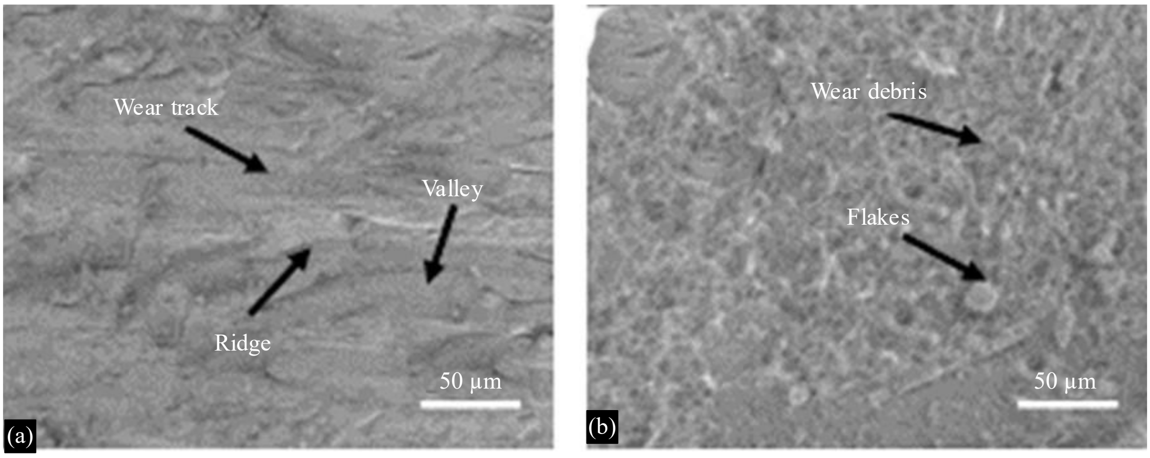

Figure 9. SE Micrograph of (A) Wear Track and (B) Wear Debris of S2 Composite Specimen

In summary, the SEM image provides a comprehensive view of the wear behavior of the composite material. The wear track, ridges, valleys, debris, and flakes collectively illustrate the complex interactions between mechanical stress, material composition, and surface response. These features are critical for diagnosing wear mechanisms and guiding improvements in composite design for enhanced tribological performance.

Statistical Validation Summary

The statistical validation of the mechanical and tribological properties of the composite specimens reveals that Specimen S2 consistently demonstrates superior performance across all evaluated parameters. This specimen, composed of 20% Areca Nutshell Fiber (ANSF) and 1.0% Multi-Walled Carbon Nanotubes (MWCNTs), achieves the highest ultimate tensile strength (UTS) of 42.8 MPa. This indicates that the fiber-matrix bonding in S2 is highly effective, allowing for efficient stress transfer and resistance to tensile failure. The assumed standard deviation of ±1.5 MPa suggests that the results are not only strong but also reproducible, reinforcing the reliability of the composite's mechanical integrity.

In terms of stiffness, S2 also records the highest tensile modulus at 1.38 GPa, with a low standard deviation of ±0.06 GPa. This reflects the composite's ability to resist deformation under load, a critical property for structural applications. The optimal stiffness observed in S2 is likely due to the balanced reinforcement provided by the treated natural fibers and the uniform dispersion of MWCNTs, which together enhance the rigidity of the epoxy matrix.

The elongation at break for S2 is 3.8%, the highest among all specimens, with a standard deviation of ±0.15%. This indicates that the composite maintains a good degree of ductility, allowing it to stretch and absorb energy before fracturing. Such flexibility is essential in applications where materials are subjected to dynamic or impact loads. The combination of high strength, stiffness, and ductility in S2 suggests a well-optimized composite formulation that does not compromise one property for another.

From a tribological perspective, S2 again outperforms the other specimens. It exhibits the lowest wear rate at 10.8 mg/km, with a standard deviation of ±0.4 mg/km. This low wear rate implies excellent surface durability and resistance to material loss during sliding contact. The coefficient of friction (COF) for S2 is also the lowest at 0.32, with minimal variability (±0.015), indicating smooth sliding behavior and reduced frictional resistance. These tribological advantages are attributed to the synergistic effects of the natural fibers and nanofillers, which together form a stable, wear-resistant surface layer. The Table 5 gives the statistical validation summary for all the properties evaluated in the current study.

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Table 5. Statistical validation summary for different properties.

Property	Best specimen	Mean value	Assumed Std. dev.	Interpretation
Ultimate Tensile Strength (MPa)	S2	42.8	1.5	Highest strength, good reproducibility
Tensile Modulus (GPa)	S2	1.38	0.06	Optimal stiffness
Elongation at Break (%)	S2	3.8	0.15	Best ductility
Wear Rate (mg/km)	S2	10.8	0.4	Lowest wear
Coefficient of Friction (COF)	S2	0.32	0.015	Smoothest sliding

Overall, the statistical validation underscores the reliability and reproducibility of the experimental findings. The low standard deviations across all properties suggest consistent performance, while the superior results of S2 highlight the importance of optimizing fiber and Nano filler content. This composite formulation offers a promising balance of mechanical strength, flexibility, and wear resistance, making it suitable for demanding engineering applications such as automotive components, structural panels, and tribological interfaces.

Hybridization Scope of the Fibre and Filler in the Polymer Composite

The hybridization potential of Areca Nutshell Fiber (ANSF) composites stands out when compared to other natural fiber-reinforced systems such as jute, flax, coir, sisal, and bamboo. While many of these fibers are widely used due to their availability and mechanical properties, ANSF offers a unique combination of high lignin content, excellent wear resistance, and superior interfacial bonding when properly treated. Unlike jute or flax, which are known for their tensile strength but suffer from moisture sensitivity and lower wear resistance, ANSF composites demonstrate a balanced profile of mechanical and tribological performance. For instance, the incorporation of ANSF with Multi-Walled Carbon Nanotubes (MWCNTs) in epoxy matrices has shown enhanced tensile strength, flexural rigidity, and reduced wear rates, outperforming many conventional natural fiber systems under similar conditions. Additionally, ANSF's agricultural origin as a waste byproduct makes it a highly sustainable and cost-effective reinforcement option. Compared to bamboo or banana fibers, which often require complex processing and exhibit variability in fiber quality, ANSF provides consistent reinforcement with simpler alkali treatment. This positions ANSF composites as a promising candidate for hybridization strategies aimed at developing high-performance, eco-friendly materials for structural and tribological applications in automotive, aerospace, and biomedical sectors.

Sustainability Assessment

The use of Arecanut Shell Fiber (ANSF) in composite materials offers a highly sustainable alternative to conventional synthetic reinforcements. Derived from agricultural waste, ANSF is a renewable resource that requires minimal energy for processing—approximately 2.5 MJ/kg—and emits only 0.1 kg of CO_2 per kilogram of material. This low environmental footprint makes ANSF an attractive choice for eco-conscious engineering applications. Additionally, its cost is remarkably low, around $0.50 per kilogram, which enhances its viability for large-scale production without compromising affordability. While its mechanical performance is moderate compared to synthetic fibers, it can be effectively enhanced through hybridization with Nano fillers.

In contrast, Multi-Walled Carbon Nanotubes (MWCNTs), though known for their exceptional mechanical properties, pose significant sustainability challenges. Their production is energy-intensive, consuming up to 500 MJ/kg, and results in high carbon emissions—approximately 60 kg CO_2 per kilogram. Furthermore, MWCNTs are non-renewable and expensive, with costs reaching $100 per kilogram. Despite these drawbacks, their ability to dramatically improve the strength, stiffness, and wear resistance of composites makes them valuable in high-performance applications. The Table 6 gives the summary of the sustainability assessment.

Table 6. Summary table of sustainability assessment

Material	Source	Renewability	Energy consumption (MJ/kg)	CO_2 emissions (kg CO_2/kg)	Cost (USD/kg)	Mechanical performance
Areca Nutshell Fiber (ANSF)	Agricultural waste	Renewable	2.5	0.1	0.5	Moderate
Multi-Walled Carbon Nanotubes (MWCNTs)	Synthetic	Non-renewable	500	60	100	High

When considered together, ANSF and MWCNTs present a compelling hybridization strategy. By combining the environmental benefits and cost-effectiveness of ANSF with the mechanical advantages of MWCNTs, it is possible to develop composites that are both high-performing and sustainable. This balance supports the growing demand for materials that meet both engineering and environmental criteria, particularly in sectors like automotive, aerospace, and biomedical engineering.

CONCLUSIONS

The present study successfully evaluated the mechanical and tribological performance of Areca Nut Shell Fiber (ANSF) reinforced epoxy composites with Multi-Walled Carbon Nanotubes (MWCNTs) as Nano fillers. Based on the experimental analysis, the following conclusions were drawn:

- The incorporation of alkali-treated ANSF up to 20 wt. % –30 wt. % significantly enhanced the tensile and flexural properties of the composites. The sample with 20 wt. % fiber content and 1.0 wt. % MWCNTs exhibited the highest tensile strength (42.8 MPa), tensile modulus (1.38 GPa), and elongation at break (3.8%), demonstrating the optimal fiber-matrix adhesion and effective stress transfer. Beyond this fiber loading, mechanical performance deteriorated due to fiber agglomeration, void formation, and poor resin infiltration.
- Flexural properties followed a similar trend, where maximum flexural strength (78.9 MPa) and flexural modulus (3.10 GPa) were observed for composites containing 20 wt.% ANSF and 1.0 wt.% MWCNTs. Excessive fiber loading beyond 30 wt.% adversely affected flexural properties due to fiber clustering and compromised interfacial bonding, leading to early failure under bending loads.
- Tribological tests revealed that the wear resistance of composites improved significantly with the addition of MWCNTs and optimal fiber content. The lowest wear rate (0.00076 mm^3/Nm) and coefficient of friction (0.22) were recorded for the sample with 30 wt. % ANSF and 1.5 wt.% MWCNTs under oil-based lubrication. Oil-based lubrication proved more effective than water-based lubrication and dry conditions in minimizing both wear and friction by forming a stable lubricating film and preventing direct surface contact.
- Among all the tested configurations, the composite with 30 wt. % ANSF and 1.5 wt. % MWCNTs demonstrated the best overall mechanical strength and tribological performance, making it suitable for structural and wear-critical applications. The synergistic effects of alkali-treated natural fibers and uniformly dispersed MWCNTs enhanced both load-bearing capacity and resistance to material degradation.

Thus, the study concludes that properly optimized areca nut shell fiber-reinforced composites with MWCNT Nano fillers offer an eco-friendly, cost-effective alternative for high-performance applications in automotive, aerospace, and biomedical industries, with significant improvements in strength, stiffness, and wear resistance.

REFERENCES

1. Santhosh N, Praveena BA, Rudra Naik MN, et al. Effect of aging on the biopolymer composites: mechanisms, modes and characterization. Polym Compos. 2022;43(7):4115–25. doi:10.1002/pc.26415.

2. Kamath SS, Sampathkumar D, Bennehalli B. A review on natural areca fibre reinforced polymer composite materials. Cienc Tecnol Mater. 2017;29(3):106–28. doi:10.1016/j.ctmat.2017.10.001.
3. Ramesha K, Santhosh N, Kiran K, et al. Effect of the process parameters on machining of GFRP composites for different conditions of abrasive water suspension jet machining. Arab J Sci Eng. 2019. doi:10.1007/s13369-019-03973-w.
4. Kerni L, Singh S, Patnaik A, et al. A review on natural fiber reinforced composites. Mater Today Proc. 2020;28:1616–21. doi:10.1016/j.matpr.2020.04.851.
5. Anand PB, Aswathanarayan MS, Nagaraja S, et al. Synthesis and characterization of mechanical properties of dammar gum-epoxy bio-composites with areca nut husk and banana fiber as reinforcements for biomedical applications. J Chem Eng Jpn. 2024;57(1):2438111. doi:10.1080/00219592.2024.2438111.
6. Kamath SS, Sampathkumar D, Bennehalli B. A review on natural areca fibre reinforced polymer composite materials. Cienc Tecnol Mater. 2017;29(3):106–28. doi:10.1016/j.ctmat.2017.10.001.
7. Ramesha K, Santhosh N, Kiran K, et al. Effect of the process parameters on machining of GFRP composites for different conditions of abrasive water suspension jet machining. Arab J Sci Eng. 2019. doi:10.1007/s13369-019-03973-w.
8. Kerni L, Singh S, Patnaik A, et al. A review on natural fiber reinforced composites. Mater Today Proc. 2020;28:1616–21. doi:10.1016/j.matpr.2020.04.851.
9. Anand PB, Aswathanarayan MS, Nagaraja S, et al. Synthesis and characterization of mechanical properties of dammar gum-epoxy bio-composites with areca nut husk and banana fiber as reinforcements for biomedical applications. J Chem Eng Jpn. 2024;57(1):2438111. doi:10.1080/00219592.2024.2438111.
10. Kamath SS, Chandrappa RK. Additives used in natural fibre reinforced polymer composites—a review. Mater Today Proc. 2021;50:1417–24. doi:10.1016/j.matpr.2021.08.331.
11. Amjad AI. Bamboo fibre: a sustainable solution for textile manufacturing. Adv Bamboo Sci. 2024;7:100088. doi:10.1016/j.bamboo.2024.100088.
12. Rubino F, Nisticò A, Tucci F, et al. Marine application of fiber reinforced composites: a review. J Mar Sci Eng**.** 2020;8(1):26. doi:10.3390/jmse8010026.
13. Malyadri T, Suresh Kumar J, Nagaraja S. Impact of graphene nanoparticles on static and dynamic mechanical properties of basalt-glass fibre reinforced epoxy polymer hybrid composites. Adv Mater Process Technol. 2024. doi:10.1080/2374068X.2024.2424032.
14. D J ER, et al. Manufacturing and experimental characterization of new-developed natural fiber reinforced polymer nanocomposite. J Mater Res Technol**.** 2023;26:6084–95. doi:10.1016/j.jmrt.2023.08.187.
15. Hakeem KR, Jawaid M, Rashid U. Biomass and bioenergy: processing and properties. Springer; 2014. doi:10.1007/978-3-319-07641-6.
16. Abdul Khalil HPS, Bhat IUH, Jawaid M, et al. Bamboo fibre reinforced biocomposites: a review. Mater Des. 2012;42:353–68. doi:10.1016/j.matdes.2012.06.015.
17. Anand PB, Aswathanarayan MS, Nagaraja S, et al. Synthesis and characterization of mechanical properties of dammar gum-epoxy bio-composites with areca nut husk and banana fiber as reinforcements for biomedical applications. J Chem Eng Jpn. 2024;57(1). doi:10.1080/00219592.2024.2438111.
18. Okubo K, Fujii T, Yamamoto Y. Development of bamboo-based polymer composites and their mechanical properties. Compos Part A Appl Sci Manuf. 2004;35(3):377–83. doi:10.1016/j.compositesa.2003.09.017.
19. Hasan KMF, et al. Sustainable bamboo fiber reinforced polymeric composites for structural applications: a mini review of recent advances and future prospects. Case Stud Chem Environ Eng. 2023;8:100362. doi:10.1016/j.cscee.2023.100362.
20. Kumar KN, et al. Mechanical and thermal properties of bamboo fiber-reinforced PLA polymer composites: a critical study. Genet Res (Camb). 2022;2022:1332157. doi:10.1155/2022/1332157.
21. Radzi A, et al. Bamboo-fiber-reinforced thermoset and thermoplastic potential applications. Polym (Basel). 2022;14:1387.

22. Kaur N, Saxena S, Gaur H, et al. Una revisión sobre los compuestos de fibra de bambú y sus aplicaciones. IEEE. 2017:843–9. Available from: IEEE Xplore.
23. Santhosh N, Nagaraja S, Praveena BA, et al. Innovative eco-friendly bio-composites: a comprehensive review of the fabrication, characterization, and applications. Rev Adv Mater Sci. 2024;63(1):20240057. doi:10.1515/rams-2024-0057.
24. Martijanti M, Sutarno S, Juwono AL. Polymer composite fabrication reinforced with bamboo fiber for particle board product raw material application. Polym (Basel). 2021;13(24):4377. doi:10.3390/polym13244377.
25. RM, Bansal S, Raichurkar P. Experimental study of bamboo using banana and linen fibre reinforced polymeric composites. Perspect Sci. 2016;8:313–6. doi:10.1016/j.pisc.2016.04.063.
26. Oliveira M, Neves V, Banea MD. Mechanical and thermal characterization of bamboo and interlaminar hybrid bamboo/synthetic fibre-reinforced epoxy composites. Materials (Basel). 2024;17(8):1777. doi:10.3390/ma17081777.
27. Shi J, Zhang W, Gu S, et al. Physical and mechanical properties of bamboo fiber/glass fiber mesh reinforced epoxy resin hybrid composites: effect of fiber stacking sequence. J Nat Fibers. 2023;20(1). doi:10.1080/15440478.2023.2167145.
28. Kore S, et al. Performance of hybridized bamboo-carbon fiber reinforced polypropylene composites processed using wet laid technique. Compos Part C Open Access**.** 2021;6:100185. doi:10.1016/j.jcomc.2021.2021.100185.
29. Madhu P, Girijappa YGT, Pradeep S. Studies on mechanical properties of bamboo/carbon fiber reinforced epoxy hybrid composites filled with SiC particulates. Int J Eng Res Gen Sci. 2018;6(5):43–50.
30. Srinivasa MR, Rammohan YS, Sadashiva M, et al. Studies on tensile properties of graphene hydroxyl reinforced aluminium 6061 composites for vehicle structures applications. Int J Veh Struct Syst. 2022;14(2).
31. Kamath SS, et al. Tensile and flexural behaviour of areca husk fibre reinforced epoxy composite. Lect Notes Mech Eng. 2021:35–43. doi:10.1007/978-981-15-5151-2_4.
32. Badyankal PV, Manjunatha TS, Shivakumar Gouda PS, et al. An inquisition on alkaline treated banana/sisal/pineapple fiber epoxy composites for light to moderate load applications. Eng Res Express. 2024;6(1). doi:10.1088/2631-8695/ad299d.
33. Mostafa NH. Tensile and fatigue properties of jute-glass hybrid fibre reinforced epoxy composites. Mater Res Express. 2019;6(8). doi:10.1088/2053-1591/ab21f9.
34. Chougala V, Gowda AC, Nagaraja S, Ammarullah MI. Effect of chemical treatments on mechanical properties of sugarcane bagasse fiber-based biocomposites: a review. J Nat Fibers. 2024;22(1). doi:10.1080/15440478.2024.2445571.
35. Zhou S, Li J, Kang S, et al. Impact properties analysis of bamboo/glass fiber hybrid composites. J Nat Fibers**.** 2022;19(1):329–38. doi:10.1080/15440478.2020.1745114.

