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Tribology of Plant-Based Natural Fiber Reinforced Polymer Matrix Composites – a Short Review

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ABSTRACT

In the framework of environment-friendly materials, natural fiber polymer matrix composites are in demand in the current years. Natural fiber-reinforced polymer matrix composites (NFRPCs) involved massive attention to the industries and academia due to their excellent strength, modulus of elasticity, and Tribo properties. This article focuses on the application of natural fiber-reinforced composite materials in many engineering systems and the effect of different material parameters – like the length of the fiber, fiber weight fraction, fiber surface treatment, fiber orientation, etc., and different operating parameters – like load, speed, sliding distance, temperature, etc., on the friction and wear behavior of the NFRPCs. The different wear mechanisms and the principle used in wear test rigs are also presented, aiming to showcase a scope of composite as Tribo material and highlight further research directions to accomplish a comprehensive outline on the tribo behavior of various natural fiber-reinforced composite materials.

摘要

在环保材料的框架下, 天然纤维聚合物基复合材料是近年来的需求. 天然纤维增强聚合物基复合材料(NFRPC)因其优异的强度、弹性模量和摩擦学性能而受到工业界和学术界的广泛关注. 本文重点介绍了天然纤维增强复合材料在许多工程系统中的应用, 以及不同材料参数(如纤维长度、纤维重量分数、纤维表面处理、纤维取向等)和不同操作参数 (如载荷、速度、滑动距离、温度、, 等对NFRPC的摩擦和磨损行为的影响. 还介绍了不同的磨损机理和磨损试验台中使用的原理, 旨在展示复合材料作为摩擦材料的范围, 并强调进一步的研究方向, 以全面概述各种天然纤维增强复合材料的摩擦行为.

KEYWORDS
Composite material; natural fiber reinforced polymer matrix composites; wear; friction

关键词
复合材料; 天然纤维增强聚合物基复合材料; 穿; 摩擦

1. Introduction

Tribology relates to the friction, wear, and lubricating conditions between two matching surfaces. Friction usually produces energy loss, leading to the material removal called wear (Parikh and Gohil 2019). Wear and friction are interconnected; however, growing friction does not always produce wear loss (Parikh and Gohil 2015). Wear and friction are not always unfavorable; in some cases, it is required for the efficient performance of the elements, this called productive friction and wear. Few unproductive and productive frictions and wear examples are shown in Figure 1.

One of the main reasons for any engineering part failure is friction and wear between interacting surfaces. Thus, there is a need to study the tribological behavior of the components (Milosevic, Valášek, and Ruggiero 2020). Conventional materials are extracted from a lengthy metallurgical process and are limited in nature. Growth in urbanization caused deforestation, which is alarming for the balanced ecosystem. There is an increasing demand for new materials, which can work in

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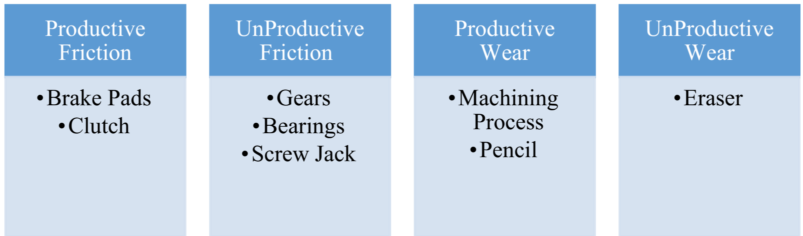


Figure 1. Examples of productive and unproductive friction/wear.

severe pressure, temperature, and corrosive conditions. So, there is a need to develop a new material that can cater to all these requirements; this has triggered the concept of composite material (Pachta et al. 2014). Composite materials are currently on rise nowadays due to their high strength, low weight, high corrosion resistance, high fatigue strength, etc. (Shahinur and Hasan 2020). Polymer composites have huge demand because of their self-lubricating properties, corrosion resistance, and lightweight properties (Periyasamy, Ramamoorthy, and Lavate 2019). Nowadays, plant-based natural fibers are in demand in industrial and structural applications because of their ease of accessibility, low cost, less weight, biodegradability, and low density over synthetic fibers (Khot and Kumar 2021). Plants, animals are the primary source of natural fibers as it is plotted in Figure 2 according to Saxena et al. (2011).

Many natural fibers polymer composites give compatible properties with synthetic fibers reinforced composites and are used in many engineering systems listed in Table 1; however, natural fibers have certain drawbacks like high moisture absorption – hydrophilic nature, less strength than synthetic fibers, variation in properties based on harvesting place, time and season. These negatively impact the tribo mechanical behavior of the natural fiber polymer composite material (Balla et al. 2019; Ruggiero, Valášek, and Müller 2016). Surface treatment of fibers or the addition of fillers during composite material manufacturing reduces its hydrophilic nature.

As such, Tribo tests on natural fiber reinforced, composites are critical for the better performance of tribological systems. Initially, Tribo testing is performed at laboratory level. In this process, a selection of proper geometry, contact surface, load, sliding speed, and contact pressure, wear/friction analysis is carried out. Most common contact configurations include a pin on flat, flat on flat, rotating

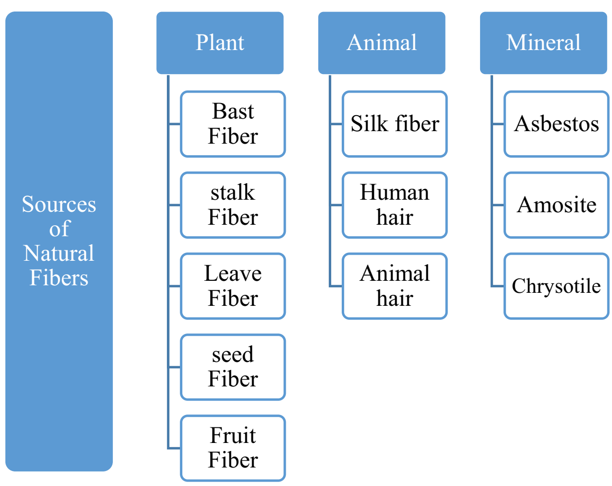


Figure 2. Sources of natural fibers.

Table 1. Applications of NFRCs.

Fiber	Matrix	Applications	Research
Sisal	Polypropylene, Epoxy	Body parts of automobiles, Roof sheet	Saxena et al. (2011)
Cotton	Polypropylene, Polyethylene	Textile, Bearing, Automobile parts	Kamath et al. (2005); Kamath (2004)
Hemp	Polypropylene, Polyethylene,	Automotive tools, Furniture, Bearing	Shahzad (2012)
Kenaf	Polylactic acid, Polypropylene, Epoxy resin	Automobile body parts	Chin and Yousif (2009)
Flax	Polypropylene, polyester, epoxy	Structural, Textile, Musical Instrument top plate	Huang et al. (2018); Goutianos et al. (2006); Phillips and Lessard (2012).
Rice Husk	Polyethylene	Automobile body parts, Structural	Arjmandi et al. (2015)
Jute	Polyester, Polypropylene, phenolic	Rope, Roofing, door panel, lifeboat slipway launches	Das et al. (2019); Khan and Khan (2014); Thomas, Hadfield, and Austen (2009)
Coir	Polypropylene, epoxy resin, Polyethylene	Automobile parts, Insulating board	Munde, Ingle, and Siva (2018); Verma et al. (2013)

pin on disc, pin on rotating disc, cylinder on a cylinder, pin on rotating cylinder, etc. (Chand and Fahim 2020).

In the present study, the author has focused on tribo behavior of different natural fiber polymer composites and studied the effect of various material parameters like length of the fiber, orientation of fiber, fiber weight fraction, fiber treatment, fiber type, etc., and various operating parameters like speed, temperature, load, sliding distance, etc., on friction and wear behavior of composite material.

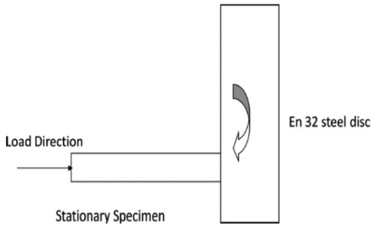
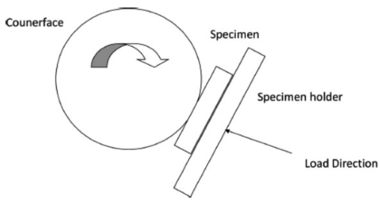
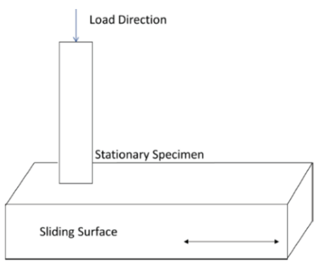
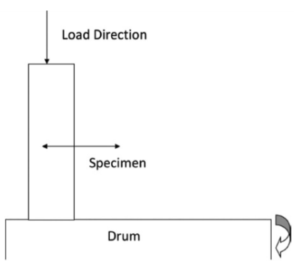
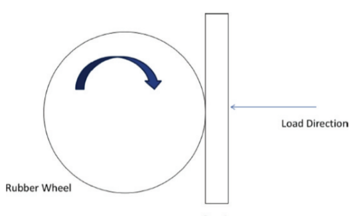
2. Tribology in NFRPCs

Tribology relates to the study of wear, friction, and lubrication between two interacting surfaces. Friction is an essential aspect of life. The discovery of fire is due to friction, which has changed human life. We cannot imagine our life without friction. But the friction creates an adverse effect in the machinery lead to wear. Wear is a gradual loss of material from the operating surfaces, which causes vibration, misalignment, noise, dimensional changes, cracks, and finally leads to the failure of parts (Aldousiri, Shalwan, and Chin 2013; Basavarajappat 2005; Fernández et al. 2003). Some most common wear mechanisms are abrasive, adhesive, erosive, and corrosive. A comprehensive view of different wear mechanisms, their application areas, and research on the materials by researchers is listed in Table 2.

Table 2. Wear mechanisms.

Wear Mechanism	Application area	The material used for the study	Research
Adhesive wear	Cycle chain, slider-crank mechanism, gear and pinion.	Metal Matrix composites, Synthetic fiber reinforced polymer composites	Rajeev, Dwivedi, and Jain (2010); Suresha (2006); Munium and Algbory (2011); Mishra, Sheokand, and Srivastava (2012).
Abrasive wear	Rope and pulley, grinding	Metal Matrix composites, Synthetic fiber reinforced polymer composites	Rajeev, Dwivedi, and Jain (2010); Suresha, Seetharamu, and Kumaran (2009)
Corrosive wear	Iron structure without coating like nut, bolts, civil structure.	Metal Matrix composites	Das, Saraswathi, and Mondal (2006)
Fatigue wear	Pulley or gear mounted on a shaft	Thermoset and thermoplastic composites	Jollivet, Peyrac, and Lefebvre (2013)
Erosive wear	Pressurized fluid from the pipe	Synthetic fiber polymer matrix composites	Boggarapu, Gujjala, and Ojha (2020); Mendoza et al. (2021)

Table 3. Wear test rigs (Parikh and Gohil (2015)).

Wear Test Rigs	Contact Geometry	Application Areas
Pin on Disc ASTM G 99		Abrasive and adhesive wear: gears, cam and follower, bearing etc.
Block on ring ASTM G77, ASTM D2714 ASTM D3704		Rolling and sliding wear – bearing.
Linear tribo machine		Sliding wear – slider-crank, racks
Pin on drum		Belt moving on rotating rollers
Dry sand rubber wheel ASTM G65		Abrasive wear: bushes, grinding

The majority of the mechanical elements fail due to abrasive and adhesive wear, leading to the shutdown of industry (Hashmi, Dwivedi, and Chand 2007). Different wear test rigs used to measure adhesive and abrasive wear with their working principle are shown in Table 3.

The unproductive wear and friction cannot be recovered totally, but choosing the right tribo pair can be reduced to a possible range. Nowadays, composite materials are in demand as Tribo material, which reveals significant wear resistance.

3. Friction and wear of NFRPCs

Tribo behavior of natural fiber reinforced polymer matrix composites has been evaluated by numerous researchers (Goriparthi, Suman, and Rao 2012; Nirmal et al. 2010; Raghavendra et al. 2014; Rodríguez-Tembleque and Aliabadi 2014; Shireesha and Nandipati 2019; Xess 2012; Yallew, Kumar, and Singh 2014). Tribological properties of the NFRPCs are affected by various material parameters and operating parameters. An overview based on the literature survey on various plant-based fibers is presented below.

3.1. Jute fiber

Jute fiber is obtained from the bast of the plant (Corchorus capsularis and Corchorus olitorius). Jute polymer composites – Jute/epoxy, jute/polyester, jute/polypropylene – were developed by researchers for different applications like low-cost housing, small fishing boat, etc. As the jute fiber mainly consists of cellulose, surface treatment of the fibers plays a significant role in enhancing the composite material's performance. The abrasive wear behavior of jute fiber reinforced polyester composites under the effect of coupling agent was studied by Chand and Fahim (2020) and revealed its effect with scanning electron microscopy. The test results showed that the coupling agent enhances the wear resistance of the composite material. Effect of surface treatment and jute fiber orientations on the friction and wear behavior of the material were studied by researchers and revealed its sound effect on the tribo behavior of the material (Acha, Marcovich, and Reboredo 2005; Dwivedi and Chand 2009). Jute fiber reinforced polyester composites were used in bearing and evaluating the effect of fiber volume fraction and fiber orientation on the tribo behavior of the composite material (El-Sayed et al. 1995). The test results revealed that 33% volume fraction of fiber increased the friction coefficient by 14% and reduced the wear rate by 95% for normal fiber orientation.

3.2. Coir fiber

The coir fiber is a fruit fiber obtained from the husk of coconut trees. Coconut is found in many parts of the world; most coir fibers come from India, Sri Lanka, Malaysia, the Philippines, and Indonesia. Due to the increasing demand for coconut products, waste products from the coconut fruit is also increasing. The coir fiber is mainly used for producing ropes, yarns, mats, rugs, etc. However, only a tiny portion of the coconut husk is utilized for total coconut husk production. So, many researchers are working on the tribological and mechanical behavior of the coir fibers to make valuable industrial products (Ayrilmis et al. 2011).

Aireddy and Mishra (2011) have studied the erosive and abrasive wear behavior of coir-filled epoxy matrix composites with different impingement angles and various impact velocities for silica of 200 to 600-micron size. Erosive wear is reduced with the increased coir dust. The abrasive wear was studied on a pin on a disc wear tester for different loading conditions. The test results revealed that with increasing fiber concentration, wear resistance of the material increases for higher loading conditions (Yan, Su, and Chouw 2015). Many researchers evaluated the result of fiber treatment on the wear performance of coir fiber epoxy composites with varying fiber weight fractions. All the research reach to same conclusion that fiber treatment and fiber weight fraction substantially influence the wear behavior of the composite material (Adeniyi et al. 2019; Khan et al. 2014; Rao et al. 2012; Valášek et al. 2018). Yousif (2009) has studied the friction and wear behavior of coir reinforced polyester composites. The test results revealed that weight fraction of fibers has significant effect on the friction and wear behavior of the material.

3.3. Sisal fiber

Sisal fiber is removed from the plant leaves. More commonly found in South America specially in Brazil and North America, particularly in West Indies. The soil rich in magnesium, potassium, nitrogen, and phosphorus is preferred for the sisal. Different types of sisal plants are found across the world. Fibers obtained from the plant depend on the time, place, and season of harvesting. Sisal is one of the most commonly used natural plants, and it is easily cultivated. The fibers have good strength, good elasticity, and good resistance against corrosion; however, they degrade quickly due to their hydrophilic nature when exposed to the environment (Balla et al. 2019). The fiber treatment can reduce the hydrophilic effect nature of the fiber. Priyanka (2013) has studied the result of fiber treatment on the composite material's moisture absorption behavior and mechanical behavior. The author has revealed that the alkaline treatment enhanced the moisture absorption behavior of the material and improved mechanical behavior. Short sisal fiber-reinforced epoxy composites were studied for various loads, sliding distances, and sliding speeds. The test results revealed that all three variables substantially affect the wear behavior of composite material (Maurya, Jha, and Tyagi 2017; Vigneshkumar and Rajasekaran 2018). Sisal and glass hybrid composites were prepared and evaluated for tribological characterization. These studies revealed the natural fiber as the potential substitute for synthetic fibers in Tribo composites (Aslan, Tufan, and Küçükömeroğlu 2018; Gehlen et al. 2020). Sisal fibers with diverse shapes, namely undulated, spiral, and straight shapes, were combined with resin to evaluate the effect of different shapes of natural fibers on the composite's tribological, morphological, and mechanical performance. Friction composites are prepared using binders, reinforcements, fillers, and friction modifiers using the compression molding process. The test results revealed that the helical-shaped sisal fibers showed better tribological behavior than undulated and straight shape fibers (Wu et al. 2021).

3.4. Sugar cane fiber

Sugarcane is commonly found in tropical areas, and the fibers remain as residue after extracting juice from the stalks of sugarcane. Because of its low cost, it is usually used as fuel to produce energy, and nowadays, it is more commonly used as filler to produce composite materials. Various chemical treatments like silane and alkaline treatment modify the fiber's surface for proper adhesion with the matrix material and improve mechanical strength, acoustic properties, and aging properties of the composite material. Sugarcane ash as filler material in concrete gives thermal stability to the structure at elevated temperatures (Devadiga, Bhat, and Mahesha 2020). The wear rate of sugarcane fiber polyester composites was evaluated for different fiber lengths and compared with the glass fiber composite. A dry sliding wear test was performed at a speed of 2.5 m/s, 2.25 km sliding distance, and ambient temperature conditions. The wear resistance of chopped sugar cane fibers reinforced composites plotted for various loading conditions compared with chopped glass fiber polyester composites (CGRP) is shown in Figure 3.

The test results revealed higher wear resistance and a higher coefficient of friction for composites reinforced with sugarcane fiber than for those reinforced with glass fiber. Therefore, the composite reinforced with sugarcane fiber is a more promising material than the one reinforced with glass fiber (El-Tayeb 2008). Wear behavior of chopped sugarcane fiber polyester composites (C-SCRP) with varying fiber length was evaluated. Less abrasive wear was observed for small fiber length (1 mm), and

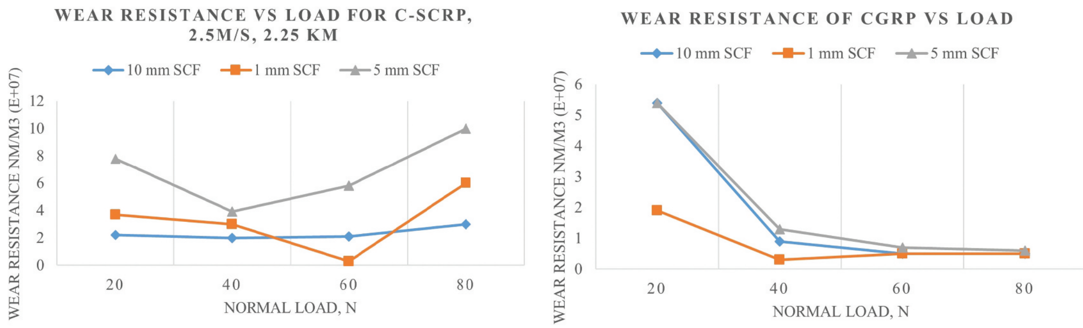


Figure 3. Wear behavior of glass and sugarcane fiber composites (El-Tayeb 2008).

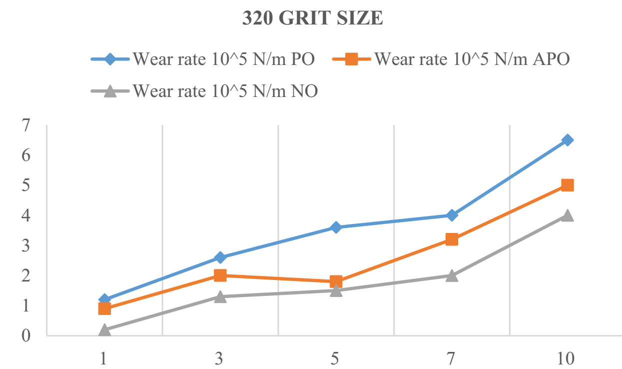


Figure 4. Influence of Fiber orientation on wear performance of sugarcane composites (Mishra and Acharya 2010).

higher wear was observed with the increasing length of the fiber. Advanced optimization techniques are used to determine the optimum fiber length for abrasive wear conditions. The suggested best size of the fiber length is 7–8 mm for minimum abrasive wear (Mahapatra and Chaturvedi 2009). Fiber orientation plays a vital role in controlling the wear of the material. Figure 4 indicates the influence of normal orientation (NO), antiparallel orientation (APO), and parallel orientation (PO) of unidirectional sugarcane fiber/polyester composite on the abrasive wear behavior. The wear rate was evaluated for 150, 180, 320, and 400 grit sizes and revealed that wear rate is strongly affected by load and grit size and increased with growing load and grit size (Mishra and Acharya 2010).

3.5. Cotton fiber

Cotton belongs to the genus Gossypium, sub-tribe Hibisceae family Malvaceae and it is a vital farming crop. It is most commonly used in clothing and has high demand worldwide. Also, its strength and easy blending characteristics with the other fibers make it more favorable for fibers to produce composite materials.

Graphite, fly ash, and SiC fillers with varying weight fractions (0, 3, 5 wt. percentage) were used with cotton fiber reinforced polyester composites for evaluating composite friction properties. The experiments results revealed that the different weight concentration of fillers has a significant effect on the friction behavior of the material. As the weight fraction of SiC is increased from 3% to 5%, coefficient of friction increased due to more uniform distribution of fillers gave good adhesion, shown

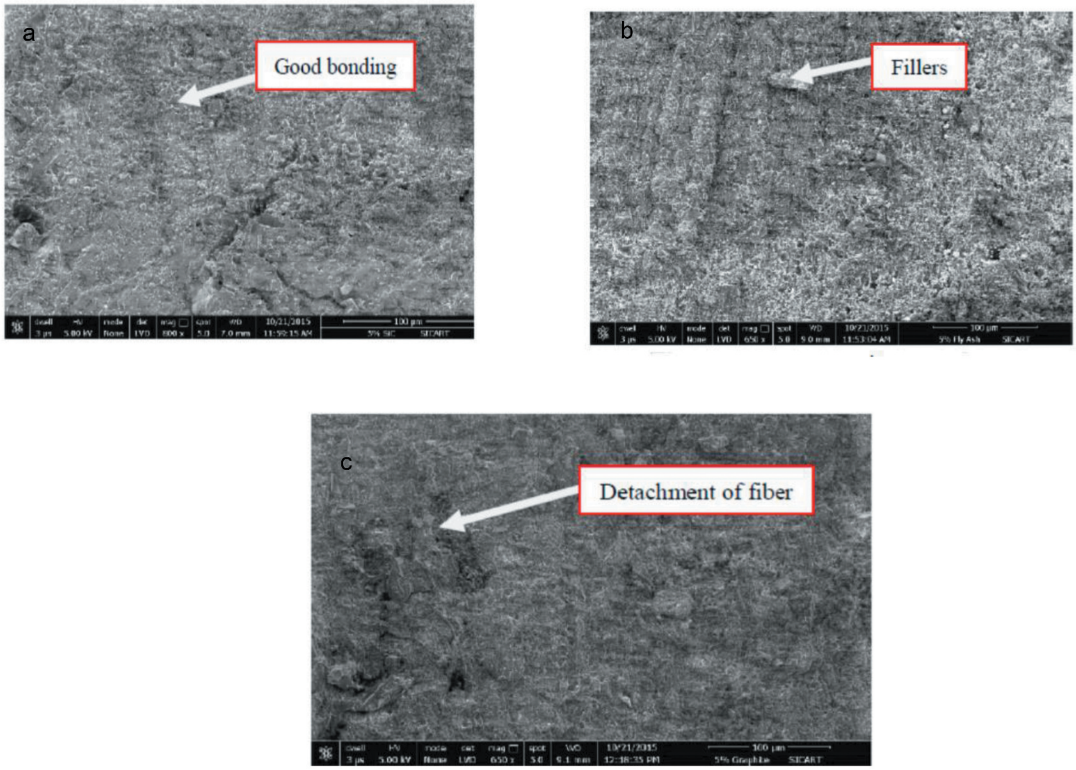


Figure 5. SEM Image of A) Graphite B) SiC C) Flyash filled cotton fiber reinforced polyester composites (Parikh and Gohil 2021).

in Figure 5; on the other hand, the increasing weight fraction of fly ash from 3% to 5% and graphite fillers from 3% to 5% reduce the coefficient of friction. The higher weight fraction of fillers showed a more uniform fillers distribution in Figure 5 (Parikh and Gohil 2021).

3.6. Banana fiber

Tropical plant banana belongs to the genus Musa, family Musaceae. Mainly four types of Musa varieties are cultivated for the fruits – Sentuluvan, Aethalpalal, Rasagatali, and Palayannkottai. Sentuluvan is red and produces red-brown fibers mainly cultivated from southern India. Banana natural fibers are used for making household products like bags, bins, mats, etc. Banana fibers contain 9% lignin, 43.46% cellulose, 38.54% hemicellulose, and exhibit a tensile strength of 142.9 MPa (Jústiz-Smith, Virgo, and Buchanan 2008). The studies revealed that when the polymers are reinforced with banana fibers, it improves the mechanical and tribo properties of the polymers (Asabe Popat and Bhosale 2017; Idicula et al. 2005; Joseph et al. 2002; Sapuan et al. 2006; Thwe and Liao 2002; Zhu et al. 1994). Rahul et al. (2017) has revealed that when epoxy is reinforced with banana fibers wear resistance of the epoxy increases. Also, adding the nano fillers like silica and clay further increase the wear resistance of the banana fiber epoxy composites. There is still a vast scope of work in the tribology of banana fiber polymer composites.

Table 4. Summary of hybrid plant-based fiber reinforced polymer composites.

Research	Fibers	Resin	Manufacturing	Test Carried out
Chaudhary, Bajpai, and Maheshwari (2018)	Jute fiber + Hemp fiber	Epoxy	Hand Layup	Wear and Friction behavior, Dynamic Mechanical Behavior
Gupta and Srivastava (2016)	Sisal fiber + Jute fiber	Epoxy	Hand layup	Wear and Friction behavior, Dynamic Mechanical Behavior
Yousif and El-Tayeb (2009)	Oil Palm fiber + Glass fiber	Polyester	Hand Layup	Wear behavior and Mechanical strength
Kumar, Mohan, and Bongale (2019)	Coir fiber + banana fiber + glass fiber	Unsaturated Polyester	Hand Layup	Friction and wear behavior
Parikh and Gohil (2017)	Cotton fiber + Graphite fillers	Polyester	Hand Layup	Friction properties

Table 5. Summary – tribological characterization of NFRPCs.

Research Publication	Fiber	Resin	Variables	Manu Tech.	Dry Sliding: Wear resistance	Dry Sliding: Coefficient of friction	Wear Mechanism
Nirmal, Hashim, and Low (2012)	Bamboo	Epoxy	Fiber Orientation, Sliding Velocity	Hand Lay up	Improved with low speed for APO – 60 % higher than neat Epoxy	Higher at low speed for APO – 44% as compare to the higher speed for same orientation	Back Film transfer for APO and formation of groove on worn surface.
Ajay and Navin (2007)	Bamboo fibers of size less than 350 micron	Polyester	Filler weight fraction	Close molding technique	Improved abrasive wear resistance for 20 wt. % bamboo powder	——	Micro Cracks and Micro cutting
Deo and Acharya (2010)	Lantana Camara	Epoxy	Fiber weight fraction, load	Close molding technique	Improved wear resistance for 40 wt. % of fiber content. Wear rate increased with load.	——	Micro cracks
Kranthi et al. (2010)	Wood Dust fillers of 100 micron	Epoxy	Filler content, load, sliding speed	Hand Layup	10% wood dust revealed better wear resistance than 0 and 5 wt %.	——	——
Boopathi, Sampath, and Mylsamy (2012)	Borassus Fruit Fiber	Epoxy	Fiber Length	Hand layup	5 mm fiber length composites revealed better wear resistance compared to the 10 mm and 3 mm fiber length.	———	Worn out debris, Fiber pull out
Yousif and El-Tayeb (2010)	Oil Palm Fiber	Epoxy	Fiber treatment	Hand layup	Wear behavior of polyester improved by 30 to 50 and 65 to 75% respectively in the case of POD and BOR with treated fiber.	Higher coefficient of friction for treated fiber composites.	Debonding, Fiber breakage
Yousif, Lau, and McWilliam (2010)	Betelnut fruit fiber	Polyester	load	Hand Layup	More wear resistance under wet condition compared to dry condition.	Less coefficient of friction for wet condition than dry condition.	Micro and Macro cracks
Singh, Yousif, and Rilling (2011)	Kenaf Fiber	polyurethane	Load, Fiber orientation	Molding process	Wear resistance improved by 59% compared to neat polymer	Friction behavior improved by 90% compared to neat polymer.	Macro cracks, fiber tearing, fiber detachment, and delamination
Nordin et al. (2013)	Kenaf Fiber	Epoxy and Polyester	Resin, load	Hand layup	With increasing load from 5N to 30 N wear rate also increasing. Epoxy kenaf composite revealed more wear resistance than polyester kenaf composite	——-	——
Chin and Yousif (2010)	Kenaf Fiber	Epoxy Resin	Fiber orientation, abrasive particle size and load	Hand lay up	Presence of kenaf fiber in NO improve the wear performance of epoxy by 85%	0.52 to 0.68 Coefficient of friction for normal oriented kenaf fiber epoxy composite	Micro cracks (in NO), Debonding (in PO) fibrous region.
Narish, Yousif, and Rilling (2011)	Kenaf Fiber	Polyurethane	Load, sliding distance, fiber orientation	Hand layup	T-KFRP (in AP-O) has a high degree of wear resistance compared to neat polyurethane	——	Fiber detachment, pitting, delaminating, and micro-cracks.

3.7. Hybrid/Fillers filled composite

Bio-degradable fibers spectrum is increasing globally in a wide range of applications in many engineering disciplines. Researchers have combined two or more fibers/added fillers to develop more versatile composite materials. The work done by researchers is listed in Table 4.

Table 5 summarizes the tribological characterization of natural fiber polymer matrix composites (NFRPCs) found in scientific works.

4. Summary

Many plant-based natural fibers (like jute, cotton, coir, sugarcane, banana, sisal), animal fibers, and mineral fibers are used in the different matrices to create an eco-friendly composite material. Plant-based natural fiber polymer composites are getting the attention of several engineering fields, automobile research, and fundamental research. Tribological performance of natural fiber polymer composites is a novel research field as its application directly affects the performance of parts.

Different researchers' work has been reviewed, and a few points summarized:

- The vast scope of FRP composites as Tribo material, without lubricating conditions because of its self-lubricating nature.
- The reinforcement of natural fibers in the polymers enhances the wear performance of the polymer matrix composites.
- Research reveals the sound effect of material parameters like fiber length, the weight fraction of fiber, fiber surface treatment, fiber arrangement, fillers concentration, etc., on the wear behavior of the composite material. Functioning parameters like load, speed, sliding distance, temperature, etc., also revealed a significant effect on tribo behavior of the NFRPCs.
- Tribo – Mechanical properties of natural fibers has revealed that few fiber reinforced composite materials are likely to substitute the synthetic material; however, the evaluation of the tribological and mechanical properties of different composite materials using varying operating parameters allows to achieve a more global and useful overall view of the tribological performance of these materials.

The future scope for further study in the context of tribology of NFRPCs should be underlined in this way: Detailed investigation on tribo behavior of natural fiber polymer composites by changing various material parameters and operating parameters. Development and Tribological characterization of totally environment-friendly biocomposite. Tribological characterization of composites under both dry and wet conditions.

Disclosure statement

No potential conflict of interest was reported by the author.

Highlights

- A comprehensive discussion on the scope of Natural Fiber Reinforced Polymer Composites as Tribo Material.
- An overview of different wear test rigs for Tribo testing.
- Emerging applications of Natural Fibers are also analyzed to reduce carbon foot print.

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