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Edited by Chandrasekar Muthukumar, Senthilkumar Krishnasamy,
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Preface

Biocomposites are touted as a promising substitute to conventional composites in various applications due to their biodegradable characteristics, low density, and moderate mechanical properties. As these materials are intended for applications in the automotive, aerospace, biomedical industries, etc., it is essential to explore their tribological behavior.

The chapters in this book cover a broad range of topics, including the tribological properties of biocomposite based on thermoset and thermoplastic resins, the influence of fiber pretreatment techniques, and nanofillers for the enhanced tribological performance. In addition to this, the characterization methods employed to assess wear and friction characteristics of the biocomposites were discussed.

This book aims to provide researchers, engineers, and students with a comprehensive knowledge of tribology in the context of fundamental principles, experimental techniques, and practical applications. This book will serve as a valuable resource to understand the factors influencing the tribological performance of the biocomposite materials and their suitability for various applications. We sincerely hope that this book will inspire further research and innovation in the field of tribology and can unlock the full potential of biocomposites.

The contributors to this book are distinguished researchers and experts in the field of tribology and biocomposites. Their collective expertise enables us to gain deeper insights into the tribological behavior of biocomposites, making this book a valuable reference for both academia and industry. So, we express our sincere appreciation to the contributors.

1

Tribological Characterization of Biocomposites: An Overview

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1.1 Introduction

The desire for environmentally acceptable materials fueled the establishment of a slew of pollution control laws, and the engineering imperative for cost-effectiveness in all areas pushed us to seek low-cost alternatives. Fossil-emerged sources are limited; hence, researchers and experts are now looking for alternative sources of conventional sources. Green technology, housing, solutions, energy, lifestyle, and materials are all part of the green environment [1, 2]. Natural fiber polymer composites (NFPCs) are a versatile material with a wide range of applications due to their capabilities and unique characteristics. Sisal, coconut coir, jute, *Calotropis gigantea*, kenaf, palm, banana, bamboo, bagasse, flax, and hemp are among the most often used natural fibers. Natural fibers provide several advantages, including low price, low mass per volume, minimal energy inputs, and superior mechanical qualities [3, 4]. Plant fibers, on the other hand, have some limitations. They can absorb moisture from the environment, resulting in a weak connection between the resin and the reinforcement. To overcome these conditions, fibers require some chemical treatment to modify their surfaces [5]. NFPCs are used for a wide range of engineering applications, like structural/nonstructural and tribological applications, because of their significant qualities. Biocomposites are used in the automobile industry to produce different parts like window linings, bike mudguard headliners, package trays, cupboards, and other vehicle internal spare parts. Other applications such as sliding panels, linkage, bearings, and bushings are fast-growing. Bio-composites are occasionally subjected to a variety of tribological loading environments, exposing the component to various forms of wear mechanisms such as adhesive, erosion, corrosion wear, and two-and three-body abrasive sliding wear. To improve the usefulness of composites in various technical sectors, it is essential to examine and investigate their tribological performance [6].

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1.2 Tribological Characterization

The term “tribology” derives from the Greek word tribos, which means “rubbing.” Tribology is the study of lubrication, wear, and friction between surfaces in relative motion. Friction is the force that prevents two bodies from moving in the same direction. The friction coefficient is the proportion of the frictional force to the perpendicular force acting on the outer layer. The sources of tribological effects are presented in Figure 1.1 [7].

It is a dimensionless number that indicates how much friction exists between two surfaces. Tribometers are devices that are used to measure the friction coefficient. The friction coefficient is independent of the contact area and sliding speed and is determined by the surface roughness and nature of the material. When two surfaces come into contact, they wear away at each other, removing material. Adhesive wear, abrasive wear, surface fatigue wear, and corrosive wear are the four types of wear that can occur as a result of friction. When two adjacent surfaces slide against each other, adhesive wear occurs. Large values of friction coefficients occur from adhesion wear. Abrasive wear is the wear that occurs when a rough surface moves over a soft surface [7].

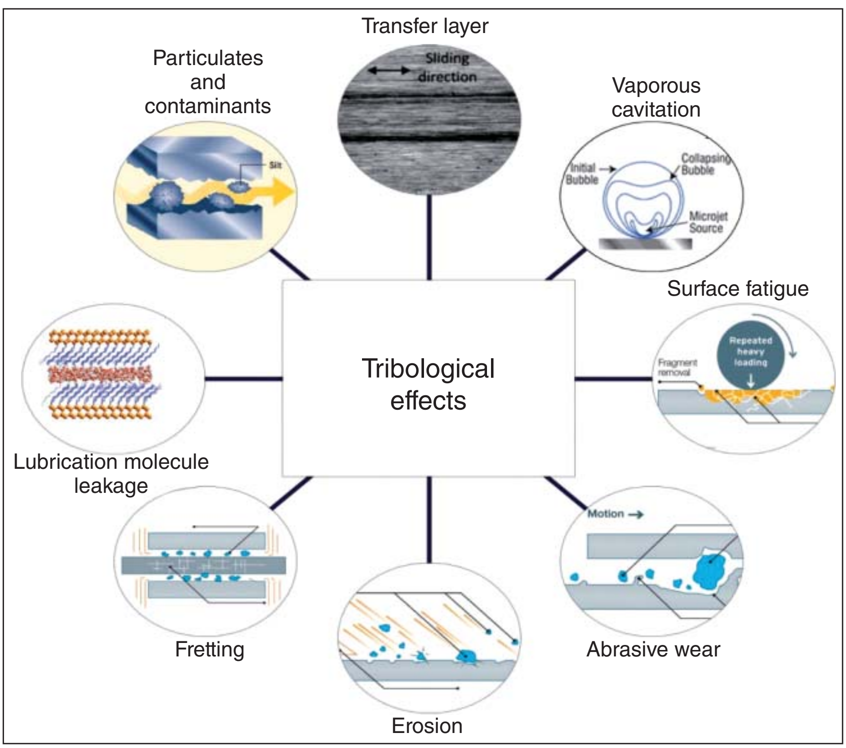

Figure 1.1 Various sources of tribological effects. Source: Karthikeyan et al. [7]/with permission of Sage Publications, Inc.

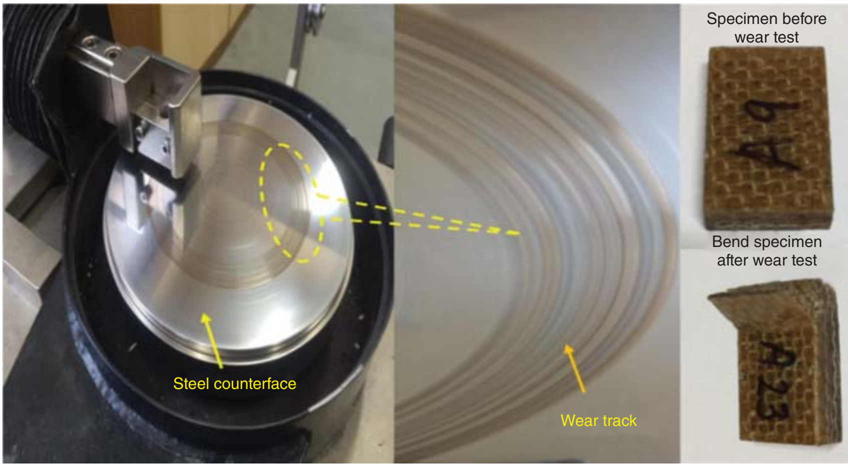

Figure 1.2 Wear experiment for jute/hemp/sisal epoxy laminates. Source: Chaudhary et al. [6]/with permission of Springer Nature.

1.2.1 Flax Reinforcement

The tribological performance of low-cost and regionally available jute/hemp/flax fibers was checked by using the hand-layup method. The tribological performance of the novel bio-composites was evaluated in terms of frictional characteristics and sliding wear in dry contact, employing a range of process parameters such as applied load, sliding speed, and sliding distance. Natural fibers with epoxy polymer improved the wear resistance rate, and the effect of speed is insignificant on the coefficient of friction (CoF) at higher speeds [6]. Natural fibers (jute, hemp, and flax) combined with epoxy polymers improved the tribological performance of all the laminates studied. At higher speeds, the effect of speed on CoF is minimal, while the impact of applied load on CoF is insignificant. Each form of specimen has a distinct average CoF. As a result, the friction conditions on the created composites are influenced by the type of natural fiber used. Epoxy's wear performance has been significantly improved by using various combinations of natural fibers as reinforcement. Sliding speed, in addition to the applied stresses, has a significant influence on the wear performance of the composites generated [6, 7]. Wear experimental setup is depicted in Figure 1.2 [6].

An investigation has been made on the friction and tribo properties of natural fiber 3D braided yarn polylactic acid (PLA) composites with woven fabric reinforcement exposed to dry sliding. For various weights and sliding velocities, the impact of different fiber weight fractions is examined. The natural-fiber-reinforced PLA composites are found to have a high CoF and wear rate. The addition of natural fiber braided yarn to PLA, aliphatic polyester, increases the frictional force and decreases the composite specimen height loss. With increasing normal loads, the wear rate and specific wear rate of pure PLA and natural fiber/PLA composites increase. The specific wear rate of PLA is reduced by roughly 95% when natural fiber reinforcement is used at 35 wt% [8].

1.2.2 Coconut Coir Reinforcement

Coir, obtained from the fibrous middle layer of coconut fruits, is a hard and stiff biodegradable lignocellulosic fiber. It has a high lignin content that makes it weather resistant and strong, and it can be chemically modified [9]. It is found that coir fibers, when chemically treated, improve their interfacial interaction with PLA resin and are thermally stable up to 265 °C. Coir-fiber-reinforced polyester laminates were made and evaluated for wear and frictional behavior using a block-on-disc (BOD) machine. The worn-out surfaces are examined by scanning electron microscopy (SEM). By adjusting the applied stresses, the particular wear rate and friction coefficient are investigated as a function of sliding distance. It is found that the composites have better wear performance than the neat polyester. SEM observation showed that there was no pull-out, tear, or breakage of fibers, but there was deformation and micro-plowing in the resinous regions [10].

1.2.3 Banana Reinforcement

Banana fibers, known as Musa fiber, are extracted from the outermost layer of the banana trees by the retting process, which improves the quality of the fiber. Banana-reinforced epoxy composites were fabricated by hand-layup, and their mechanical and tribological behavior was tested at different orientations using a pin-on-disc tribometer. It is found that at 0°, the wear rate is less than at 90°, as the fiber area is at its maximum at 90° orientation [11].

It is observed in the tribological behavior of banana/coir composites reinforced with glass fibers that were made using a compression molding procedure. The fibers are silane treated, and the composites' wear resistance is tested on a pin-on-disc tribometer by altering the force on the pin, disc speed, and fiber weight percentage. According to the wear characterization performed using SEM, the dry body abrasive wear test demonstrated that integrating natural fiber with synthetic fibers enhances the wear resistance capability and increases the wear life of the composites. According to Taguchi's design of experiments and analysis of variance methods, the most influencing factor is the type of composite fiber (96.11%), followed by the speed of disc rotation (1.85%), and the load on the pin (1.85%) [12].

1.2.4 Hemp Reinforcement

Hemp fiber is extracted from the stem of the plant by various processing techniques such as retting, decortications, softening, combing, and spinning, and it is the oldest fiber with a high heat capacity. More research work has been done to understand the mechanical behavior of hemp fiber [7]. The tribological behavior of hemp-phenolic resin-based fiber was studied by few researchers. Modifiers such as alumina, vermiculite, and graphite are used to improve the frictional properties. Phenolic (C_6H_6O) resin as constant 20, mineral reinforcement as constant value of 10, and alumina (Al_2O_3), graphite, and vermiculite as constant value of 5. The tribological properties were assessed by the IS2742–4 standard chase machine. The nomenclature is presented in Table 1.1. The result revealed that with 5% weight hemp fiber, it exhibits

Table 1.1 Composite nomenclature.

Composition (wt%)	1	2	3	4
C_6H_6O matrix	Constant	Constant	Constant	Constant
Mineral reinforcement	Constant	Constant	Constant	Constant
Al_2O_3	Constant	Constant	Constant	Constant
Graphite	Constant	Constant	Constant	Constant
Vermiculite	Constant	Constant	Constant	Constant
Hemp reinforcement	5	10	15	20
$BaSO_4$	50	45	40	35

Source: Adapted from Kumar et al. [13].

the highest friction performance, the highest friction stability, and the lowest wear and least friction variability compared to 15–20% weight hemp fiber [13].

1.2.5 Ramie Reinforcement

Ramie fiber, also known as *Boehmeria nivea*, comes from the stem of the nettle family. The water absorption behavior of ramie/epoxy composites and their effects on mechanical and tribological behavior fabricated by hand layup method with 30% fiber loading are investigated. Friction and wear behavior were also tested against the dry specimen. The worn-out surfaces and fractured spots were examined by SEM. The ASTM D3039 standard is used for the mechanical characterization.

Friction and wear behavior changed after the water absorption test was done on Ducom TR-20 LE-PHM400 pin-on-disc tribometer. The tribological performance is done by varying the sliding speeds (1, 1.5, and $2\,m\,s^{-1}$) with different normal loads (10, 15, 20, 25, and 30 N) at a constant sliding distance of 1000 m. Due to the hydrophilic nature of natural fibers, the fiber loading increases, which increases the weight gain percentage. With the increase in sliding speed, the wear loss increases significantly from 1 to $1.5\,m\,s^{-1}$ and reduces from 1.5 to $2\,m\,s^{-1}$ sliding speed [14]. The wear rate of ramie fiber is presented in Figure 1.3 [14].

1.2.6 *Calotropis gigantea* Reinforcement

Calotropis gigantea, popularly known as mudar or milkweed, is a wasteland plant that has yet to be commercially exploited. *Calotropis* is a member of the Asclepiadaceae family, which has 280 genera and 2000 species with a global distribution. It is most common in the subtropics and tropics and rare in colder climates. This shrub is evergreen, perennial, and soft-wooded. Mudar is a medium-sized shrub with a stem diameter of 25 cm and a height of 2–3 m. *C. gigantea* fibers are preferred as they are abundant and biodegradable [15] It is produced and tested in composites with various amounts of multi-walled carbon nanotube (MWCNT) in phenolic resin reinforced with *C. gigantea* fiber for tribological performance (0.25, 0.5, 1, and 2 wt%).

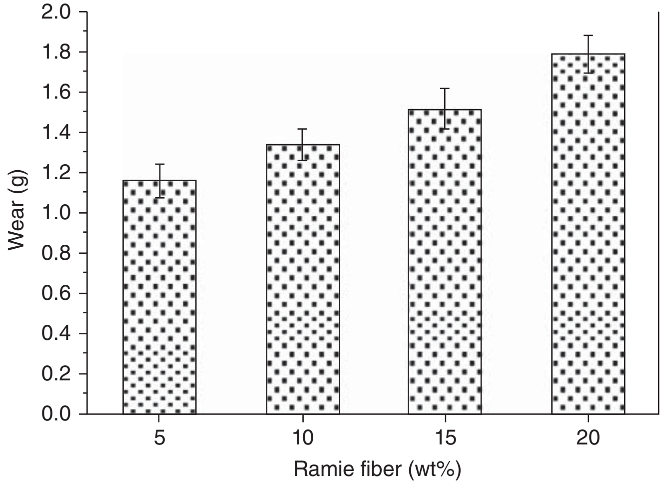

Figure 1.3 Ramie fiber (wt%) vs. wear (g). Source: Adapted from Kumar et al. [14].

The manufactured composites were tested on a conventional pin-on-disc tribometer for adhesive wear and frictional behavior against an EN-31 steel disc under varied applied loads (up to 100 N). The results revealed that adding MWCNT to a phenolic resin composite reinforced with *C. gigantea* fibers considerably enhanced the pressure velocity limit and lowered the friction coefficient value. The friction coefficient decreases as the applied load increases. The amount of MWCNT in a product has a significant influence on the rate of wear. The contact temperature of sliding surfaces rises as applied tension increases. The worn surfaces of the samples were examined using a field-emission scanning electron microscope. According to the tribological study, *C. gigantea* fiber has a lot of promise as a tribomaterial. MWCNT has a significant impact on reducing composite wear. The value of pure phenolic resin indicated the maximum friction coefficient at varied applied loads [16].

Ramesh et al. [17] studied the tribological behavior of surface-treated *C. gigantea* with sodium hydroxide and potassium permanganate solutions. The composites were prepared by compression molding by reinforcing them with untreated, sodium hydroxide and potassium permanganate treated fibers. Friction force and CoF were found to vary with the time of wear. It was also found that the frictional force value and rate of wear are the lowest for sodium hydroxide-treated *C. gigantea* fibers compared to other treated fibers.

1.2.7 Kenaf Reinforcement

Kenaf fibers come from the family Malvaceae, which has a pithy stem surrounded by fibers. It can grow up to a height of 5 m, resulting in a high production of fibers. The most attractive point is that kenaf plants contain 20–25% fiber. The adhesive wear property of thermoplastic treated kenaf fiber reinforced with polyurethane is investigated. The wear property is found by using the BOD apparatus. The composite performance was studied by varying the sliding distance, orientation of fibers, and applied loads. It was found that the adhesive wear property is better in the antiparallel direction compared to normal and parallel directions. The friction coefficient is less in thermoplastic kenaf fibers reinforced with polyurethane [18]. A newly built BOD machine is used to investigate the adhesive wear and friction characteristics of kenaf fiber composites made by closed mold process against clean epoxy at 50 N applied load, sliding lengths (0–4.2 km), and sliding velocity of 2.8 m s^{-1}. The wear performance of the epoxy was improved by around 70% when kenaf fiber-reinforced composites were used. The debonding of the fibers was thus shown to dominate the wear processes [19].

1.2.8 Betel Nut Fibers

The wear and frictional performance of betel nut fiber as reinforcement for polyester composites were investigated. The fibers were removed from the betel nut fruit after it had been steeped in water for 48 hours [20]. The composites were made with 13 layers of randomly dispersed betel nut fibers and 15 layers of polyester composites using a manual lay-up approach. The wear behavior was tested by BOD machine. The wear behavior was tested at different conditions, i.e. by varying the applied loads in the range of 5–30 N, sliding distance from 0 to 6.72 m, and sliding velocity of 2.8 m s^{-1} with different fiber orientations.

The betel nut fiber in parallel orientation concerning sliding speed has better wear and frictional performance compared to other orientations. The performance is enhanced by about 98% to 73%. Debonding of fibers is the main mechanism to be found in parallel orientation. Micro and macrocracks, plastic deformation, debonding, and fiber pullout dominated the wear mechanism for AP—O, whereas microcracks, plastic deformation, debonding, and fiber pullout dominated the wear mechanism for P—O. Meanwhile, SEM revealed micro-and micro-cracks, polyester fracture, delamination, detachment, pullout, and fiber breaking in N—O [20]. The surface roughness with respect to fiber orientation is given in Figure 1.4 [20]. A comparative study on the performance of chopped-strand mat glass-fiber-reinforced polyester as an alternative to treated betelnut-fiber-reinforced polyester composites was made. The tribological performance check was carried out both in dry and wet conditions, and it was found that treated betelnut-fiber-reinforced polyester composites revealed an increase in wear of 98% and 90.8% with a reduction in friction coefficient of about 9.4% and 80%, respectively. The presence of trichomes on the outer surface improves the interfacial adhesion strength (i.e. high fiber surface roughness), thereby minimizing fiber pullout and debonding during sliding [21]. The mechanical and tribological properties of walnut shell powder reinforced with polypropylene resin with different weight fractions, namely 30%, 40%, and 50%, are studied. A pin-on-disc tribometer is used to calculate the material loss, which shows that increasing the walnut shell powder fraction decreases the specific wear rate, thereby increasing the wear resistance [22]. The physical, chemical, tensile, and surface roughness properties of *Caryota urens* fibers, often called "toddy palm, jaggery palm, or wine palm," were investigated. It may reach a height of 20 m and is branched with an expansion at the internodes, similar to a palm. It was found that the combination of fibers with barites improved the tribological performance [23].

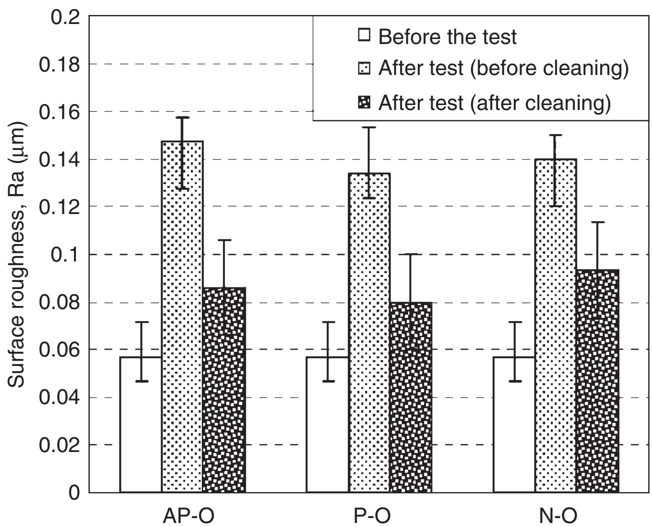

Figure 1.4 Surface roughness vs. betel nut fiber orientation. Source: Gill and Yousif [20]/with permission of Sage Publications.

1.3 Parameters Influencing the Tribological Characteristics

Parameters such as fiber orientation, fiber volume fraction, and filler percentage play a vital role in influencing the tribological characteristics, which impact wear loss, frictional force, and CoF. With the exception of biodegradable polymers, biocomposite has been studied in a variety of natural polymers. Furthermore, research on the effects of plant fiber reinforcement in biomatrix on wear properties has been found to be exceedingly limited. Furthermore, it was discovered that relatively little study has been undertaken on the wear features of plant fiber-based hybrid laminates in various matrix systems [7]. Natural fiber composites with optimal fiber alignment provide the best tensile, flexural, and wear characteristics [24].

1.3.1 Impact of Reinforcement Orientation on Wear Behavior

The reinforcement orientation plays a predominant role in influencing the wearer's behavior. Sisal fiber reinforced with epoxy, where fiber is oriented as parallel or antiparallel as shown in Figure 1.5 with respect to the wear sliding direction [25].

The experimental outcome revealed that specific wear vs. load, where parallel fiber orientation has the maximum specific wear rate corresponding to the load condition, antiparallel fiber orientation initially has 1.2×10^{-3} m^3 Nm^{-1} then normal fiber orientation has the minimum value of specific wear rate at 0.8×10^{-3} m^3 Nm^{-1} as shown in Figure 1.6 [26].

Parallel orientation, random orientation, and antiparallel orientation are needed for fabricating banana-fiber-reinforced epoxy composites in different orientations.

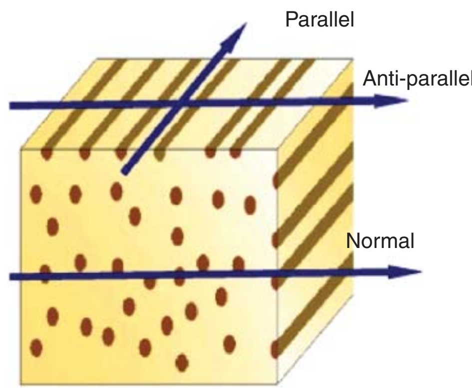

Figure 1.5 Reinforcement alignment at parallel, antiparallel, and normal directions. Source: Adapted from Ruggiero et al. [25].

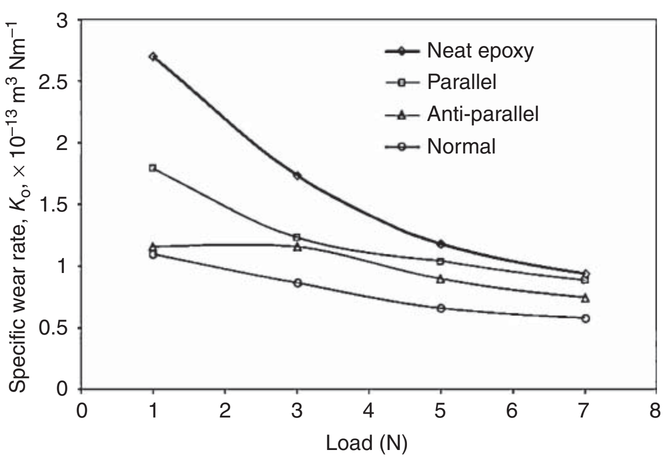

Figure 1.6 Specific wear rate for fiber orientation. Source: Adapted from Chaudhary and Ahmad [26].

Results revealed that tribological behavior of antiparallel orientation > parallel orientation > random orientation. Frictional performance is higher for antiparallel orientation with 44% at minimum value of sliding velocity, and random orientation has lower frictional performance of 9.89% at maximum sliding velocity [27]. Then fiber orientation has conflict with impact of single fiber arrangement, impact of multilayer fiber orientation, impact of continuous fiber alignment, and effect of discontinuous reinforcement orientation [28].

1.3.2 Effect of Reinforcement Volume Fraction on Wear Behavior

An investigation of sisal-fiber- and glass-fiber-reinforced polymer laminates showed the reinforcement volume% is to be discussed. In an experimental study, sisal fiber was taken at 100% and 50%, and the composites were fabricated by compression molding machines (Table 1.2). From the results, it appears that the CoF increased as fiber volume percentage increased. The presence of more sisal strands in the resin

Table 1.2 Specimen abbreviation corresponding to fiber volume fraction.

Specimen abbreviation	Fiber volume fraction (%)	Sisal fiber (% in vol)	Glass fiber (% in vol)
1	20	100	0
2	20	50	50
3	20	0	100
4	40	100	0
5	40	50	50
6	40	0	100

Source: Adapted from Ramesh et al. [29].

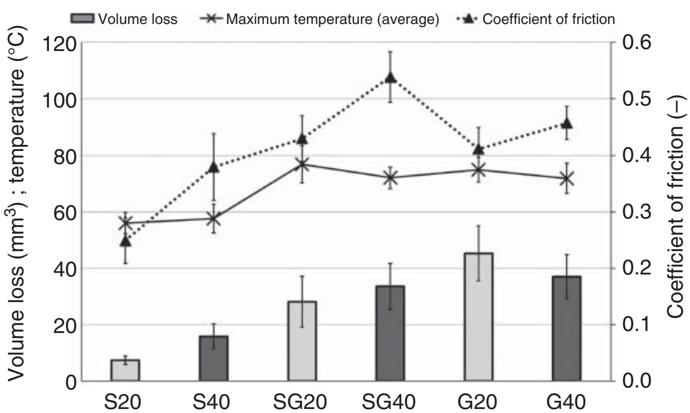

Figure 1.7 Influence of fiber volume fraction. Source: Adapted from Ramesh et al. [29].

of the laminate resulted in more discontinuous phases in the resin, which resulted in maximum friction value.

The minimum temperatures recorded for S20 and S40 samples may help elucidate how virgin sisal laminates have the maximum wear resistance. The polymeric resin of the materials softens at high temperatures, allowing for more layer interaction between the sample and the anti-side, leading to improved actual contact zone and wear. The tribological characteristics of *Ipomoea carnea* fiber-reinforced laminates were investigated in a research work. The fiber volume percentage was varied using 10%, 20%, 30%, and 40% of fibers at different ranges of sliding velocity in the tests. Abrasive wear loss may be considerably reduced by incorporating *I. carnea* into epoxy. At a particle level of 30% fiber volume percentage, the best frictional resistance characteristic was attained. However, due to weak interfacial adhesion, an excessive amount of fiber (40 wt%) causes the particles to tear away from the matrix resin throughout the test (Figure 1.7).

1.3.3 Effect of Fillers on Wear Behavior

The influence of date palm seed fillers on the wear characteristics of polymer laminates in a variety of experiment conditions is studied. The outcomes suggest that improving the date seed filler from 15% to 25% reduces the friction coefficient for polyester laminates filled with date seed filler under maximum contact pressure, and that under reduced friction force and reduced sliding velocity, date seed filler can increase by up to 10%. In practice, adding supplementary fillers to a natural-fiber-reinforced material improves wear performance by improving the interfacial strength of the reinforcement and resin [30, 31]. Natural-fiber-reinforced laminates containing filler particles such as MWCNTs, silicon dioxide, graphite, titanium dioxide, graphene, and others are a growing field where major studies may be done. Despite this, significant progress has been made in the wear analysis of composite materials [32]. Jute-reinforced polypropylene laminate tribological performance revealed that the CoF reduces as the load rises. The CoF begins to rise as the filler loading increments, but it progressively declines. The minimum CoF was discovered under high loads and 0% fiber loading. At 4 kg of weight, the CoF was 0.3854, while at 8 kg of load, it was 0.3325. This might be due to a strong binding between resin and reinforcement, resulting in a lower composite CoF [33].

The influence of nanomaterials oil palm empty fruit bundle additives on fiber-reinforced kenaf in nonwoven matting form with laminates is studied. Due to the nanotechnology fillers' capacity to eliminate free spaces, the research finding implies that utilizing nano-oil palm empty fruit bundle filler with kenaf-reinforced composites enhances mechanical strength when compared to kenaf epoxy composites. A nanofiller hybridization composite's fracture toughness has been increased by 28.3% [34]. The influence of fillers on the tribological characteristics of glass-coir-reinforced polymer laminates with various proportions of molybdenum disulfide and titanium dioxide fillers is used to make different compositions. When evaluated against unfilled and titanium dioxide filler-filled glass-coir-reinforced epoxy composites, molybdenum disulfide-integrated filler demonstrated improved tribological performance. The inclusion of molybdenum disulfide as a filler will improve the CoF. This is due to molybdenum disulfide's structure, which generates a thin black layer that offers cushioning [35].

1.3.4 Influence of Surface Modification on Wear Behavior

The influence of surface treatment on *C. gigantea* fiber-reinforced epoxy laminates is that the rate of wear of raw *C. gigantea* fiber laminates is notably higher than that of alkaline and potassium permanganate-treated materials, as shown in Figure 1.8. The alkaline-treated *C. gigantea* fiber composites wore out less than the potassium permanganate-treated *C. gigantea* fiber composites. The rate of wear was shown to be enhanced due to the improved coupling between alkali-treated *C. gigantea* fiber and resin. Overall, the wear behavior of alkaline-treated *C. gigantea* fiber composites was superior to that of the other materials, and the wear behavior of these laminates

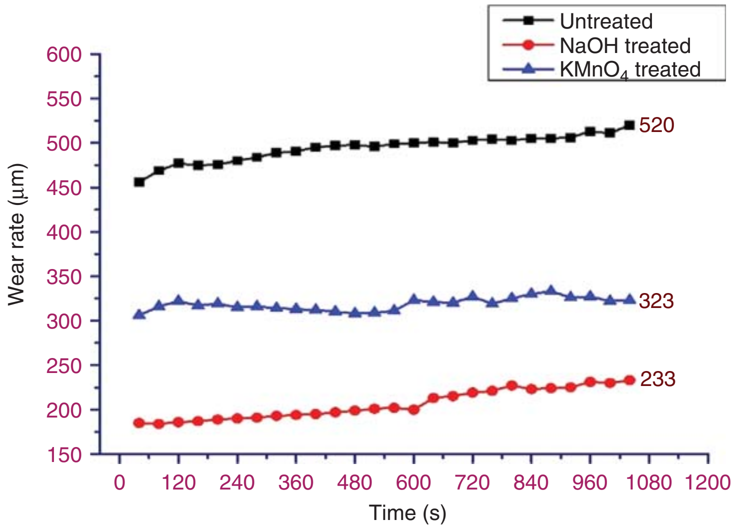

Figure 1.8 Wear rate analysis of *Calotropis gigantea*–fiber-reinforced laminates. Source: Ramesh et al. [17]/John Wiley & Sons.

was found to be superior between 400 and 600 s. These composites are used in a variety of technical features, including brake lines and discs.

The impact of the silane solution concentration on the wear properties of maize-stem-fiber-reinforced polymer laminates was investigated. According to the observations, the silane-treated maize-stem-fiber-reinforced polymer laminates exhibited a possible low-density feature. The silane-treated corn stalk fiber did not considerably enhance the frictional behavior of the polymer composites, but it did greatly increase the abrasive wear. When compared to the raw maize-stem-fiber-reinforced laminates, the cumulative wear rate of the silane-treated maize-stem-fiber-reinforced laminates fell by 22.8% from 4.792×10^{-7} cm^3 (Nm)$^{-1}$ to 3.699×10^{-7} cm^3 (Nm)$^{-1}$, indicating the best wear-resistant behavior [36, 37].

A research using coccinea indica fiber as a reinforcement to explore and assess the possibilities for improving the wear resistance of epoxy laminates. Raw coccinea indica fiber reinforced with epoxy laminates was made, and two distinct surface treatments, 5 wt% alkaline treated and 2 wt% silane treated, were conducted. The laminate was made utilizing a manual lamination and open mold method for all specimens, with fiber lengths of 30 mm and a fiber proportion of 35 wt%. The weight loss of alkaline and silane-processed laminates was decreased by 14% and 38%, respectively, whereas the CoF was decreased by 40% and 38%, according to the results (Figure 1.9) [38, 39].

1.4 Morphology Analysis of Tribological Characteristics

Morphological study plays a crucial role in tribological characterization, while SEM is used to examine the worn-out region after the experiments. They clearly guide the analysis of surface layer and show the fiber interaction between matrix in detail.

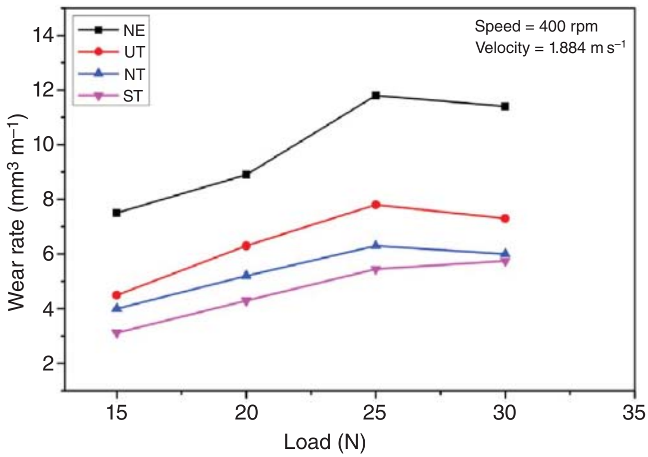

Figure 1.9 Load vs. wear rate with respect to surface treatment. Source: Mylsamy et al. [38]/with permission of Elsevier.

The impact of silane-treated maize-stem-fiber-reinforced composites is analyzed. The corn stalk fibers are silane treated at different weight fractions of untreated, 1% silane treated, 5% silane treated, 9% silane treated, and 13% silane treated. The worn surface morphology was analyzed using a TESCAN VEGA3 model SEM with an EDX-ray spectroscopy at 15 kV. The examined laminates were spray coated with gold dust using a model graphite coating technique to increase the conduction of the sample surfaces. SEM study of surface roughness demonstrated that silane-treated fibers were ideal for the formation of secondary peaks on the various polymeric layers, which might enhance wear and morphological qualities significantly (Figure 1.10) [36, 40].

The wear layer for topological analysis of sodium-hydroxide-surface-modified chopped abaca-fiber-reinforced laminates was researched. SEM morphological characterization provided visual evidence that abaca fiber epoxy with 25 wt% abaca content had the lowest abrasive wear rate and remarkable wear resistance. Fiber fracture, matrix breaking, microcracking, large fractures, and pit generation were notable wear causes on the worn surfaces. Composites with no or low fiber content wore down quicker, according to SEM micrographs. In 25% weights fiber-epoxy samples, fiber pullouts produced by applied load were found to be minimal (Figure 1.11) [41].

The structural, thermal, and wear performance of untreated, NaOH, $C_5H_9NO_4$, and combinations of NaOH + $C_5H_9NO_4$-treated sisal reinforcement polymer laminates were studied. On the surface of the UT fibers, wax, lignin, hemicellulose, silica, pectin, and other impurities can be seen, and they were primarily responsible for the poor reinforcement–resin interaction. Alkali treatment was responsible for the elimination of wax and various contaminants from the reinforced surface. As a result, the waviness of the fiber increases and the diameter of the fiber decreases. This could explain the improvement in fiber–matrix bonding [42].

The natural-waste-reinforced epoxy multilayer laminates and their mechanical and wear behavior are investigated . Composites with varying weight proportions of

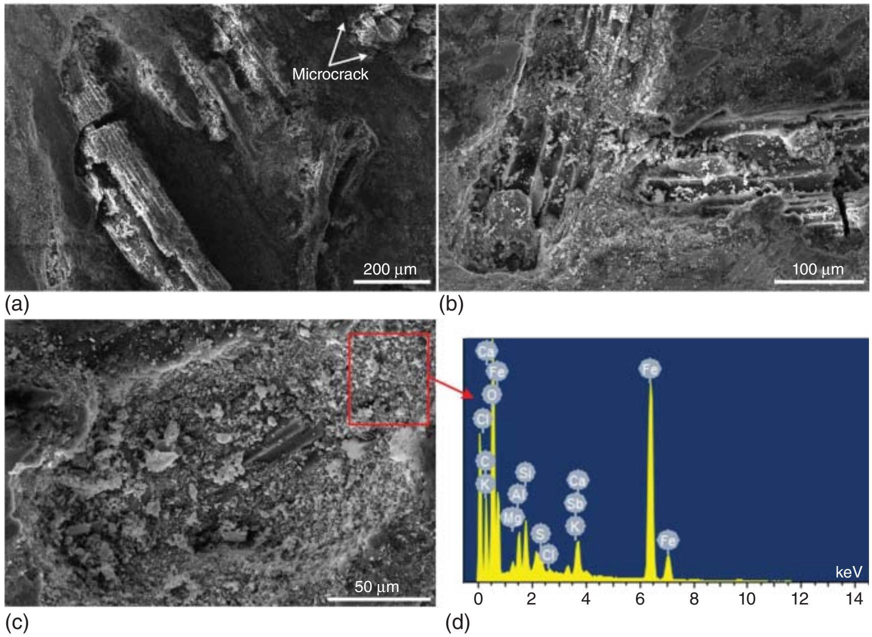

Figure 1.10 SEM image for CMU; (a) SEM image of 200 μm; (b) 100 μm; (c) 50 μm; (d) EDX analysis. Source: Liu et al. [36]/with permission of Elsevier.

fiber content were fabricated with varying lengths of reinforcement and resin. They used a Carl Zeiss Sigma 300 microscope to study the microstructural and structural appearance. The uniform dispersion of banana and hemp fiber within the vinyl ester bio-hybrid composites was investigated using SEM. It was discovered that the resin and the fibers in hemp and banana fiber reinforced with vinyl ester had a significant interaction. It was also observed that the banana and hemp fiber (20% each) diffused nicely. The hemp fiber is shedding within the vinyl ester resin, according to SEM photographs. This is due to the fiber's consistent distribution. The inclusion of hemp and banana fibers increases material characteristics as well as surface roughness, which is self-evident. As an outcome, the vinyl ester and 20% (banana + hemp) bio-hybrid composite had a smoother texture than the other materials [43].

1.5 Conclusion

Recent research in the green tribology industry includes the quest for energy-saving substances that also have sustainable and environmental properties, as well as adapting to worldwide demand through a cost-effective approach. As a result, plant-based fiber-reinforced and self-lubricated epoxy laminates are gaining popularity as a viable tribomaterial option with cost savings. One of the most essential criteria in determining the usefulness of biocomposites in appropriate tribo-applications is reinforcement selection. With the use of brief literary classics,