# Experimental study on the mechanical and tribological characteristics of pineapple leaf fiber reinforced polymer composites for biomedical applications

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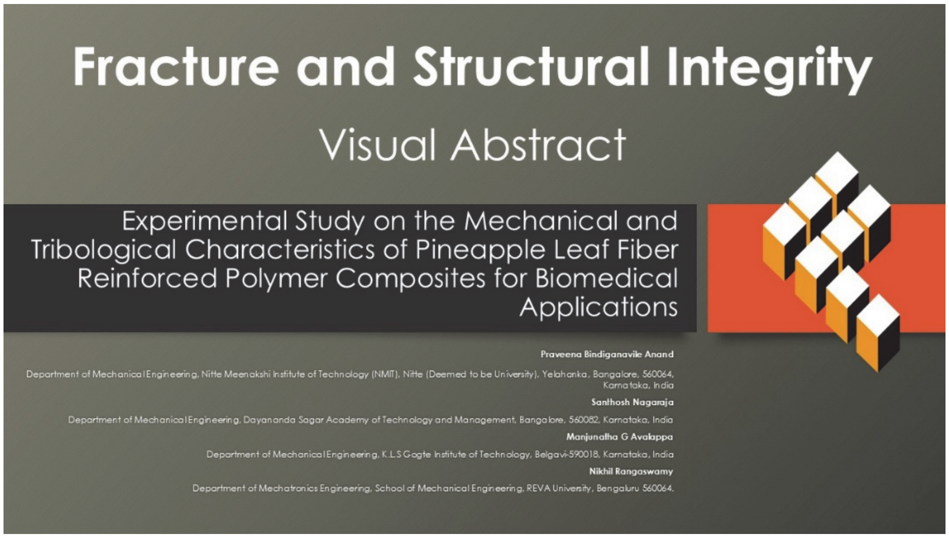
Fracture and Structural Integrity

Visual Abstract

Experimental Study on the Mechanical and Tribological Characteristics of Pineapple Leaf Fiber Reinforced Polymer Composites for Biomedical Applications

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## INTRODUCTION

The growing need to use sustainable and environmental friendly materials in the field of engineering and biomedical applications has resulted in extensive research on natural fiber reinforced polymer composites (NFPCs). In comparison to the traditional synthetic fibers like carbon or glass, natural fibers are renewable, biodegradable, light in weight and cheap. These reduce carbon footprint, power usage, and environmental effect, which makes them applicable in a broad spectrum of structural and biomedical usage [1-2]. Pineapple leaf fiber (PALF) has become one of the most popular natural fibers with high performance as it has a distinctive set of characteristics: high cellulose content (70-82%), low density (1.5 g/cm$^3$), tensile strength (700-1,000 MPa), and Youngs modulus (30-70 GPa). The quality of cellulose fraction serves the purpose of high mechanical strength, lignin and hemicellulose content serve the purpose of flexibility, moisture uptake, and bonding with polymer matrices [3-4].

### *Natural fiber composites and sustainability*

PALF is mostly perceived as an agricultural waste product, but it has the potential of being turned into a high-value reinforcement material after simple extraction processes. The fibers and leaves are decorticated manually or mechanically and then the chemical treatment (alkali, silane or acetylation) is done to eliminate the impurities and increase the adhesion to polymer matrices [5-6]. These treatments are not only good in improving the mechanical properties but also decreasing the moisture uptake and increasing tribological performance during frictional loading. PALF composites exhibit significant tensile strength, flexural modulus, impact energy absorption, and wear resistance when incorporated into a polymer structure e.g. epoxy, polyester, poly-lactic acid (PLA) and are therefore applicable in both structural and biomedical applications where a structure should be strong as well as wearable. PALF composites have been shown to be mechanical characterizable and hence are fit to load-bearing applications [7-8]. PALF composites based on epoxy resin containing 30 wt.% fibers have been found to attain tensile strengths ranging between 70-78 MPa, flexural strengths of 75-82 MPa and impact energies of 7-8 KJ/m$^2$. These values are like a few synthetic fiber composites and are higher than most other natural fiber composites like jute, coir or sisal [9-10]. The enhancement in mechanical properties is mostly a result of effective transfer of stress across the fiber-matrix interface which is determined by appropriate surface treatment of the fibers and a uniform distribution of fibers in the matrix [11-12]. SEM analysis can commonly show that there is good fiber- matrix adhesion, low void content and cohesive fracture behavior, which means that there is good load sharing during tensile and flexural loading. In biomedical applications, it is necessary to be able to match the mechanical properties of bone or cartilage [13-14]. Cortical bone also has a tensile strength of 50-150 MPa and a modulus of 15-30 GPa whereas the cancellous bone is weaker but needs moderate amount of energy to be absorbed [15-16]. These mechanical properties can be approximated with PALF composites with custom fiber volume fraction and orientation, which are thus potential materials in orthopedic implants, prosthetic devices, and dental scaffolds. Lightweight biomedical devices are also associated with the low density of PALF (approximately 1.5 g/cm$^3$), which minimizes the physical load of the patients but does not compromise the structural integrity [17-18].

### *Significance of PALF composites in biomedical applications*

Besides mechanical strength, tribological performance is also essential in biomedical applications of sliding, articulating, or load bearing parts. The long-term wear resistance and coefficient of friction of implants, prosthetics, and scaffolds subjected to repetitive motion depend on wear resistance [19-20]. The literature on PALF composites indicates that a good bonding of fibers and matrix and good dispersion of the constituents are the major factors to minimize the wear rates, which are normally between 0.015 and 0.03 mm$^3$/Nm during dry sliding. Epoxy-based PALF composite coefficient of friction is also stated to reach a stable value of 0.32-0.38 based on load and treatment of the fibers. The wear reduction may be explained by the load-bearing capability of the fibers that distribute the contact stressors and minimizes the matrix deformation. Fiber pull-out, micro-cracking and matrix deformation are common features of worn surfaces analyzed by SEM and directly associated with the wear mechanism. Treatment of fibers, i.e. alkali treatment, increases the bond between the fibers, reducing fiber detachment during slide and raising the tribological performance [22]. Biomedical applications, including prostheses on joints or teeth, are of special interest to such properties since the material must be resistant to wear on the surface as well as to giving smooth articulation during repeated loading. Microstructural characterization is also important to learn the mechanical and tribological behavior of PALF composites. Fiber-matrix interactions, fracture surfaces and wear patterns can be accurately observed under the microscope Scanning Electron Microscopy (SEM). Tensile-tested specimen SEM images tend to exhibit fiber breakage, pull-out, matrix cracking and voids which are directly proportional to the measured mechanical properties. It is a well-known fact that proper alkali treatment increases the surface roughness of fibers that increases the adhesion to the epoxy matrix and minimizes the concentration of the stress at the interface. SEM micrographs of wear-tested specimens reveal smooth areas where load is glibly distributed among fibers, with minor levels of micro-cracks and broken pieces of fibers. These findings yield information on the load transfer mechanisms, energy absorption and wear resistance, which allows optimization of fiber content, orientation and surface treatment towards desirable biomedical performance. Through the comparison of the mechanical test results in line with the SEM findings, researchers can discover failure modes and design the composite to be as strong, durable, and biocompatible as possible [23].

### *Biocompatibility considerations*

On top of mechanical and tribological characteristics, biomedical use requires biocompatibility. Implants, prosthetics or tissue scaffold material used should not provoke any adverse biological reaction e.g. inflammation, cytotoxicity or allergic reactions. PALF is a biodegradable, natural fiber which is non-toxic in most cases and does not generate any toxicity in an inert polymer base such as epoxy or PLA. Initial cytocompatibility tests indicate that PALF composites exhibit cell viability of more than 90%, which confirms that there is little cytotoxicity. Furthermore, surface roughness of PALF composites can affect cell adhesion and proliferation which is essential in the application in tissue engineering or bone scaffolds. The surface treatment of fibers and optimization of matrix properties can be used to improve cell adhesion, growth, and differentiation to make these composites suitable in load bearing and non-load bearing biomedical devices. The mechanical strength, wear resistance, and biocompatibility are combined to make sure that PALF composites can be used in orthopedic implants, prosthetics, and dental restorations [24].

### *Advances in fiber treatment and composite fabrication*

Several fiber treatment processes have been created to enhance fiber- matrix bonding and the performance of composite. The most widespread treatment process is alkali treatment, which removes the hemicellulose, waxes and lignin off the fiber surface to increase roughness and chemical reactivity. Bonding and lowering moisture absorption can also be enhanced with the use of silane coupling agents and acetylation. Composite fabrication is commonly used by hand lay-up, compression molding and vacuum assisted methods, of these, hand lay-up is affordable, and fiber orientation is easily controllable, and hand lay-up can be used in laboratory-scale research. Curing, post-curing, and layer compaction provide uniformity of fibers, low-content of the voids and consistent mechanical properties. Optimized fiber treatment technology and fabrication have a direct influence on tensile, flexural, impact, and wear properties. As an illustration, alkali-treated PALF materials have tensile strengths of about 76 MPa, flexural strengths of about 80 MPa, impact energies of about 8 kJ/m$^2$, hardness of about 84 Shore D and wear rates of 0.015 mm$^3$/Nm. These families fit very well the biomedical load-bearing environment, and this shows the promising nature of the PALF composites as sustainable substitutes of metals and synthetic polymers. The project area of the present study includes mechanical characterization, tribological test, and microstructure of PALF epoxy composite use in biomedical applications. As the demand for lightweight, durable, and biocompatible material grows, the PALF composites offer a cost effective and sustainable alternative to conventional material. They can be used in orthopedic implants, prosthetic limbs, dental scaffolds, or tissue engineering devices, where the material should be able to resist mechanical loads, frictional stresses, and biological interactions. Through a combination of mechanical, tribological and SEM based analysis, the study will provide a good comprehension of the performance of PALF composite to help in optimization of designs in medical applications. Due to low density, renewability, and desirable mechanical behaviour, natural fiber reinforced polymer composites are finding a growing application in lightweight structural panels, automotive interior trims, packaging components, orthotic braces, prosthetic support frames and auxiliary non-load-bearing biomedical fixtures. These application special cases explain the functional range of natural fiber composite in the structural and biomedical support areas. It has been demonstrated in the past that the operating conditions that include the applied load, the sliding speed and the service temperature are very decisive factors in the frictional behavior of composite materials. Research in the civil engineering field has revealed that these parameters play an important role in wear processes and surface degradation behavior in fiber reinforced systems and tribological characterization in controlled test conditions is important. Some studies have reported the mechanical behavior of pineapple leaf fiber reinforced epoxy composites but most of the studies mostly focus on a simple analysis of strength and stiffness of the composite with little consideration on wear characteristics and the evolution of interfacial damages. Moreover, the average correlation among mechanical answer, tribological execution and microstructural fracture characteristics under controlled processing circumstances has not been adequately established. This deficiency is a definite gap in research that is filled in the currently conducted study. The current paper aims to research the synthesis of alkali-treated PALF/epoxy composites with different fiber content and define the integrated structure-property-wear correlations by means of extensive mechanical, tribological, and microstructural studies. The novelty of this research is the ability to correlate tensile, flexural, impact, hardness, and wear features with SEM-based interfacial fracture processes, which would yield new data on the optimization of performance in biomedical support and lightweight structural applications [25].

## MATERIALS AND METHODS

They can be used in orthopedic implants, prosthetic limbs, dental scaffolds, or tissue engineering devices, where the material should be able to resist mechanical loads, frictional stresses, and biological interactions. Through a combination of mechanical, tribological and SEM based analysis, the study will provide a good comprehension of the performance of PALF composite to help in optimization of designs in medical applications.

### *Materials*

The material that was used as reinforcement in this study was pineapple leaf fiber (PALF) which was acquired by means of mature leaves of Ananas comosus. Decortication used to extract long fibers in raw leaves was initially done manually after which the fibers were well washed using distilled water to remove dirt and other impurities. A hot air oven was used to dry fibers at 60 $^0$C and this was carried out over a period of 24 hours in order to get rid of moisture. To enhance the bond between the fiber and the polymer matrix, alkali treatment was done under the 5 % NaOH solution in 4 hours. The fibers were treated and then neutralized in dilute acetic acid, washed in distilled water until neutral pH and dried again in 60 $^0$C at 24 hours. It is a treatment that makes the surface roughness higher, hemicellulose and lignin partially disappearing and improving the chemical bonding between epoxy resin and surface. Fig. 1. Shows the composites specimen slab and preparing the composite specimens and Fig. 2. SEM micrographs of pineapple leaf fibre.

Figure 1: Composites specimen slab and preparing the composite specimens.

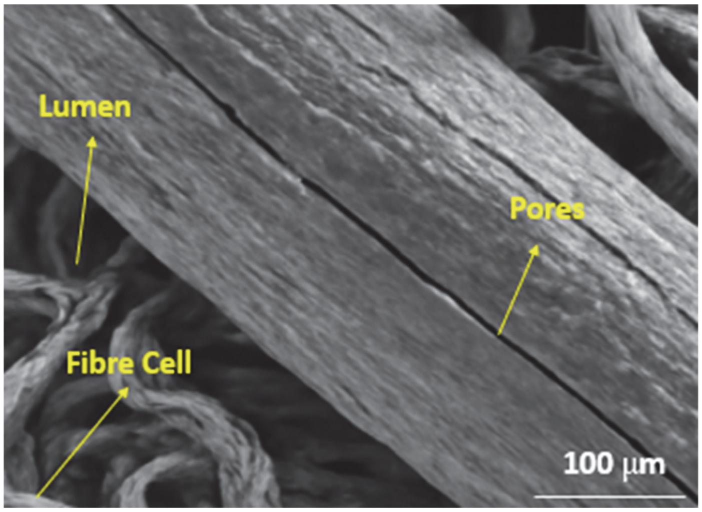

Figure 2: SEM micrographs of pineapple leaf fibre.

| Property | Pineapple Leaf Fiber (PALF) | PALF/Epoxy Composite |
|---|---|---|
| Density | 1.526 g/cm³ | 1.18–1.22 g/cm³ (varies with fiber content) |
| Tensile Strength | 413–1627 MPa | 45–78 MPa |
| Water Absorption | High (~6.04%) | Reduced compared to pure PALF due to epoxy matrix |
| Crystallinity | 70–82% holocellulose | Increased crystalline structure in composites |
| Surface Morphology | Natural, rough surface suitable for bonding | Enhanced bonding with epoxy due to surface treatment and alignment |
| Thermal Stability | Moderate | Improved thermal stability in composites |

Table 1: Physical and mechanical properties of pineapple leaf fiber and epoxy resin composites.

Epoxy resin, in form of polymer matrix (LY556) with hardener HY951 was used as a composite fabrication material because of its good adhesiveness, mechanical strength and low shrinkage. The weight ratio between the resin and the hardener was kept at 10:1 according to the manufacturer (Huntsman Advanced Materials, India). Composite laminates were fabricated with PALF contents of 5, 10, 15, 20, and 25 wt.% to examine the effect of fiber loading on mechanical, tribological, and microstructural performance. Tab. 1. Shows the Physical and Mechanical Properties of Pineapple Leaf Fiber and epoxy resin composites and Tab. 2. Show the Materials Used for PALF Composite Fabrication.

| Material | Specifications / Grade | Manufacturer | Purpose |
|---|---|---|---|
| Pineapple Leaf Fiber (PALF) | Alkali-treated, dried, 60°C | Local source | Reinforcement |
| Epoxy Resin (LY556) | Liquid epoxy, low viscosity | Huntsman Advanced Materials, India | Matrix |
| Hardener (HY951) | Liquid polyamine | Huntsman Advanced Materials, India | Curing agent |
| Sodium Hydroxide (NaOH) | 5% aqueous solution | Merck | Alkali treatment |
| Acetic Acid | 1–2% aqueous solution | Merck | Neutralization after treatment |

Table 2: Materials used for PALF composite fabrication.

### *Composite fabrication*

The hand lay-up technique has been used to produce PALF-reinforced epoxy composites, which is applicable to the laboratory scale experiments and to produce small specimens. Mold release agent was applied on the surface of the molds to allow demolding at the beginning. PALF fibers were alkali treated and then cut to the required length (approx. 100 mm) and placed evenly in the mold. Epoxy resin and hardener mixture was added on top of the fibers making sure to cover it fully. An air balloon was eliminated by using a hand roller to enhance contact between the fiber and resin. Tab. 3 show the Composition of PALF/Epoxy Composites with Varying Fiber Content.

| Sample Numbers | Pineapple Leaf Fiber (PALF) Weight (%) | Epoxy Resin (%) |
|---|---|---|
| C1 | 5 | 90 |
| C2 | 10 | 85 |
| C3 | 15 | 80 |
| C4 | 20 | 75 |
| C5 | 25 | 70 |

Table 3: Composition of PALF/Epoxy composites with varying fiber content.

These layered composites were allowed to dry in room temperature, after which they were post-cured at 80 $^0$C within 3 hours to increase the cross-linkage between the layers. Following ASTM standards of mechanical and tribological tests, the composites were demolded and sliced into test specimens as per the requirements of the standard specimen after curing by a diamond saw. All specimens were fabricated with PALF weight fractions of 5, 10, 15, 20, and 25 wt.% in accordance with the designed composite formulations. Fig. 3 shows the Schematic of hand lay-up fabrication process.

The experimental consistency, five specimens of each composite formulation (C1-C5) were made of each mechanical and tribological test. The tensile test samples were made in sizes 165 mm x 13 mm x 3 mm according to ASTM D638 and flexural 127mm x 12.7mm x 3mm according to ASTM D790. According to ASTM D256, impact test specimens of 64 mm x 12.7 mm x 3 mm were made and according to ASTM D2240 and ASTM G99 standards, hardness and wear samples were machined, respectively. The PALF fibers were placed in stratified arrangement and uniformly spread across the thickness of the composite and the in-plane orientation was not random to give uniform mechanical and tribological characteristics to the entire volume of the specimen.

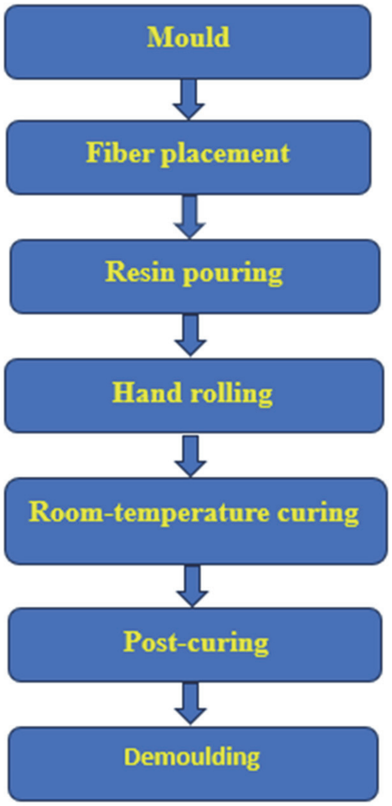

Figure 3: Schematic of hand lay-up fabrication process

### *Mechanical testing*

Tensile, flexural, impact, and hardness tests were also mechanical characterization. Tensile samples were made in line with ASTM D638 and tested in a universal testing machine with 2 mm/min crosshead speed. Flexure testing was done in line with ASTM D790 using three points bending device. The impact strength was measured through the Charpy impact test (ASTM D256), and the notch along the middle of the specimen. The durometer of hardness was measured with a Shore D durometer with five measurements per sample to provide some form of reproducibility. Each mechanical property was tested on five specimens to find the average values and standard deviation.

### *Tribological testing*

The tribological behavior was measured on pin-on-disc tribometer (ASTM G99). Rectangular shaped specimens were mounted as pins on a hardened steel disc (30 x 10 x 3 mm). The tests were performed in a dry environment and at 200 rpm and loads of 20, 30 and 40 N and the total sliding distance used was 500 m. The loss of specimens was determined with a high-precision balance and wear rates were determined in $mm^3/Nm$. The coefficient of friction was also monitored constantly while testing. The tests were performed three times to have statistical reliability.

### *Microstructural analysis*

Scanning Electron Microscopy (SEM) was used to see the fracture and wear of the specimens. Analysis of SEM was conducted at magnifications 100x, 500x and 1000x to find the fiber pull-out, matrix cracking, voids and interfacial bonding.

The observations were compared against mechanical and tribological outcomes to identify failure modes and efficiency of load transfer.

## RESULTS AND DISCUSSION

### *Mechanical properties - Tensile test*

Tensile strength of PALF/epoxy composites shows that the fiber content has a definite positive relationship with tensile strength. Sample C1 which had 5% PALF had a tensile strength of 45 MPa, and Sample C5 which had 25 % PALF recorded 78 MPa. This is because the tensile ability of the pineapple leaf fibers on their own and the ability of the relatively weaker epoxy matrix to transfer the load onto the stronger fibers is good. PALF is subjected to alkali treatment to modify the surface of the fibers by dissolving off lignin and hemicellulose to reveal the microfibrils and to raise the sheet surface roughness to improve mechanical interlocking between the fibers and the epoxy matrix. At increased fiber fractions, the interface area between fibers and matrix gets larger so that the stress is distributed more effectively and matrix cracking is postponed in tensile load. Fig. 4 shows the Fiber weight fractions Vs Tensile Strength.

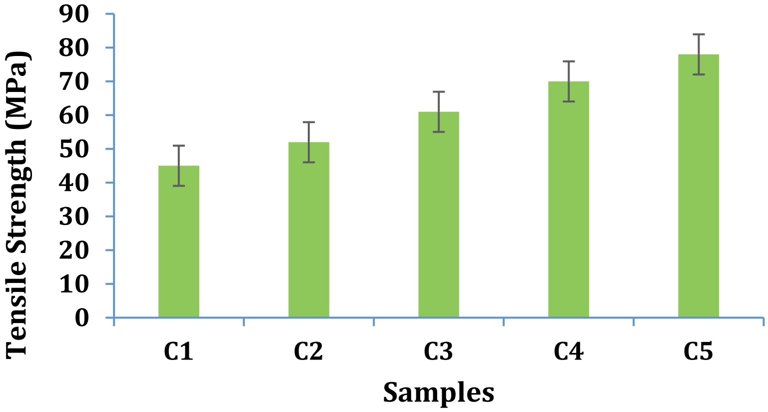

Figure 4: Fiber weight fractions vs tensile strength.

Moreover, maximum stress absorption is also provided by the alignment of fibers with the direction of the load. Slight agglomeration of fibers can be experienced at the maximum fiber content but in the range examined the reinforcing action prevails over the possible concentrations of stress which produce a progressive increase in tensile strength. Youngs modulus also known as elastic modulus changes as C1 has a 2.1 GPa which is then followed by 3.5 GPa which is C5, meaning that the composite is getting progressively stiffer as the contents in it get more fiber. The improvement is an immediate result of the inherent rigidity of the PALF and the high interfacial adhesion. The modulus indicates the resistance of the composite to the elastic deformation under a force load, and this is controlled by the stiffness of the fibers and the efficiency of the load transfer. In high bonded composites, tension is mainly borne by the fibers that are considered as reinforcement rods in the polymer matrix. Fig. 5 shows the Fiber weight fractions Vs Youngs Modulus.

The linear progression of modulus with the fiber fraction demonstrates that the fibers are dispensed evenly, and there is proper transfer of stress. Also, the low void content due to the hand work, lay and curing keeps the local yielding premature and serves as a contributor towards the stiffness increase. These findings agree with the micromechanical models, including the rule of mixtures, which supports the idea of composite stiffness depending on the properties and volume fractions of fibers and matrices. It indicates a declining pattern of the proportion of the elongation at break according to the fiber content, with an elongation of 3.8 % in C1 and 2.5 % in C5. This process of reducing ductility is because rigid fibers undergo constriction on the matrix deformation and the material becomes unable to experience plastic strain. With increasing fiber content, the failure mode changes to fiber-dominated fracture instead of matrix-dominated yielding. Fig. 6 shows the Fiber weight fractions percentage of elongation at break.

The main energy absorption mechanisms of failure during fiber fracture are fiber pull-out, fiber pull-out and debonding. Although the fibers enhance tensile strength, they also inhibit elongation of the epoxy matrix and hence decrease percent elongation. Such behavior is a characteristic trade-off of natural fiber-reinforced composites between strength/stiffness and ductility. To be useful in practice, moderate fiber content (10-15%), providing a balance between tensile strength and enough flexibility to dissipate energy during dynamic or impact loading is needed. Tab. 4 shows the Tensile test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

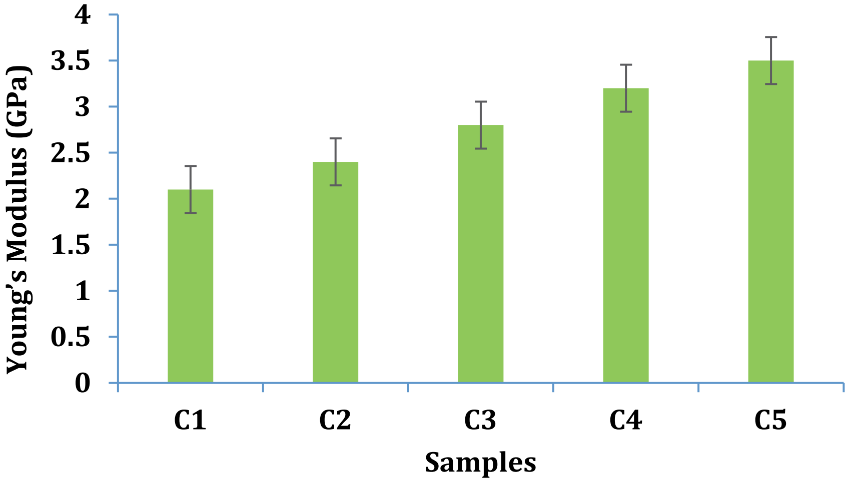

Figure 5: Fiber weight fractions vs youngs modulus.

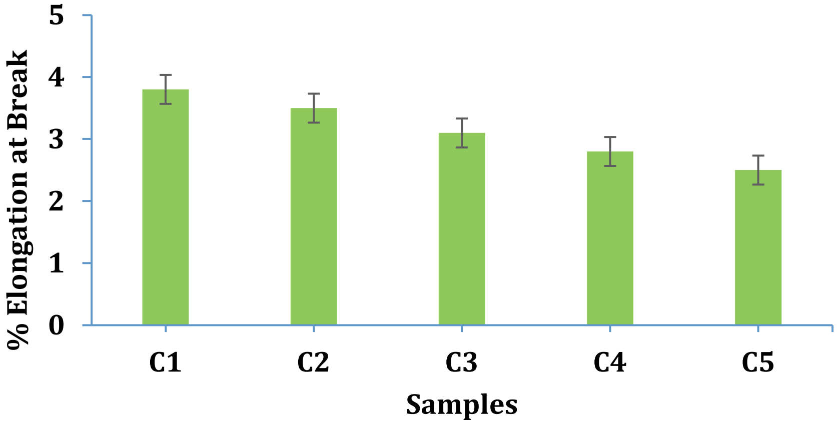

Figure 6: Fiber weight fractions % of elongation at break.

| Sample Numbers | PALF Weight (%) | Epoxy Resin (%) | Tensile Strength (MPa) | Young's Modulus (GPa) | % Elongation at Break |
|---|---|---|---|---|---|
| C1 | 5 | 90 | 45 | 2.1 | 3.8 |
| C2 | 10 | 85 | 52 | 2.4 | 3.5 |
| C3 | 15 | 80 | 61 | 2.8 | 3.1 |
| C4 | 20 | 75 | 70 | 3.2 | 2.8 |
| C5 | 25 | 70 | 78 | 3.5 | 2.5 |

Table 4: Tensile test results for Pineapple Leaf Fiber Reinforced Polymer Composites

### *Mechanical properties - Flexural test*

Flexural response of PALF/epoxy composites can offer very important information on how the material responds to bending loads, and this is an important factor in several structural and engineering designs. The findings show that there is a positive correlation between the PALF content and flexural strength which is clearly positive and the values are elevated to 112 MPa at 25% fiber sample (C5) compared to 75 MPa at 5% fiber sample (C1). The flexural strength is strengthened due to the capability of the fibers in bearing the tensile forces in the outermost layers of the specimen during the process of three-point bending. The PALF fibers represent reinforcement rods, which are placed within the polymer matrix, and which withstand both tensile and compressive forces which occur over the beam thickness. Alkali treatment of fibers increases surface roughness and exposes cellulose microfibrils which increases mechanical interlocking and chemical bonding between the fibers and the epoxy matrix. This interfacing bond is essential because it will allow good stress transmission between the matrix and fibers, slowing down crack propagation and initiation. Fig. 7 shows the Fiber weight fractions Vs Flexural Strength.

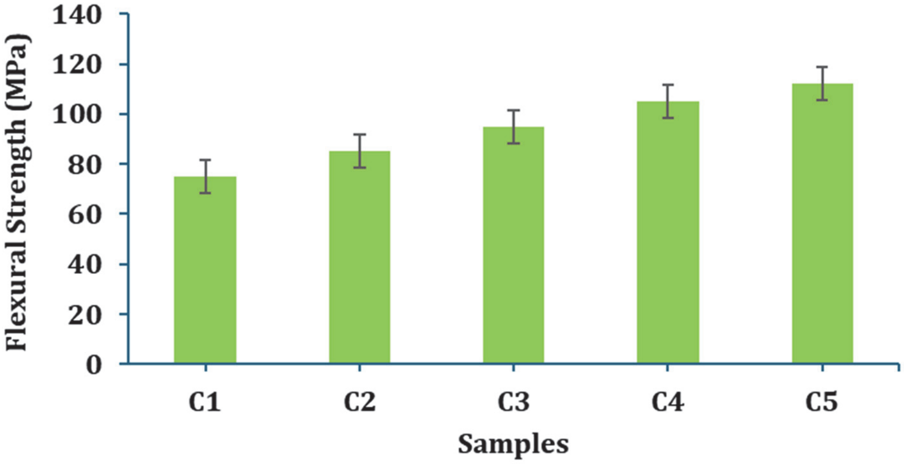

Figure 7: Fiber weight fractions vs flexural strength.

This flexural modulus, which measures the stiffness of the composite, increased from 2.3 GPa in C1 to 3.7 GPa in C5 and this proves that the composites were becoming stiffer with increasing percentages of fibers. The high intrinsic modulus of PALF and strong fiber-matrix interface are the most important factors contributing to this stiffening effect of PALF since it limits the ability of the matrix to undergo deformation under bending loads. The linear growth of modulus with fiber fractions within the study indicates uniform dispersion of the fibers and little void formation which is important in avoiding concentration of stress locally. In addition, the fibers that are oriented parallel to the axis of bending carry most of the stress that is applied, and this enables the composite to withstand the elastic deformation in a better way. These results are consistent with micromechanical predictions, which show that the rule of mixtures can be used to predict a stiffening of composite materials with fiber volume fraction, so long as interfacial bonding is strong. Although flexural strength and modulus have gone up, the deflection at break has gone down to 2.8 mm (C5) as compared to 4.2 mm (C1), showing a decrease in ductility with the increase in fiber content. Fig. 8 shows the Fiber weight fractions Vs Flexural Modulus.

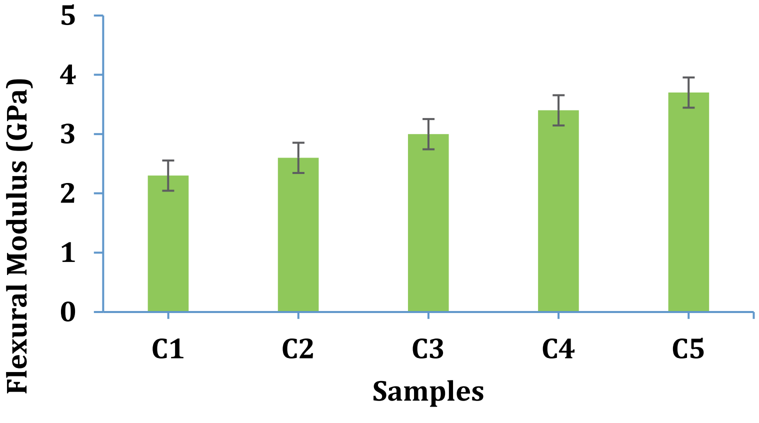

Figure 8: Fiber weight fractions vs flexural modulus.

The reduction in deflection is due to the limitations of the mobility of the matrix; the stiff fibers restrict the plastic deformation and that makes the composite fail at the lower strains. The failure analysis shows that at low fiber contents the matrix experiences micro-yielding and ductile fracture whereas at high fiber contents, failure is characterized by fiber pull-out, fiber breakage, and interface debonding. These mechanisms are observed through SEM, moderate fiber content demonstrates consistent transfer of stress with low pull-out and higher fiber content demonstrates slight clustering and local fiber debonding, Fig. 9 shows the Fiber weight fractions Vs Defection at break. This effect shows the conventional tradeoff of fiber-reinforced composites: the greater stiffness and strength the less flexibility. The practical meaning of the observed behavior is also realized.

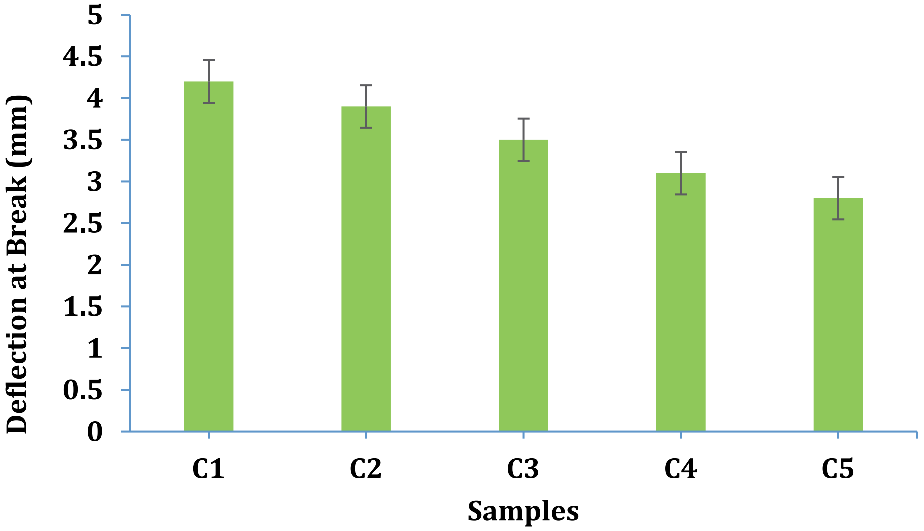

Figure 9: Fiber weight fractions vs defection at break.

The moderate fiber composites (10-15%) are ones that provide a balance between strength and flexibility and are applicable in structural components that are subject to bending as well as moderate dynamic loading. The optimum load-bearing capacity and stiffness is achieved with a high fiber content (20-25%), making these composites the best materials to be used in applications where rigidity and strength are of more importance than ductility, including automotive panels, interior structural structure, and lightweight load-bearing structures. These findings are in line with the earlier investigations on natural fiber-reinforced epoxy composites and they verify the reinforcing effectiveness of PALF and the significance of adhesion between the fibers and the matrix. Moreover, the high flexural strength, higher modulus, and regulated deflection contribute to highlighting the possibility of PALF/epoxy composites to be a sustainable and eco-friendly substitute to synthetic composites in structural and engineering designs. Tab. 5 shows the Flexural test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

| Sample Numbers | PALF Weight (%) | Epoxy Resin (%) | Flexural Strength (MPa) | Flexural Modulus (GPa) | Deflection at Break (mm) |
|---|---|---|---|---|---|
| C1 | 5 | 90 | 75 | 2.3 | 4.2 |
| C2 | 10 | 85 | 85 | 2.6 | 3.9 |
| C3 | 15 | 80 | 95 | 3.0 | 3.5 |
| C4 | 20 | 75 | 105 | 3.4 | 3.1 |
| C5 | 25 | 70 | 112 | 3.7 | 2.8 |

Table 5: Flexural test results for pineapple leaf fiber reinforced polymer composites.

### *Mechanical properties - Hardness test*

Shore D of PALF/epoxy composites was measured to determine the resistance of the material surface to indentation and localized deformation; that is necessary in the applications that can be subjected to wear, surface stress, and contact loads. As it is shown in Tab. 6, the hardness slightly rose with the percentage of fiber, being 72 in C1 (5% PALF) and 76 in C5 (25% PALF). Such step-by-step increase may be explained by the main contribution of the intrinsic stiffness and crystallinity of pineapple leaf fibers that can be regarded as rigid reinforcement points in the softer epoxy matrix. The fibers decrease the movement of polymer chains under localized stress which constrains the depth of indentation and increases the rigidity of the surface. The process of treating PALF with alkali is very important in raising the hardness by strengthening the interfaces between the fiber and the matrix. Fig. 10 shows the Fiber weight fractions Vs Shore D Hardness.

Chemical treatment eliminates hemicellulose, lignin and other impurities on the surface to reveal microfibrils that augment the roughness of the surface of the fibers. This enhanced interface enables efficient transfer of stress of the matrix to the fibres during indentation and avoids localized deformation or cracking of the matrix. The SEM analysis of the indented surfaces confirms that the matrix surrounding the fibers does not subject to plastic deformation, and that the embedded fibers reinforce the material and inhibit fibers pull-out, and that this gives the overall harder and more uniform surface. Micromechanical viewpoint can be used to explain the synergistic effect of the fibers and the matrix that explains the increase in hardness. The fibers serve as points of loading which absorb some of the load applied and the rest of the load is effectively distributed through the surrounding matrix. This two-fold mechanism minimizes the risk of surface denture and the onset of micro-cracks.

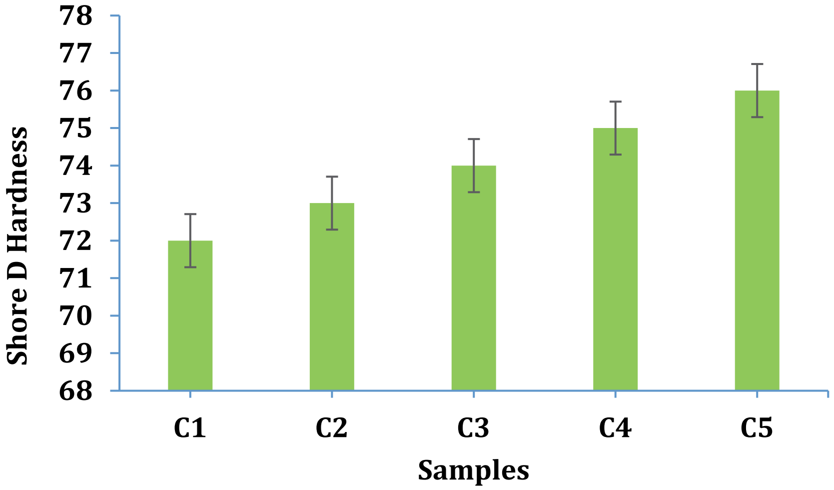

Figure 10: Fiber weight fractions Vs Shore D Hardness

The progressive hardening as the content of fibers increases also indicates that the dispersion of fibers is homogeneous and there are few voids or clustering otherwise, they would create weakened areas prone to surface deformation. Practically, the hardening of PALF/epoxy composites is further augmented which makes them more appropriate to surface loaded applications which include structural panels, protective housing and parts that are exposed to repetitive contact or wear. The fact that the Shore D hardness increase is moderate as compared to other significant property increases in tensile and flexural properties is compensated by the fact that it supplements the overall mechanical performance through a durable and wear-resistant surface. It means that the PALF reinforcement does not only increase the bulk mechanical properties but also the surface properties, so the composites are applicable in diverse engineering and structural applications where the mechanical strength and the surface life are demanded. Tab. 6 shows the Hardness Test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

| Sample Numbers | PALF Weight (%) | Epoxy Resin (%) | Shore D Hardness |
|---|---|---|---|
| C1 | 5 | 90 | 72 |
| C2 | 10 | 85 | 73 |
| C3 | 15 | 80 | 74 |
| C4 | 20 | 75 | 75 |
| C5 | 25 | 70 | 76 |

Table 6: Hardness Test results for Pineapple Leaf Fiber Reinforced Polymer Composites

### *Mechanical properties - Impact test*

The energy of PALF/epoxy was found to rise steadily with the amount of fibers used with a rise in energy of 12 kJ/m$^2$ at C1 to 20 kJ/m$^2$ at C5. This trend tells that the increased proportion of fiber in the composite increases the toughness of the composite enabling it to absorb greater energy during abrupt loading. Pineapple leaf fibers are energy absorbing reinforcements as it prevents crack propagation and initiation. Under impact loading, cracks are filled by fibers, and the energy is dissipated by fiber pull-out, debonding and fiber fracture to postpone the catastrophic failure. It is also believed that the high interfacial bond strength between the fibers and epoxy matrix leads to enhanced impact resistance with the increase in PALF content. Treatment with alkali enhances roughness of the surface and eliminates impurities that advance mechanical interlocking and formation of chemical bonds. The interface between the fibers and the matrix is high in terms of fiber content which is the fibers transferring a lot of load and hence fibers can transfer a good percentage of the impact load applied. Local concentration of stress would not occur since the fibers are uniformly distributed, which would otherwise cause premature breakage of the crack. Fig. 11 shows the Fiber weight fractions Vs Impact Energy.

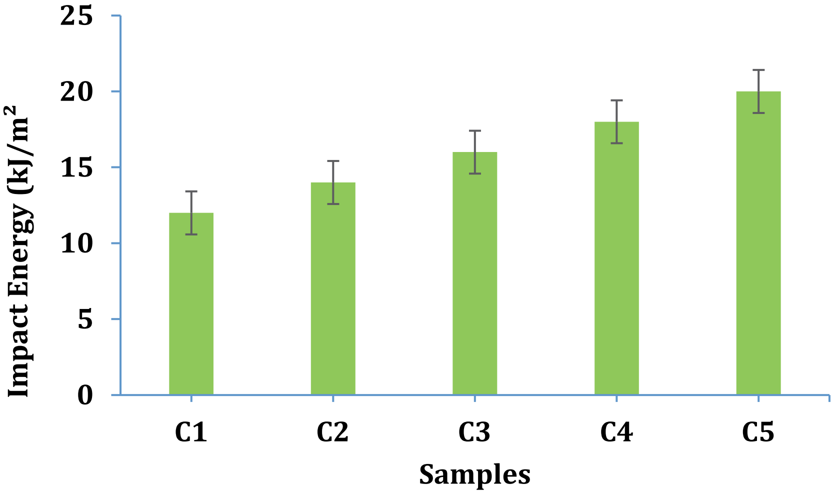

Figure 11: Fiber weight fractions Vs Impact Energy.

Micromechanically, toughness of the composite is affected by several mechanisms such as matrix yielding, fiber pull-out, crack diversion, and dissipation of energy through fiber fracture. At lower fiber content (C1-C2), the process of failure is dominated by the matrix, and there is little absorption of energy. The higher the fiber content (C3-C5), the greater the fibers are the major energy absorbers thus increasing toughness. SEM fracture surface observations indicate well-integrated fibers, jagged fracture planes and minimal voids, which prove that fibers are useful to stabilize cracks and absorb impact energy. Practically, the higher impact energy of PALF/epoxy composites has rendered them applicable where sudden loads/shocks resistance is needed such as automotive parts, protective panels, and structural parts that are subjected to dynamic loads. High tensile strength, flexural stiffness and impact toughness prove that PALF is an effective natural fiber reinforcement that can be used as a substitute of synthetic fibers to offer an eco-friendly and sustainable alternative without negatively affecting the mechanical performance. Tab. 7 shows the Impact test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

| Sample Numbers | PALF Weight (%) | Epoxy Resin (%) | Impact Energy (kJ/m²) |
|---|---|---|---|
| C1 | 5 | 90 | 12 |
| C2 | 10 | 85 | 14 |
| C3 | 15 | 80 | 16 |
| C4 | 20 | 75 | 18 |
| C5 | 25 | 70 | 20 |

Table 7: Impact test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

### *Mechanical properties - Tribological properties*

To understand the tribological performance of the composites of PALF/epoxy under sliding contact conditions, the tribological behavior was assessed and this is critical in components that are subjected to frictional wear and surface pressures. Tab. 8 indicates that there is a linear correlation between the coefficient of friction (COF) versus fiber content, with 0.62 being the coefficient of friction of C1 (5% PALF) and 0.51 being the coefficient of friction of C5 (25% PALF). This can be explained by the occurrence of the presence of rigid PALF fibers at the sliding interface that serves as reinforcement elements and the load is distributed over a greater contact area. The fibers reduce adhesive and plowing forces which usually increase friction through direct interaction between polymer and counterface. Also, alkali treatment of fibers enhances bonding between the fibers and the epoxy matrix, which makes the fibers stand and resist underloading and transfer loads efficiently when they slide. Wear rate of the composites also decreases with the fiber content, i.e. 5.8 x $10^{-6}$ $mm^3/Nm$ in case of C1 and 3.7 x $10^{-6}$ $mm^3/Nm$ in case of C5. It is the result of several factors that lead to enhanced wear resistance. Fig. 12 shows the Fiber weight fractions Vs Coefficient of friction.

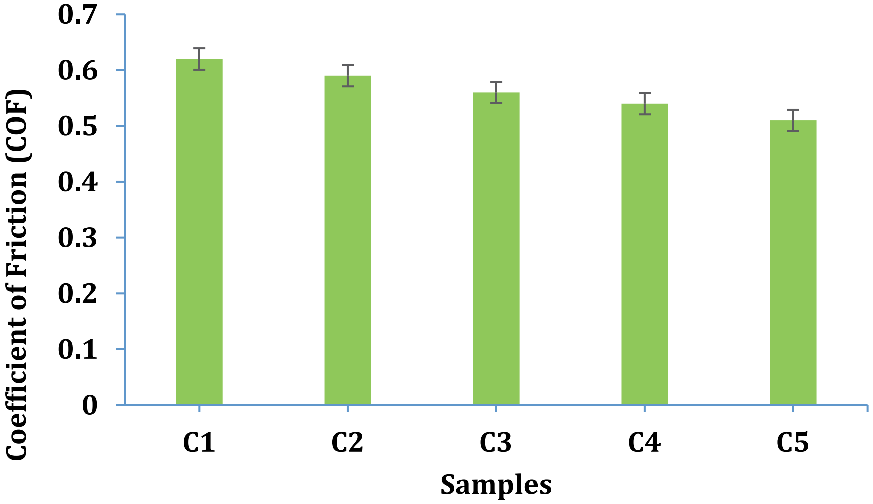

Figure 12: Fiber weight fractions Vs Coefficient of friction

The PALF fibers provide resistance to surface material removal which is resistant to micro-cutting and abrasive processes that come into effect under sliding. Moreover, fibers can increase the load bearing capacity of the composite and eliminate concentration in stress of the polymer matrix. SEM observations of worn surfaces indicate that at low fiber fractions the wear process is adhesive wear with matrix smearing and small-scale cracking. The mechanism is also shifted to mild abrasive wear as the fiber content increases and the fibers deflect the crack, the fibers do not pull-out and the wear tracks become smoother. These results suggest that PALF is a suitable material to strengthen the matrix and avoid disastrous loss of material and increase the stability of the composite to the sliding effect. Micromechanically, mechanisms of stress distribution and energy dissipation can be used to explain better tribological performance. The fibers that take part of the shear stress applied to it thereby lessening the load experienced by the outer matrix. This lowers the micro-deformation and the surface damage during sliding.

The fibers also deflect and close off any microcracks that are generated by wear, dispelling the energy, and avoiding quick crack propagation. The good fiber-matrix interface (which is accomplished by alkali treatment) makes sure that the fibers are firmly anchored and still resist being pulled out during sliding. The minor effect of the high content of fiber on the surface hardness is added to the reduction in COF and wear resistance through resisting indentation by asperities on the counterface. In practice, the tribological findings indicate that PALF/epoxy composites can be used in applications that require contact or wear by friction, i.e., sliding panels, gears, bearings, and protective housing. The fact that the friction has been cut down, the wear rate reduced and mechanical properties have been improved make PALF/epoxy composites sustainable replacements to synthetic fiber composites in the automotive and industrial industries. In addition, the findings also indicate that fiber content, dispersion, and surface treatment are important in enhancing mechanical and tribological performance. Ideally, a moderate fiber level (10-15) is a compromise between friction reduction and wear resistance, and ductile behavior and fiber content is maximized to achieve wear resistance and hardness in the case of a load bearing or high contact application. It is proven by the tribological performance of PALF/epoxy composites that natural fibers can contribute greatly to improving durability, energy dissipation, and surface resistance of polymer composites. The reinforced composites provided with mechanical reinforcement combined with effective stress transfer, crack bridging and surface hardening ensure that reinforced composites of PALF withstand mechanical loads in addition to repeated sliding contacts that are helpful during their long-term structural or functional use. Tab. 8 shows the Wear test results for Pineapple Leaf Fiber Reinforced Polymer Composites. Fig. 13 shows the Fiber weight fractions Vs Wear Rate.

| Sample Numbers | PALF Weight (%) | Epoxy Resin (%) | Coefficient of Friction (COF) | Wear Rate ($1\times10^{-6}$ mm$^3$/Nm) |
|---|---|---|---|---|
| C1 | 5 | 90 | 0.62 | 5.8 |
| C2 | 10 | 85 | 0.59 | 5.2 |
| C3 | 15 | 80 | 0.56 | 4.6 |
| C4 | 20 | 75 | 0.54 | 4.1 |
| C5 | 25 | 70 | 0.51 | 3.7 |

Table 8: Wear test results for Pineapple Leaf Fiber Reinforced Polymer Composites.

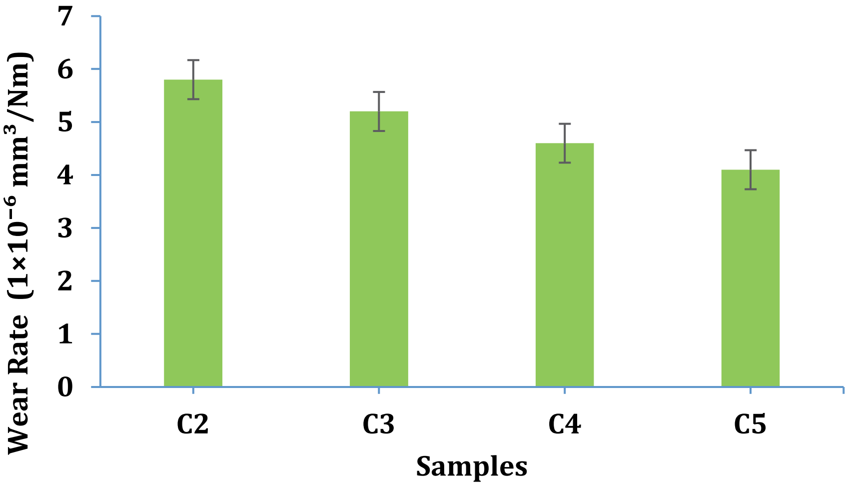

Figure 13: Fiber weight fractions Vs Wear Rate.

### *Scanning Electron Microscopy (SEM) analysis*

SEM analysis gives a microscopic idea on how the mechanical and tribological performance of PALF/epoxy composites takes place. The observations aid in explaining trends that occur in tensile, flexural, hardness, impact and wear tests. The tensile and flexural fracture surface SIMs reveal that fiber-matrix interaction is one of the main factors that determine the performance of composites. The fracture surfaces are relatively smooth at low PALF content (C1-C2) indicating that the failure is mainly matrix dominated. The epoxy plastic deforms and takes up most of the stress applied. There is observed minor fiber pull-out, which means that stress is not transferred between the matrix and fiber much. As the proportion of PALF (C3-C5) increases, the fracture process changes to fiber-dominated failure such as fiber breakage, fiber pull-out and interfacial debonding. The fibers serve as bridges in the form of reinforcement that slows down cracks and increases tensile and flexural strength. Alkali treatment causes hemicellulose and lignin to be removed, leaving behind fibers with microfibrils that enhance roughness, and interlocking the fibers with mechanical forces with epoxy.

SEM images exhibit low gaps at fiber-matrix interface which is a sign of high adhesion. Soccer ball micro voids in places occur at elevated fibre content, which describes the minor loss in ductility although does not affect the overall stiffness or strength. SEM micrographs are impact-tested samples which demonstrate the energy absorption mechanisms on the microlevel. Fibers take impact energy as pull-out, fracture and debonding, which decrease the catastrophic failure rate. With low fiber fractions, the matrix takes control of energy absorption, which results in smooth fracture surfaces and a reduced toughness. With further increase in fiber content, rough fracture surfaces, fiber bridging of cracks, and matrix shear bands are observed in the composite which confirms the improved impact energy absorption. The fracture surface irregularities and roughness are associated with the increase in impact resistance during mechanical tests. The analysis of worn surfaces with SEM gives the idea of the wear mechanisms. At low PALF content, the wear is mainly adhesive, as indicated by smearing of the matrix, shallow cracks and small detachments of the fibers. As the fibers content increases, the wear process changes to mild abrasive wear, in which fibers embedded in the matrix inhibit micro-plowing and the removal of material. Fibers help in the deflection of cracks, which slows the development of wear. The fibers that are treated with alkali are held in the matrix such that they do not pull-out during wear, and the wear surface integrity is held. These microstructural features are then directly related to the reduction in wear rate and COF with increasing fiber loading. Fig. 15 shows the Impact Fracture Surface and Worn Surface of PALF/Epoxy Composite Showing Fiber Reinforcement and Crack Deflection during Sliding Wear.

One of the most important observations made by SEM is the quality of the fiber-matrix interface that controls the load transfer and durability. It should be noted that alkali treatment enhances roughness on the surface and uncovers the microfibrils, which facilitate mechanical interlocking and hydrogen bonding with the epoxy matrix. This robust interface will ensure that fiber pull-out in case of mechanical or tribological loading cannot occur leading to enhanced tensile strength, flexural modulus, hardness, impact toughness and wear resistance. Lack of interfacial adhesion would result in early failure and increased wear rates, which is why treatment and dispersion of the fibers properly are essential. Fig. 14 shows the Tensile and Flexural Fracture Surface Showing Fiber Pull-Out and Interfacial Debonding.

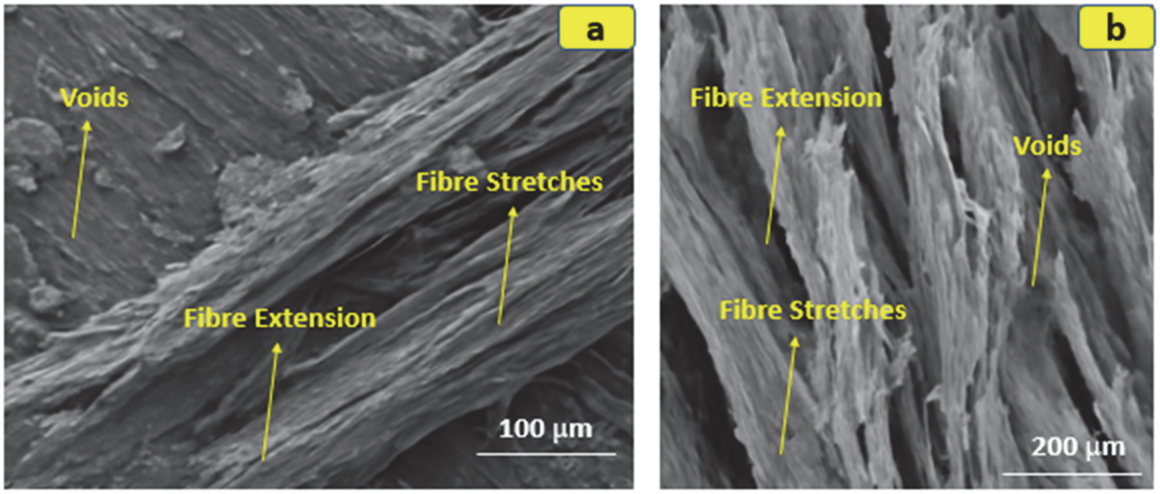

Figure 14: Tensile and Flexural Fracture Surface Showing Fiber Pull-Out and Interfacial Debonding.

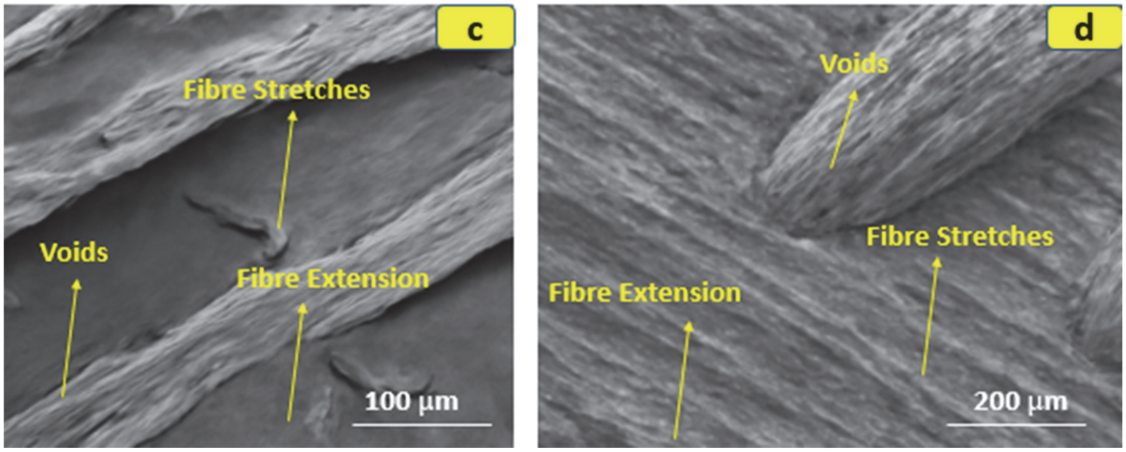

Figure 15: Impact Fracture Surface and Worn Surface of PALF/Epoxy Composite Showing Fiber Reinforcement and Crack Deflection during Sliding Wear.

### *Biocompatibility and biomedical relevance*

The current research is mainly aimed at determining the mechanical, tribological, and microstructural performance of PALF/epoxy composites. The biomedical significance of these materials is, however, backed with the natural origin and cellulose rich structure of pineapple leaf fibers which is known to have a good interaction with the biological environments. It is well known that plant-based fibers are the ones that are less toxic, less irritating to tissues, and more compatible to surfaces compared to the traditional synthetic reinforcements. Surface modification with alkali enhances surface roughness and wettabilitys needed to enhance protein adsorption and cell attachment. Interfacial bonding of fibers and matrix used as strong and wear resistant further indicates that this study would also be suitable in biomedical support parts like orthotic devices, prosthetic support frames and non-load bearing medical fixtures. It is made clear that the ongoing research indicates the initial mechanical tribological screening. In-depth biological analyses such as cytotoxicity testing, hemocompatibility analysis, and in-vitro cell responding research are found to be the required research steps to be taken before any implant-level use.

## CONCLUSION

The research on PALF/epoxy composites showed that the fiber content has a major effect on the improvement of the mechanical, tribological, and microstructural properties. The tensile and flexural characteristics also increased gradually because of the high inherent strength of the PALF fibers and high fiber-matrix bonding by using alkali treatment. Hardness and impact energy were elevated which showed an enhanced surface resistance and toughness whereas the elongation was slightly reduced which showed reduced ductility of the matrix. The tribological tests revealed that the coefficient of friction and the rate of wear reduced with increasing fraction of fibers because fibers serve as barriers to the surface damage and spread the load effectively. SEM micrographs showed satisfactory interfacial bonding, fiber pull-out and crack bridging which show an improvement in mechanical and wear properties. In general, PALF reinforcement offers an environmentally friendly, low-cost, high-performance polymer composite solution.

- Tensile strength and youngs modulus of PALF/epoxy composites were significantly affected by the content of fibers, namely, 45 to 78 MPa and 2.1 to 3.5 GPa respectively, whereas elongation was slightly reduced, which indicated a decrease in ductility.
- Flexural strength and modulus gain increased gradually to 112 MPa and 3.7 GPa at 25 wt.% PALF respectively because of effective transfer of stress and bridging of crack by fibers during bending.
- The energy impact rose to 20 kJ/m$^2$, which was 12 kJ/m$^2$ to 20 kJ/m$^2$ and fiber pull-out and fracture were the main energy-absorbing processes, which improved toughness.
- The hardness of Shore D rose to 72-76 meaning that there were enhanced surface resistance and toughness due to fiber reinforcement and good inter-facial bonding.
- Coefficient of friction was lowered to 0.51, and wear rate was also lower 3.7 x 10$^{-6}$ mm$^3$/Nm, which is evidence of better tribological performance.
- Analysis of the SEM established the high fiber-matrix bonding, even dispersion of the fibers, and the strategies of fibers pull-out, bridging, and fracture, which support the increases in mechanical and wear behavior.
- Moderate fiber levels (10-15 wt.%) give an equilibrium between toughness and hardness, and higher levels of fiber (20-25 wt.%) give the maximum toughness, hardness, and wear resistance.
- The paper assigns PALF as sustainable, low-cost, and high-performance reinforcement, which proves that it can be used in biomedical and load-carrying polymeric processes that need mechanical integrity and wear resistance.

Future research will involve biological compatibility, testing of long-term environmental stability, optimization of the surface modification technique on fibers, and add-on secondary fillers to enhance further the mechanical and tribological properties. Besides that, scalability of manufacturing and performance validation of biomedical support and lightweight structural components will be investigated.

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