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REVIEW

A comprehensive overview on tribo-mechanical characteristics of hybrid plant fiber–based biocomposites

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Abstract

Plant fiber is one of the sorts of environmentally friendly resources that have been replenished over several years by nature and human invention. For the past few years, application of plant fibers as reinforcements into polymer matrixes has gained considerable interest due to their biodegradable nature. Introducing just one type of reinforcing element does not result in composites with remarkable physical and tribo-mechanical characteristics. Lately, significant research and innovation have been observed on hybrid plant fiber–based biocomposites (HPFBCs) in structural and automotive industries. One of the crucial topics that must be reviewed is the tribo-mechanical performances of these composites. Hence, the present review article aims to provide the friction and wear behaviors and mechanical properties of different HPFBCs under different operational conditions. Based on the understanding of tribo-mechanical aspects of HPFBCs, some prospects have also been suggested that need to be addressed and resolved in the future. This review article is anticipated to provide readers and researchers with valuable insights into the significance of tribo-mechanical performances in the assessment of HPFBCs for specific applications.

Keywords Tribology · Wear · Friction · Mechanical characteristics · Plant fiber · Polymeric composites

1 Introduction

Synthetic polymers alone cannot be employed in a wide field of practices, comprising the automotive, aerospace, wind turbine blades, etc., due to their inability to transmit load effectively and low strength. Therefore, reinforcing must be included in plastics [1]. In 1935, work with fiber-based composites began. However, there was a need for these composites at the time of World War II due to the need for lightweight components. More polymer matrix and man-made fibers were created later, which entirely altered the way traditional materials were used [2, 3]. Now, fiber-reinforced polymers made of man-made fibers (such as glass, carbon, and aramid) have diverse uses in industries including aircraft, automotive, and constructions due to attractive material properties. However, the fundamental issue with these composites is the non-biodegradability of synthetic fibers and the issues with their post-service disintegration. Also, synthetic fiber synthesis poses substantial health risks. The massive loss of natural resources can be exacerbated by increased demand for polymers made from petroleum. Governments are attempting to encourage the manufacturing of ecologically friendly products at a reasonable cost to safeguard the environment from global warming. As more energy, basic materials, and cost requirements increase, it is getting harder to produce the materials utilized in engineering various applications. Therefore, researchers are looking for viable substitute materials and have discovered that resources with low energy needs might be the ideal replacements. One method is the extraction of fibrous materials from the already available agricultural resources.

Now, natural fibers have received enough popularity as reinforcements for polymeric composites from economic and environmental perspectives [4]. By 2024, the natural fiber composite market will be worth \$10.89 billion, and it is anticipated to expand up to a compound annual growth rate of 11.8% [5]. The major sources of natural fiber are plants and animals. As compared to animal fibers, fibers produced from plants have received a lot of attention because they are capable of replacing synthetic reinforcements [6]. Natural

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fibers are frequently referred to as "vegetable fibers or plant fibers" in the composite business. Plant fibers are the most often applied natural fibers in the composite fabrication field and are also the most extensively researched. Leaves, seeds, fruit, wood, stalks, and grass or reeds of plants can all be used to extract the cellulose, hemicellulose, and lignin that make up the vegetable fibers [7]. Plant fibers are typically obtained from plant material through a retting or decortication process aimed at eliminating unwanted cell wall components like pectin, extractives, hemicellulose, and lignin [8]. Plant fibers have special benefits over synthetic fibers like being abundant, non-toxic, and not irritating to the skin, eyes, or respiratory system and anti-corrosive in nature. Other environmental benefits of natural fibers are less in weight, energy-efficient, fuel-efficient, and low emission. Cellulose-based plant fibers, extensively researched, can be classified based on the plant species and plant tissue utilized, as depicted in Fig. 1 [9]. Plant fibers have been easily reinforced with a thermoset/thermoplastic polymer matrix. Plant fibers can be incorporated into polymer matrixes in several various ways, including chopped, unidirectional, and randomly oriented fibers [10–12]. Other benefits include the fact that plant fibers are cheaper and use fewer resources to create than conventional reinforcing fibers like carbon and glass [13]. Pant fibers have not yet completely replaced synthetic ones because of a few drawbacks, including their poor matrix bonding due to their high moisture absorption rates, variation in physico-mechanical properties, and lower durability/strength. The wide range of attributes mostly relies on the plant's type, the environment in which it grows, and the process used for getting the fiber.

Not long ago, there was tremendous progress made in order to increase the performance of natural fiber composites like the development of hybrid composite material. The hybrid composite materials involve the reinforcement of two or more fibers with a single matrix. Multiple reinforcing agents employed in a matrix show higher improvements in properties than single fiber-reinforced composites. Hybridization of plant fibers is done to give them more strength than synthetic fiber. One natural fiber combined with another fiber (either natural or synthetic) in a single matrix has been shown to improve the tribo-mechanical and thermal characteristics of polymeric composites more than using only one fiber [14]. More focus has been put on substituting various conventional fibers used for various applications with the fibers which are light in weight, easily available, and more affordable. Plant fibers have several of these features, including low density, affordability, and accessibility; thus, significant study has been done on using them to replace a portion of traditional synthetic fibers.

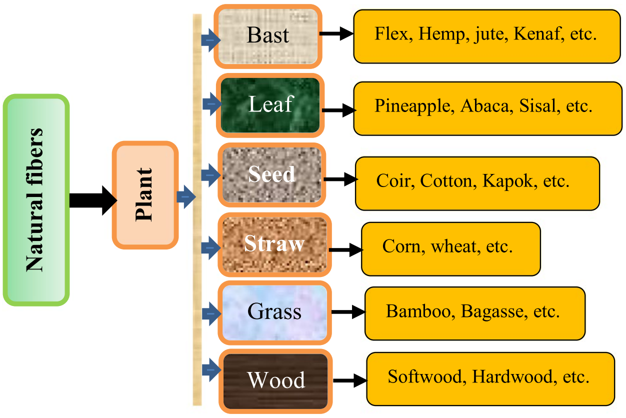


Fig. 1 Classification of plant fibers [9]

The goal of the green tribology revolution is to reduce human's reliance on artificial materials and fossil fuels while managing reliable environmental integrity by avoiding material waste from wear and friction [15]. Presently, plant fiber–based composites are also applied to develop sliding and rolling parts including bearings, rollers, gears, and seals. These mechanical parts experience heavy tribological loadings, which cause wear and friction. Wear and friction can be controlled significantly by using appropriate polymeric matrix and fibers. In addition to these, wear and friction can also be influenced by composite fabrication techniques, test parameters, fiber length, surface modifications, fiber's length/type, etc. Erosion of material due to wear influences the strength and material's reliability can lead to failure and is expensive as well. It is noteworthy to analyze any fiber-based composite suitability for a certain application before choosing it, and this is done by examining its mechanical characteristics, including tensile, flexural, and impact strengths. The mechanical characteristics of composites rely on the fiber/matrix materials, interfacial strength, fiber dispersion, fiber orientation, fiber orientation, etc. [16]. In comparison to conventional composite materials, most plant fiber–based composites show lower mechanical attributes. Solutions including natural fiber's hybridization and fiber/resin optimization have been used to solve this deficiency. In order to create a composite panel, two or more different fibers are mixed in a single matrix in a hybrid composite. Combining different lengths and diameters of distinct short fibers also results in hybridization; this method has significantly enhanced the mechanical characteristics of HPFBC composites [17]. Therefore, studying the tribo-mechanical characteristics of plant fiber–based composites is crucial to enhancing component performance and service life. Also, HPFBCs have great application prospects where a substantial number of debris is developed due to wear [18]. The novelty of this review is that until now, no review paper has been published that comprehensively describes the tribo-mechanical properties of HPFBCs along with their applications in very simple and effective means. Furthermore, this review relies on the concise discussion of the hybridization of various natural fiber–based polymeric composites, factors that influence the tribo-mechanical properties, etc. This study may also contribute to promoting the use of low-cost and locally available biomaterials for the development of sustainable composite materials.

2 Key properties of plant fibers

Understanding the roles of these chemical constituents in plant fibers is crucial for tailoring their properties and applications. The chemical composition of plant fibers can vary depending on the plant species, the part of the plant from which the fibers are derived, and the processing methods used. However, plant fibers are primarily composed of cellulose, hemicellulose, lignin, and other minor components. Cellulose, with its excellent bonding capabilities, contributes to the mechanical strength of composites. Hemicellulose content can affect factors like moisture absorption and biodegradability, making it important to consider in applications where these properties are critical. Lignin, known for its thermal stability, helps protect plant fibers from UV-induced degradation, extending their lifespan in outdoor or high-temperature environments. Along with cellulose content, the microfibrillar angle also contributes to the influence of the mechanical properties which shows the orientation of cellulose fibrils in the major wall with the stress axis. Plant fibers with lower microfibrillar angles tend to have higher tensile properties [19]. Small-diameter plant fibers offer advantages in composite materials by providing a higher surface area-to-weight ratio, better dispersion, improved wetting, and a strong interface with the matrix material [20]. These factors collectively contribute to the composite's superior load transfer mechanism and overall strength performance. Additionally, treatments and compatibilizers can further enhance the properties of smaller-diameter fibers, making them a valuable choice for reinforcement in composites [21]. Physical and chemical compositions and mechanical properties of popular plant fibers used for manufacturing HPFBCs are listed in Table 1.

The primary factors influencing the mechanical properties of plant fibers are particularly the non-cellulosic elements like hemicellulose, lignin, pectin, etc. Eliminating these non-cellulosic elements significantly improves the mechanical properties of plant fiber–based composite material, as their presence on the fibers obstructs the bonding capacity between the fibers and the matrix. Consequently, it is imperative to subject raw fibers to treatment to remove these impurities to the greatest extent possible. Various methods are employed for treating natural fibers, including physical techniques, chemical reagents, and biological and organic approaches. Chemical treatments alter the surface properties of the fibers, enhancing both the fiber's bonding capability and its compatibility with the matrix. Chemical treatments effectively eliminate impurities, resulting in improved interaction between the fiber and the matrix [24]. These processes enhance the wear resistance and durability of the composites. To achieve efficient interfacial bonding, it is necessary to modify the fiber surface using a combination of chemical treatments, reactive additives, and coupling agents. This approach facilitates effective coupling with the matrix, ultimately enhancing the overall performance of the material. In a recent study, Samanth et al. [25] delved into the exploration of chemical treatments applied to natural fibers, both through traditional and innovative approaches. Their research revealed that effective chemical treatments of fibers lead to enhanced tensile properties, improved impact strength for machining, greater thermal stability, superior

Table 1 Physical, mechanical, and chemical compositions of commonly used plant fibers [20, 22, 23]

Name of plant fiber	Chemical composition				Physical and mechanical properties				
	Hemi cellulose (%)	Cellulose (%)	Pectin (%)	Lignin (%)	Diameter (μm)	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Abaca	15–17	56–63	0.5–1.8	7–9	10–30	1.5	430–813	31.1–33.6	2.9–10
Bamboo	30	36–43	–	5–31	88–125	0.91–1.26	503	35.91	1.4
Bagasse	16.8–31.8	41.1–55.2	–	22.3–25.3	0.01–0.04	1.2–1.5	20–290	17–27.1	1.1
Banana	10–24	60–65	3–5	5	0.012–0.03	1.35	539–914	27–32	2.6–5.9
Coir	41–45	36–43	3–4	40–45	150–250	1.15–1.25	131–220	4–6	15–40
Flax	18–21	64–72	1.8–2.3	2–2.2	25	1.4	800–1500	60–80	1.2–1.6
Hemp	15–22.4	68–75	0.8	3.7–5.7	25–600	1.4–1.6	310–900	30–80	1.6–6
Jute	14–20	61–71	0.2	12–13	25–250	1.48	393–800	0.13–26.5	1.16–1.80
Kenaf	8–13	45–57	0.6	22	0.011	1.25–1.40	284–930	21–60	1.6
Ramie	5–15	69–91	1.9	0.4	20–280	1.3–1.5	400–938	61.4–128	3.6–3.8
Sisal	10	78	–	8	50–200	1.3–1.4	390–450	12–41	2.3–2.5

flexural properties, increased resistance to wear, and reduced water absorption characteristics. Lately, Verma et al. [26] conducted a study to explore the thermal and mechanical characteristics of hybrid composites made from coconut husk-bagasse fibers treated with alkali and combined with calcium carbonate. Their findings indicated a substantial enhancement in the properties of these treated composites, with a 65% increase in tensile strength, a 70% boost in flexural strength, and a maximum thermal degradation temperature of 375 °C. The primary factor contributing to these improvements was the establishment of strong interfacial adhesion between the fibers and the matrix material. Bekele et al. [27] conducted an experiment where they treated a hybrid composite of enset and sisal with both 5% and 10% NaOH (alkali) solutions, focusing on the analysis of mechanical properties. Interestingly, their results revealed that the samples treated with the 5% NaOH solution displayed superior mechanical properties compared to those treated with the stronger 10% NaOH solution. Prabhu et al. [28] conducted a series of treatments on sugarcane bagasse fibers, beginning with alkali pretreatment and followed by treatments with $KMnO_4$ and $K_2Cr_2O_7$. The results of their experiments demonstrated the effectiveness of the chemical treatments in reducing the crystallinity index of the fibers, ultimately leading to enhanced thermal stability.

3 Hybridization of composite materials

The hybridization phenomenon spans a wide range of scientific disciplines, including electrochemistry, metallurgy, engineering mechanics, applied sciences polymeric sciences, and energy sources. Whatever the study topic, the major goal is to combine three or more components to produce a product with superior performance or features compared to the individual materials for the intended use. The term “hybridization of composite materials” can also refer to a combination of two or more fibers into a polymeric material to minimize the deficiencies in terms of mechanical and other properties of other fiber materials. Hybridization of composite materials has a wide scope and applications in advanced technologies. Last few decades, there has been a rise in interest in implementing two or more fibers into a single matrix. The hybrid effect can either be negative or positive when the hybridized composite is compared to the traditional composite, which is a single fiber-reinforced composite. The number of articles on hybrid composites that have been published has steadily increased in the last 10 years. The latest research trends regarding hybrid polymer composites are illustrated in Fig. 2. Figure 2a presents a depiction of publications spanning from 2013 to 2023 in this field, while Fig. 2b highlights the leading countries actively engaged in research on hybrid polymer composites. The data presented in Fig. 2 was retrieved from the Web of Science website by conducting a search using the keywords “hybrid polymer composites.” Three crucial elements significantly influence the characteristics of created HPFBCs [29]. The first factor is the fiber and matrix materials, which are selected according to the application. The development process for hybrid composites, which is chosen based on fiber/matrix materials, is the second component. Compatibility of the fiber with the matrix is the final consideration. Utilizing plant fibers that have been treated to increase the interfacial adhesion with polymeric material improves the hybrid product’s overall qualities. Other elements, such as the fiber’s aspect ratio, individual fiber qualities, and fiber’s

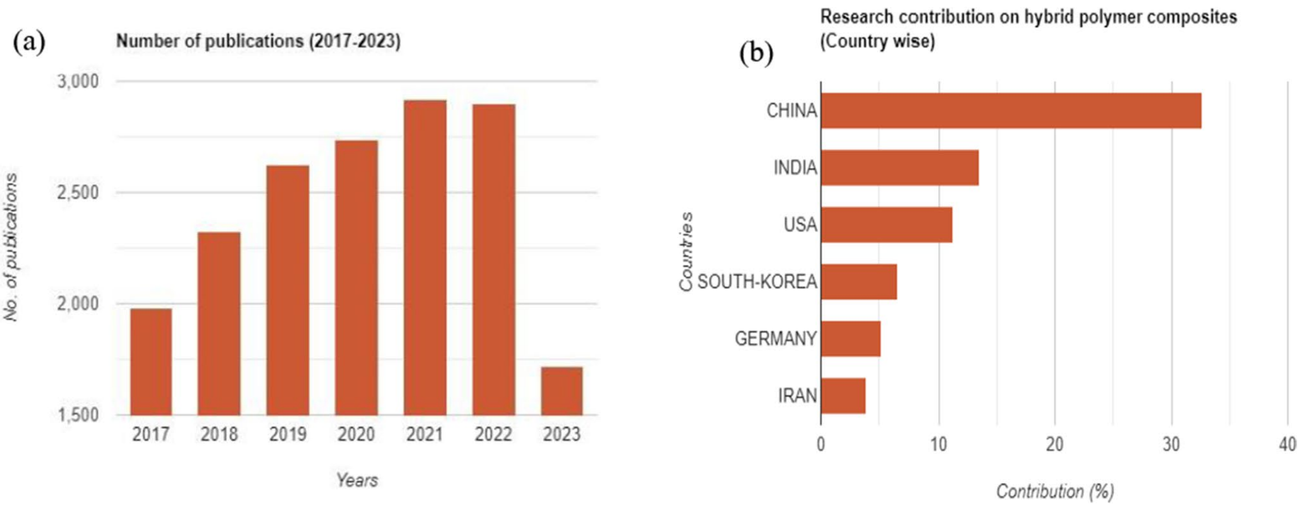


Fig. 2 Current research progress on hybrid polymer composites. **a** No. of publications per year. **b** County-wise contribution on hybrid polymer composites (top contributors)

orientation/length, and the stacking order of both fibers also influence the physico-mechanical and tribological characteristics of HPFBCs [30]. HPFBCs can be categorized as environmentally friendly and partially biodegradable, as shown in Fig. 3.

Hybrid biocomposites are fabricated with a variety of reinforcing elements, including synthetic and plant-based fibers, and a thermoset or thermoplastic kind of matrix [31]. To achieve balance in performance and cost so that the manufactured hybrid composite may be used in various applications, for instance, high load-carrying capacity structural applications, various fibers are mixed with a resin [32]. For instance, combining synthetic and plant fibers improves both the mechanical and water absorption qualities of the material [33, 34]. In a related investigation, researchers found that combining plant fiber with synthetic fiber decreased the production cost of the composite without compromising its mechanical qualities [35, 36].

3.1 Sustainability aspects of HPFBCs

HPFBCs offer a promising avenue for sustainable material development by combining natural fibers derived from plants with other materials. These biocomposites boast several sustainability aspects that make them ecofriendly alternatives to conventional composites. Firstly, they depend on renewable resources, as the primary element comprises plant fibers, which can be annually replenished without causing environmental depletion. Furthermore, their development generally results in a reduced carbon footprint compared to conventional composites, as fabrication processes for synthetic fibers and resins can be energy-intensive and emit greenhouse gases, while plant fibers demand less energy and can sequester carbon during growth. Additionally, many HPFBCs are biodegradable or compostable, minimizing the burden on landfills and reducing long-term environmental impact. Their lower toxicity levels, along with reduced energy consumption during manufacturing, contribute to a more sustainable composite option. These materials can also utilize agricultural or industrial by-products that might otherwise go to waste, promoting resource efficiency and reducing environmental impact. Moreover, the diverse properties of HPFBCs, which often match or surpass those of traditional composites, enable lightweight and fuel-efficient products across various industries, further enhancing sustainability. However, it is essential to consider factors like sustainable sourcing practices and life cycle analysis to ensure the holistic sustainability of these materials in specific industrial applications. The key attributes which make the plant fibers sustainable and vital for their use in green hybrid composites are presented in Fig. 4.

4 Review of studies on tribological performances of HPFBCs

Engineering applications for green composites are being accelerated by researchers in new fields. One such new field is tribology. On the tribo-performances of green composites, there is a broad range of information accessible. Green composites' tribological behavior has been studied by researchers. Occurrence of friction is common in both day-to-day life and industry, and it can be maintained by the mechanisms that take place on the sliding bodies' surface layers. Adhesion and deformation are considered as two primary constituents of friction and are considered for friction studies [37]. These constituents are also applicable to the studies of polymer-based composites. Wear is a natural result of friction in a sliding contact surface. Wear of polymer materials sliding against a hard surface may be termed as interfacial, cohesive, abrasive, adhesive, chemical wear, etc. Major tribological interactions and the

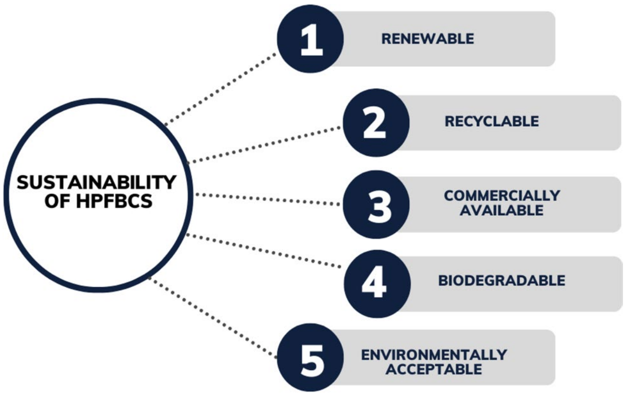
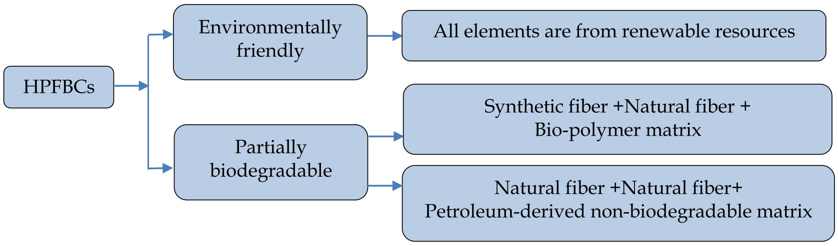


Fig. 4 Key attributes affecting the sustainability of HPFBCs

Fig. 3 Classification of HPFBCs



wear process are presented in Fig. 5 [38]. Understanding the wear process of fiber-based composites is very complicated. Understanding this process is made more challenging by the variety of fibers, both in terms of their attributes and volumetric concentration. It has been observed that adhesion is the primary wear process during the rubbing of fiber composites, but different types of filler and frictional circumstances also develop other wear mechanisms [39]. Type of filler, its size, form, concentration in the composite, and surface share of the filler particles, as well as the structure of the inter-phase border between the filler and the matrix, are the most commanding set of key criteria that affect the wear of fiber-based composites. Different wear mechanisms, operational temperature rise, frictional analysis, and other factors are included in the tribo-performances of polymeric composites. The type of applied loading; the strength of the fiber and matrix; the resistance to crack propagation; the bond strength between the fiber and matrix, as well as the fiber volume/weight fraction; its geometrical appearances (mat form, loose fiber, etc.); and dry/wet operating conditions can all affect the tribo-performances of prepared composite materials. Under difficult operating circumstances, produced composites may suffer from a few problems, including fiber debonding, fiber pull-out, fiber bridging, delamination, and matrix cracking. Fish bone schematic of tribo-performance of polymer-based composites is depicted in Fig. 6 [40].

Tribological tests are significant when it comes to evaluating the anti-wear and anti-frictional characteristics of newly developed hybrid biocomposites. These tests are typically conducted at the laboratory level, serving as a crucial step in assessing the material's performance. Before initiating tribological tests, several parameters are carefully defined, including the geometry and material of the tribo-pairs, applied load, sliding speed, and contact pressure. Among the various contact configurations available, some of the most employed ones include pin-on-flat, flat-on-flat, rotating pin-on-disc, pin-on-rotating disc, cylinder-on-cylinder, and pin-on-rotating cylinder setups. These configurations enable researchers to simulate different real-world scenarios and gain insights into how the hybrid biocomposites perform in terms of wear resistance and friction reduction. The attention of researchers in the area of tribology has changed over the last few years from synthetic to natural fibers. Over the past several years, there has been a boost in research focused on the tribological performance of composites reinforced with natural fibers. Natural fiber combined with natural fiber, natural fiber combined with synthetic fibers, natural fiber combined with carbonaceous materials, and natural fiber combined with metal can be the forms of hybrid

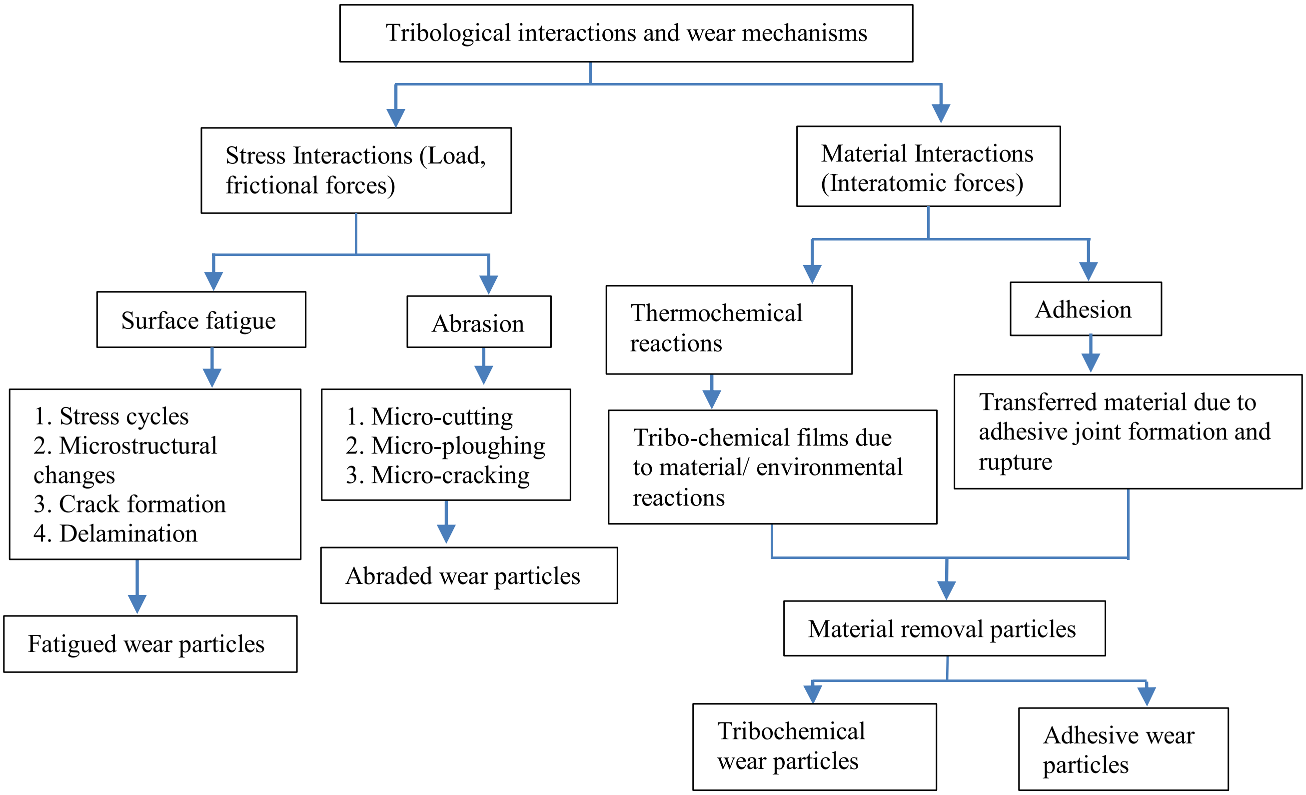


Fig. 5 Tribological interactions and wear mechanisms [38]

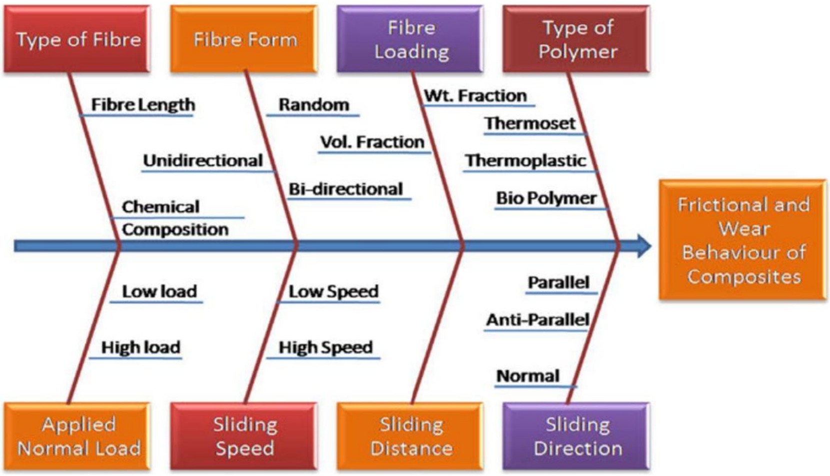


Fig. 6 Fish bone schematic of tribological performance of polymer composites [40]

natural fiber–reinforced polymer composites [41]. Recent research progresses related to the tribological performance of HPFBCs are addressed below.

Jha et al. [42] observed that it is feasible to successfully develop hybrid jute epoxy composites with silicon carbide (SiC) reinforcement made from rice husk using a plasma processing method. Prepared composites' anti-erosion property is improved by the addition of SiC fillers, and the extent of this increase relies on the filler's weight content. A study was conducted by Zhang et al. [43] on the tribological behavior of hybrid polytetrafluoroethylene (PTFE)/cotton fabric composites loaded with micro-size Sb_2O_3 and melamine cyanurate (MCA). It was discovered that the wear rate of the hybrid PTFE/cotton fabric composites rose with MCA filler but decreased with Sb_2O_3 filler. The wear resistance and friction reduction of the hybrid PTFE/cotton fabric composite under a range of loads and temperatures were also shown to be greatly enhanced by the addition of 10 wt.% micro-Sb_2O_3. Kumar et al. [44] developed sisal-glass epoxy-based hybrid composites with different fiber lengths. Hybrid composites were also subjected to chemical treatment to enhance their mechanical and tribological characteristics. It was shown that compared to untreated composites, chemically treated hybrid composites had greater levels of tribo-mechanical characteristics. Coefficient of frictional (CoF) decreased with increasing sliding speed, while the load force remained constant. They also found that treated hybrid composites had considerable optimum improvements at 2 cm fiber length (see. Figure 7 [44]).

Mantry et al. [45] successfully developed jute-epoxy composite laminates by adding SiC as filler. It was observed that SiC significantly decreases the erosion wear and the filler content plays an important role in affecting the tribo-performance of hybrid composites. The impact of stacking order on the erosive wear behavior of untreated woven jute and glass cloth–reinforced epoxy hybrid composites was

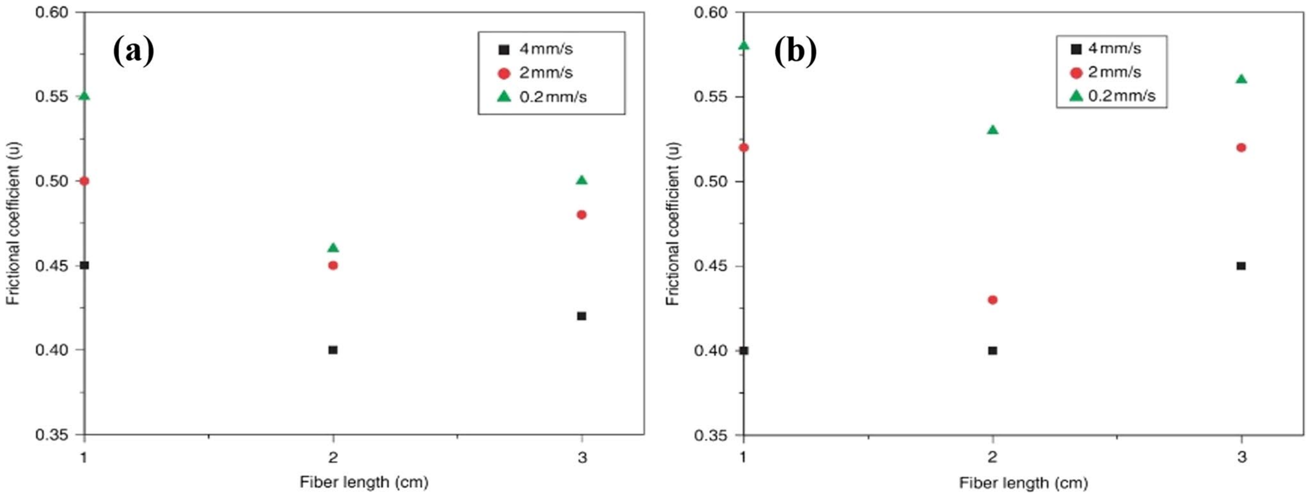


Fig. 7 Variation of CoF with fiber length: **a** treated hybrid composites, **b** non-treated hybrid composites [44]

investigated by Patel et al. [46]. The sample having two glass layers sandwiched between jute layers has the lowest value of erosive wear. Furthermore, this investigation showed that jute fiber may have its erosive strength boosted by combining it with synthetic fiber. In order to increase interfacial adhesion in hybrid composites made of sisal fiber and aramid fiber, Zhong et al. [47] chose surface micro-fibrillation of natural fiber as a simple technique. Results revealed that Greater contact between sisal fiber and resin achieved due to the micro-fibrillation process results in better mechanical interlocking strength. According to wear tests, the hybrid composite made with aramid and sisal fibers had superior wear resistance (4.9% thickness loss) than the hybrid composite made with unmicro-fibrillated (7.1% thickness loss). Shalwan and Yousif [48] investigated the tribo-performance of epoxy composites made with date palm fiber or graphite filler. It is discovered that the epoxy composites' wear/frictional performance improved by the addition of date palm fiber.

Additionally, mixing 3 wt.% of graphite to date fiber/epoxy composites helps the epoxy composites perform better. Latha et al. [49] looked at how the stacking order affected the tribological performance of woven bamboo/glass fiber–reinforced hybrid polymer composites. Outcomes revealed that the characteristics of the resultant hybrid composites are enhanced by adding glass to bamboo fiber composites. Furthermore, GGGG laminate composite has the most wear when compared to other composites, whereas the GBGB laminate hybrid composite has the least erosion wear. Experimental research by Dalbehera and Acharya examined the solid particle erosion properties of glass-jute (with sequence GJJG) hybrid epoxy composites filled with cenosphere [50]. The findings demonstrated that cenosphere-containing GJJG composites have greater wear resistance than hybrid composites. Additionally, compared to 10% and 15% by weight of cenosphere-filled produced composites, 20% by weight of cenosphere-filled sample provides enhanced erosion resistance. Jena et al. [51] investigated the wear behavior of bamboo fiber composite containing cenosphere filler to better understand solid particle erosion (SPE). Outcomes presented that, in comparison to composites without filler, the cenosphere filler improves the erosion wear resistance of the bamboo-epoxy composite. The composite sample with the best erosion resistance is made up of 33 wt.% fiber and 6 wt.% filler. It is also proved by the scanning electron microscope (SEM) micrographs (see Fig. 8 [51]).

Shuhimi et al. [52] studied and contrasted the tribological characteristics of composites formed of kenaf and oil palm fibers with epoxy (OPF/E) and oil palm fiber with epoxy (OPF/E) by altering the temperature and composition of the fibers. Authors observed that raising the temperature caused both composites' wear rates and CoF to rise. Additionally, it was discovered that the OPF/E composite suffered severely from increased fiber composition. However, the KF/E composite's wear performance improved when fiber content was increased. Kumar et al. [53] studied the tribological performance of *Bauhinia vahlii*/sisal fiber–reinforced hybrid composites using rice husk as filler. The Taguchi technique was successfully used to assess the sliding properties and their optimal regulating elements. At all filler loadings, it was felt that hybrid composites outperformed other samples in terms of wear resistance under comparable test circumstances. The erosion behavior of coir fiber–reinforced epoxy

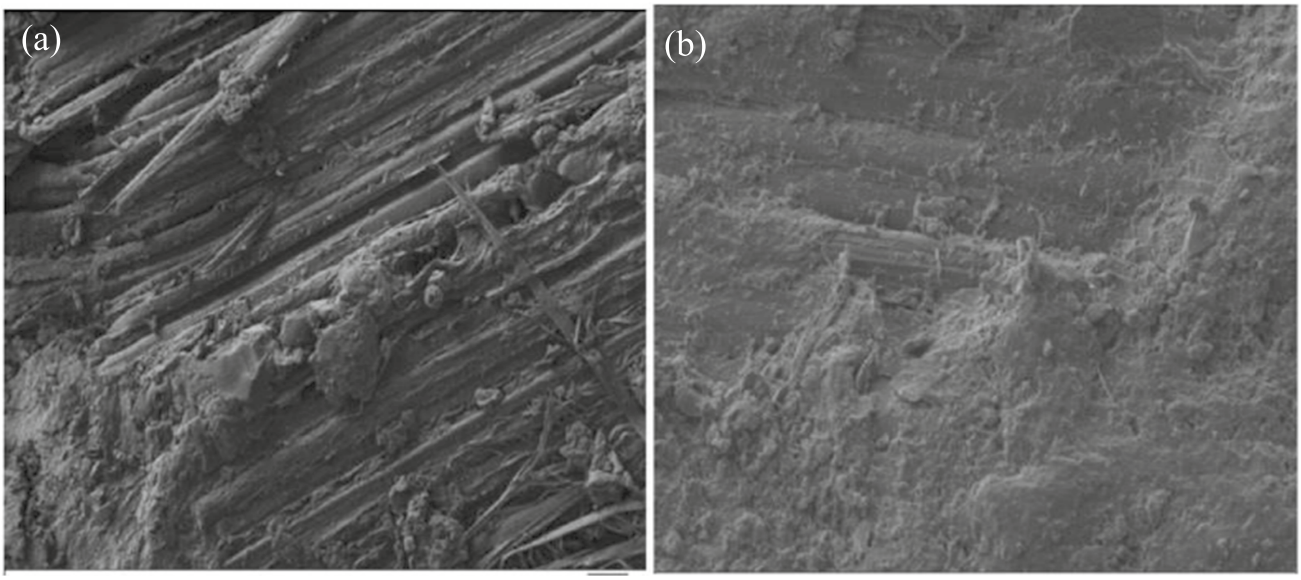


Fig. 8 SEM images of bamboo fiber–reinforced composites: **a** without filler, **b** with filler [51]

composites with/without Al_2O_3 filler was studied by Das and Biswas [54]. It has been found that regardless of other characteristics, an increase in impact velocity causes composite materials to wear out more quickly. Impact speeds of 48 m/s and 109 m/s, respectively, yield the lowest and highest wear rates, and composites with fiber lengths of 12 mm have superior wear resistance. Additionally, it has been shown that coir fiber–reinforced epoxy composites with Al_2O_3 filler exhibit superior wear resistance characteristics as compared to samples without filler. Aslan et al. [55] investigated how waste sisal/glass- and sisal/carbon hybrid fiber–reinforced polypropylene composites wear under abrasive conditions. Sisal fibers used to waste glass composites result in reduced densities, equivalent mechanical and abrasion volumes, and improved durability. Sisal/glass hybrid panels outperform single glass fibers in terms of frictional characteristics and mechanical performance when compared to both hybrid combinations. The tribo-performance of bamboo-glass hybrid polymer composites with TiO_2 and ZrO_2 ceramic filles was investigated by Latha and Rao [56]. In the hybrid composites, weight percentage of filler ranged from 3–9%. In comparison to other hybrid composites and neat polymer composites, the hybrid composite with 6 wt.% ZrO2 filler exhibits the least wear behavior. Chaudhary et al. [57] examined the tribological performance of three distinct kinds of natural fibers (jute, hemp, and flax) reinforced with epoxy matrix and their hybrid composites (jute/hemp/epoxy, hemp/flax/epoxy, and jute/hemp/flax/epoxy). The wear behavior of the composites was greatly enhanced by the introduction of natural fibers into the epoxy polymer matrix in contrast to plain epoxy polymer, according to experimental results of wear analysis. The jute/epoxy composite outperformed all other produced composites in terms of CoF, frictional force, and specific wear rate. Suresh et al. [58] examined the wear rate and friction coefficient of the hybrid banana/hemp composites' tribological properties. The fibers were chemically treated with NaOH. Sliding distances and speeds were assessed for every applied load. In all sliding situations, the 20% hybrid composite showed negligible wear loss and low CoF. From SEM micrographs, it is revealed that 20% (banana-hemp) hybrid composite sample shows a pore-free compact surface. Suresh et al. [59] examined the wear performance of a hybrid composite polymer. Hybrid composite was developed using vinyl ester as the matrix and bagasse, rice husk, and coconut shell as reinforcements. Reinforcements were added in increments of 5 to 25 wt.%. Results showed that, under all applied loads and sliding distance/speeds, the produced hybrid composite (20% bagasse + 20% rice husk + 20% coconut shell) demonstrated negligible wear loss and low CoF. The tribo-performance of a hybrid epoxy composite was examined by Acharya et al. [60] using three distinct stacking sequences of jute (J) and glass (G) fibers: S1 (GJJJJJJJJJJG), S2 (GJGJGGJGJG), and S3 (JGJGJGJJGJGJ). It is observed that the S2 hybrid composite has higher wear resistance than the S3 and S1. The order of the wear resistance is S1 > S3 > S2 (see Fig. 9 [60]).

James et al. [61] studied the tribo-performance of a hybrid epoxy composite using bamboo (B) and jute (J) fibers as reinforcements. Wear tests were performed on hybrid composites of different stacking sequences of bamboo and jute fibers under different applied loads and sliding distances. It was observed that maximum weight loss was found with the JBJ stacking sequence and minimum weight loss with the JJJ stacking sequence. Ibrahem [62] evaluated the tribo-performance of basalt fiber–reinforced epoxy composites packed with sunflower husk and peanut shell

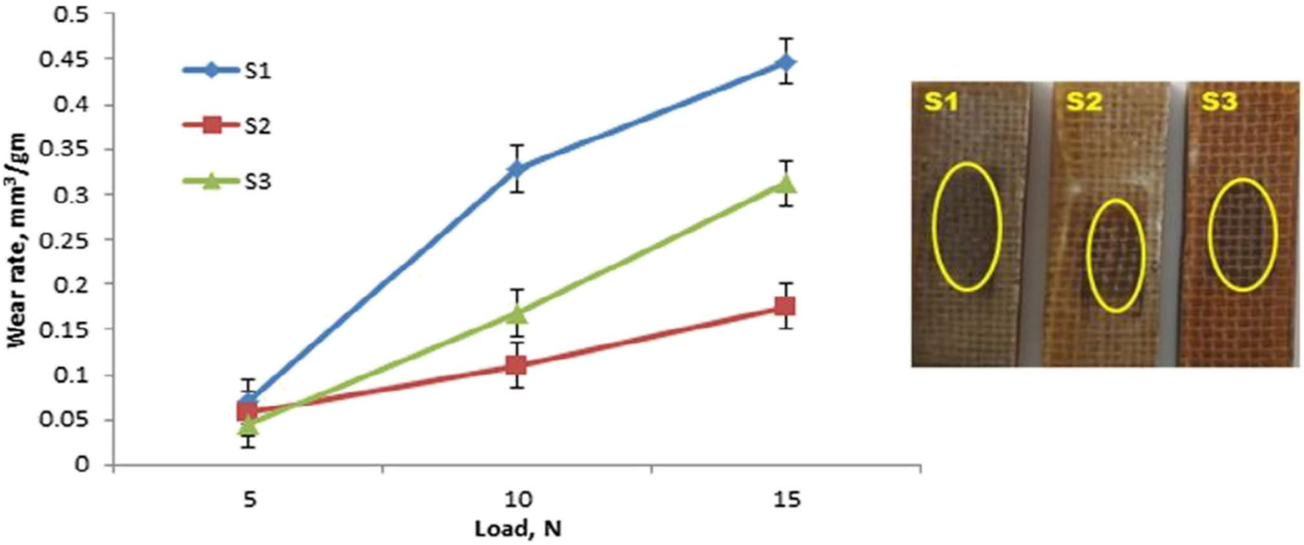


Fig. 9 Effect of load on wear rate of hybrid composites [60]

powder in addition to sesame and castor oils. Each sample's basalt chopped fiber content was maintained at 30% vol. Results indicated that adding natural fillers and vegetable oils significantly increased the CoF of the basalt-reinforced epoxy hybrid composite. Epoxy hybrid composites containing 10% peanut shell husk fillers and 10% vegetable oil are advised for tribological applications requiring low CoF and strong wear resistance. Recently, Ravikumar et al. [63] studied the tribo-performance of bidirectional jute/carbon fiber–reinforced polyester composites using the response surface technique. Variations in fiber weight percentage, stress, and sliding velocity were used to assess tribo-performance. According to the results, high sliding velocity and load cause the hybrid composites to wear out quickly, while increasing the fiber proportion causes reduced wear loss. The sample with 30% fibers had the least wear loss across all tribo-operating conditions as compared to all other samples. Thiagarajan et al. [64] examined the wear properties of composites consisting of multi-walled carbon nanotubes (MWCNTs) and banana-glass fibers in dry sliding circumstances. According to the results, MWCNTs effectively reduced wear loss caused by adhesion, which was a benefit of thin transfer film production. This effectively decreased the COF and improved wear resistance. Palanisamy et al. [65] studied the tribo-performance of hybrid kenaf/banana epoxy composites under various loads (up to 30 N) and sliding distances using varied fiber weight percentages ranging from 20 to 40 wt.% (up to 75 m). According to the authors, kenaf/banana hybrid composites with up to 40 wt.% of fires were effective for wear applications like disc brakes. Murali et al. [66] investigated the dry sliding wear properties of hybrid polymer matrix composites using different stacking sequences of Kevlar (K), bamboo (B), palm (P), and *Aloe vera* (A-V) along with epoxy as the matrix material. The authors noted that stacking in the order KPKA-VK demonstrated excellent tribological performance with a load of 5 N, a sliding speed of 3 m/s, and a sliding distance of 1500 m. Ramakrishnan et al. [67] studied the tribo-performance of sisal/pineapple hybrid polymer composites with the addition of banana fly ash (BA). Proportion of hybrid sisal/pineapple fibers and BA in the polymer composites varied from 30–50 wt.% and 1–4 wt.%, respectively. It has been shown that a little amount of BA filler of 1 wt.% and sisal/pineapple fiber of 30 wt.% shows overall good tribo-performance at a sliding distance of 1500 m and applied load of 5 N. Dhanasekar et al. [68] investigated the tribological performance of hybrid biocomposites consisting the fixed sisal/hemp fiber contents (10 wt.%) and varying silica nanoparticle concentration (0–9 wt.%). Samples were treated with a 5% NaOH solution to improve adhesive behavior. Silica nanoparticles in the hybrid biocomposites reduced the volumetric wear rate, and samples containing 6 wt.% silica nanoparticles were observed as good wear behavior at high load and sliding speed compared to other samples. Venkatesh et al. [69] developed treated Kenaf/sisal fiber–based hybrid composite samples and examined their tribo-mechanical properties. Wear behavior of samples was performed on a pin-on-disc wear testing machine with a hardened grey cast-iron plate under different applied loads ranging from 10–40 N and different sliding velocities (0.1–0.7 m/s). Results showed that the wear rate of 0.041 m/min was found at 40 N average loads at 0.75 m/s sliding speed. Ramakrishnan et al. [70] fabricated pineapple leaf (PALF)/roselle fiber (RSF)-based vinyl ester hybrid biocomposites using a hot compression molding technique and examined various properties including tribological. Results showed that a sample containing 24 wt.% PALF/16 wt.% RSF exhibited lowest specific wear rate (9.66 × 105 mm^3/nm) and coefficient of friction of 0.296. This was due to the presence of hybrid fibers and the good interfacial bonds present between the fibers and matrix interfaces. In a recent study conducted by Kumar et al. [71], hybrid composites composed of flax and ramie fibers were fabricated through manual compression molding. The researchers assessed the tribological characteristics of these composites using a pin-on-disc testing machine. Their findings indicated that the composite containing a 30% fiber loading exhibited enhanced crystallinity, stability, and superior tribological performance, with notably reduced void formation compared to the other composites that were developed. In their study, Badyankal et al. [72] produced hybrid fiber composites using sisal, banana, and pineapple fibers, incorporating various fillers such as coconut shell, sawdust, kolam, and fly ash powder. The concentrations of both fibers and fillers were held constant at 15 vol.% and 10 vol.%, respectively. The outcomes of the research demonstrated that the composite samples containing coconut shell powder yielded the most favorable tribological outcomes, as they exhibited minimal material loss. This phenomenon can be attributed to the excellent hardness properties inherent to the coconut shell filler. Venkatesh et al. [73] developed hybridized epoxy composites using jute/coconut fiber and graphite particles as fillers via a conventional casting process assisted with the mechanical interlocking route. Hybrid composite sample containing 75 wt.% of jute fiber/20 wt.% coconut coir/5 wt.% graphite nanoparticles exhibited good anti-wear properties. The existence of a complex ceramic particle in polymer matrix composite and its hardness characteristic are the main reasons for decreased volumetric wear.

5 Review studies on mechanical characteristics of HPFBCs

In order to employ HPFBCs in certain applications, it is required to examine their mechanical properties. The mechanical properties of HPFBCs depend on variables, like the dispersion of reinforcements within the polymeric matrix, the resin's and fibers' compatibility for adhesion, and the fibers' surface area, aspect ratio, mechanical properties, content/orientation, and surface treatments. Numerous studies have demonstrated that HPFBCs may be made by mixing natural fiber with natural fiber or synthetic fiber with natural fiber in the appropriate resins (thermosets or thermoplastics). The use of different fibers for the case of HPFBCs is justified by the way one type's benefits may balance out its drawbacks, enhancing the material's overall performance and qualities. Additionally, there is a growing market for the development of hybrid composites since they fulfill the standards for a sort of applications, for instance, automotive, military, and construction. The rule of mixture may be used to hypothetically evaluate the mechanical properties of HPFBCs. Oigt, Reuss, Hirsch, and Tsai-Pagano have all proposed further theoretic models based on the rule of mixture [74]. This section discusses recent research on the mechanical characteristics of different hybrid natural/synthetic fiber composites, including tensile, flexural, impact, and hardness. The mechanical testing of composites is frequently carried out in line with ASTM standards, subject to the conditions of the composites in concern. In the tensile test, it is crucial to quantify a material's capacity to endure stresses and how far it can stretch before breaking. Tensile strength/tensile modulus both come under composite material tensile characteristics. The amount of stress a composite's specimen can resist before failing and how well the stress can be transmitted from the broken to the remaining fibers through shear in the resin at the interface determine the tensile strength [75]. Testing of flexural properties is performed to measure the material's capacity to resist deformation because of the applied load. The composite specimens for flexural testing are developed in accordance with ASTM D790 specifications. The composites' capacity to withstand brittle fracture and crack propagation can be shown by their impact characteristics [76]. Testing the impact performance of composites is therefore important. When analyzing the tribo-performance of polymer composites, hardness is an important consideration. It has a significant impact on the contact area's wear resistance. The materials' toughness makes them useful for packing, furniture, and lab apparatus. By applying an indentation force that is both normal to the fiber length and normal to the fiber diameter, the hardness characteristics of the composites are examined. In a work by Ranjan and co-authors [77], they merged treated banana and sisal fibers with polylactic acid (PLA) to produce a unique hybrid composite. They then assessed the tensile, flexural, and other mechanical characteristics of this hybrid composite. Before manufacturing the composite laminate using injection molding, the researchers treated the fibers for 2 h with a 2 wt.% NaOH solution. Compared to the untreated banana/sisal hybrid composites, the treated banana/sisal hybrid composites had a greater tensile property. The chemical treatment, which produced a rougher fiber surface and eliminated lignin and hemicellulose components to increase the number of interlocking regions, was blamed for this increase in strength. Because of this, the PLA biocomposites' strength and stiffness were improved, making them appropriate for usage in civil construction components. Yusoff et al. [78] studied the tensile and flexural properties of three PLA-based composites (kenaf-coir-polylactic acid (PLA)/bamboo-coir-PLA/kenaf-bamboo-coir-PLA). Each sample of PLA-based composites had similar weight percentages (60:40) fiber-to-matrix content and was fabricated using a hot-press molding technique. It was observed that the strain energy required to shatter the kenaf-bamboo-coir-PLA composite was high per unit volume. They also observed that a hybrid composite made of bamboo-kenaf had higher tensile and flexural strengths than a composite made of only a single fiber as they could conduct high strength and stiffness together with high ductility. Asim et al. [79] investigated the mechanical properties of hybrid pineapple leaf fiber (PALF)-kenaf-based phenolic composites. Samples were prepared under different PALF/kenaf fiber ratios: 30:70 wt.%, 50:50 wt.%, and 70:30 wt.%. Results showed that the 3P7K composite sample had greater tensile properties, flexural behaviors, and impact strength in comparison to other composite samples. The interfacial strength of the composite laminate was assisted and improved by the increase in the kenaf weight ratio in the composite. This showed that phenolic resin and kenaf fiber worked together very well. However, due to incompatibility with the polymer resin, more PALF by weight fraction showed a fiber pull-out. Ibrahim et al. [80] conducted research on starch-based composites using different fiber combinations of flax (25 wt.%) and date palm (25 wt.%). They examined the tensile properties, water absorption performance, and thermal properties of hybrid composites. Findings revealed that the optimal fiber content for the starch-based composites was achieved when the fiber-to-matrix ratio was 1:1. Afterwards, a significant improvement in mechanical performance, including tensile properties, was seen when both flax and date palm fibers were reinforced, with each fiber comprising 25 wt.%. The hybrid composite exhibited a tensile value of 43 MPa, which fell between the values of 42 MPa and 62 MPa of the date palm composite and flax composite, respectively.

Jawaid et al. [81] performed an investigation to examine the impact of incorporating woven jute fabrics into oil palm empty fruit bunches (EFBs) and how it affected the tensile and flexural properties of the hybrid composites. Various fiber layering patterns were utilized during the study to explore the potential outcomes. The findings revealed that the incorporation of extremely woven jute fiber mats as a hybridization agent could enhance the tensile and flexural properties of oil palm EFB composite. The study observed that the tensile and flexural properties of the hybrid composite were superior to those of the EFB composite, although they fell short of the performance of the woven jute composite. In a study conducted by Dhakal et al. [82], flax/epoxy hybrid composites reinforced with carbon fibers were analyzed experimentally. The findings indicated that the moisture absorption rate of hybrid composites was lower than that of uni-directional (UD) flax/epoxy composites and lower than that of cross-ply (CP) flax/epoxy composites. Moreover, an improvement in both flexural and tensile strength was observed compared to the UD and CP flax/epoxy composites. Based on the experimental findings, it can be inferred that the incorporation of cellulosic flax fiber reinforcement contributed to the enhancement of toughness properties by promoting crack propagation. In contrast, the integration of carbon fiber contributed to the improvement of thermal stability and water absorption behavior, as well as the overall strength and stiffness of the hybrid composites. Davoodi et al. [83] conducted a study to investigate the mechanical properties of hybrid glass/kenaf fiber–reinforced composites intended for automotive bumper beam applications and compared the results with a bumper beam material (i.e., glass mat thermoplastic (GMT)). The results revealed that the tensile and flexural properties of the hybrid composite material were superior to those of GMT. In a study conducted by Misri et al. [84], the mechanical properties of woven glass/sugar palm fiber–reinforced unsaturated polyester hybrid composites were investigated. Various types of fibers, such as strand mat, natural, and hand-woven sugar palm fibers, were used to create several layers of fibers. The researchers utilized compression molding techniques to hybridize the woven glass/sugar palm fiber–reinforced unsaturated polyester composites, thereby enhancing their mechanical properties. The results showed that the woven glass/sugar palm fiber–reinforced unsaturated polyester hybrid composites exhibited superior tensile and impact characteristics compared to the original woven sugar palm fibers. Jawaid et al. [85] investigated the mechanical properties like flexural and impact properties of hybrid oil palm EFB/jute fiber–reinforced epoxy composites which were developed by hand lay-up technique. They found that the mechanical properties of hybrid composite with a ratio of 1:4 were higher than those of pure EFB/epoxy composite samples. Furthermore, EFB composites had better impact strength than hybrid composites. Using fiber matting reinforcement, which was shown to increase the mechanical characteristics of hybrid composites, the mechanical strength of hybrid sisal/oil palm [86] and sisal/banana fiber–reinforced polyester composites [87] was tested. Mechanics of hybrid composites made of palmyra/glass fiber were investigated by Velmurugan and Manikandan [88] in 2007. For varied palmyra/glass fiber weight ratios, two distinct types of composite plates were fabricated: one by combining palmyra and glass fiber and the other by sandwiching palmyra fiber between glass fiber matting. Different palmyra/glass fiber weight ratios required different composite plates to be made. The matrix was made of rooflite resin. The outcomes demonstrated that the inclusion of glass fibers together with palmyra fibers in the matrix enhanced the mechanical performances of the composites and reduced their capacity to absorb moisture. Pandita et al. [89] studied the comparative mechanical performance of jute epoxy–based polymer composites and jute/glass epoxy–based polymer hybrid composites. The resin infusion under flexible tooling method was adopted to develop the composite samples. The outcomes showed that increasing the thin layers of glass woven on jute-reinforced composites enhances the tensile, bending, and impact performances. Madival et al. [90] fabricated rice straw particle (RSp)/*Furcraea foetida* (FF) fiber–based hybrid composite samples and examined their physico-mechanical attributes. Results demonstrated that adding 15 wt.% of RSp decreased the density of the sample by 41.87%. The sample with 5 wt.% and 15 wt.% of RSp showed maximum tensile strength of 29.45 MPa and modulus of 3.67 GPa. At 15 wt.% of RSp, the maximum flexural strength of 43.12 MPa and modulus of 2.09 GPa were achieved and at 10 wt.% of RSp showed the highest impact strength of 101.01 J/m. Table 2 summarizes the reported various mechanical properties of HPFBCs.

6 Industrial applications of HPFBCs

Hybrid composite materials are gaining significant interest as potential replacements for conventional composites, owing to their superior performance capabilities in comparison to their traditional counterparts. HPFBCs are making an increasingly substantial contribution to advanced material technology, rendering them indispensable. With the rise of serious environmental issues, many cutting-edge applications in materials technology rely on HPFBCs. These include internal vehicles and building structural components, highlighting the pivotal role of HPFBCs in addressing environmental concerns. Over time, there has been rising attraction in the plant's potential for use in various construction materials, including fire and insect-resistant particle boards of varying densities and thicknesses, as well as in textiles, adsorbents, animal feed, and fibers for new and recycled plastics. This growing interest is attributed to the plant's proven viability for these purposes.

The versatility of HPFBCs, derived from jute, hemp, kenaf, oil palm, and bamboo, has made them a popular choice for a range of automotive and aerospace applications, including bumpers, petrol tanks, and interior-exterior panels. HPFBCs are also utilized in structural and packing materials and have been integral to the development and construction of buildings, serving as foundational boards.

Table 2 A summary of various mechanical characteristics of HPFBCs

Combination of fibers	Matrix	Fabrication method	Chemical modification	Tensile strength (MPa)/Young's modulus (GPa)	Flexural strength (MPa)/flexural modulus (GPa)	Compressive strength (MPa)/compressive modulus (GPa)	Impact strength (kJ/m^2 or J/m)	Hardness	Ref
Sisal/hemp, and silica nanoparticles	Epoxy	Hand lay-up	5% of NaOH	52.16	56.98	–	2.1 J	–	68
Treated Kenaf/sisal	Epoxy	Hand lay-up	Silane chemical treatment	57.9	78.65	–	9.1 kJ/m^2	–	69
Pineapple leaf/roselle	Vinyl ester	Hot compression molding method	6% of NaOH	31.05/0.323	36.36/0.345	89.32/569	45.18 kJ/m^2	37.75 HV	70
Flax/ramie	Epoxy	Hand compression molding	–	102.24/5.63	138.31/12.53	130/8.87	–	–	71
Sisal, Banana, Pineapple	Epoxy	Compression molding method	–	57/0.59	77/4.5	–	91 J/m	119 HRC	72
Jute/coconut coir, graphite particles	Epoxy	Mechanical interlocking	2% of NaOH	51.69	55.94	–	–	27.41 Hv	73
Bleached kraft pulp/hemp/flax/wood flour	Polypropylene	Injection molding	–	70/4.6	–	–	28	–	91
Curaua/glass	Orthophthalic polyester resin	Hand lay-up	–	92.2/2.34	144.5/7.58	–	–	–	92
Microfibrillated cellulose/bamboo	Poly (lactic acid)	Micro-scale injection molder	–	54/7	–	–	–	–	93
Banana/sisal	Polyester resin	Hand lay-up	–	58/1.4	63/3	–	37	–	94
Jute/glass	Unsaturated polyester resin (70%)	Thermoset pultrusion machine	–	–	> 1200/5	280/9.8	–	–	95
Kenaf/pineapple	High-density polyethylene (60%)	Compression molding operation	–	30/0.7	29/2.1	–	7.8	–	96
Sisal/cork powder	High-density polyethylene	Counter-rotating twin-screw extrusion machine	5% of NaOH for 2 h	21/6.6	33/1.1	–	–	–	97
Kenaf/glass	Unsaturated polyester resin (70%)	Compression molding method	6% of NaOH	38/2.2	35	–	141	–	98
Glass/sisal/jute	Epoxy resin	Hand lay-up	–	70	1.03 kN	–	–	–	99
Flax/carbon	Epoxy resin	Compression molding method	–	285/12	319/29	–	–	–	82
Jute/glass	Unsaturated polyester resin (70%)	Pultrusion	–	266/27	343/24.6	–	–	–	100
Banana/sisal/E-glass	Epoxy resin	Compression molding method	–	104/2.35	192	–	13.3	–	101
Jute/glass	Epoxy resin	Hand lay-up	–	56.68	28.81/1.8	–	5.49	–	102

Table 2 (continued)

Combination of fibers	Matrix	Fabrication method	Chemical modification	Tensile strength (MPa)/Young's modulus (GPa)	Flexural strength (MPa)/flexural modulus (GPa)	Compressive strength (MPa)/compressive modulus (GPa)	Impact strength (kJ/m^2 or J/m)	Hardness	Ref
Hemp/basalt fabric	Unsaturated polyester resin	Hand lay-up and compression molding method	–	–	169.04/9.52	–	9 J	–	103
Banana/kenaf	Unsaturated polyester resin	Hand lay-up	10% of NaOH for 8 h	104	143	–	28	–	104
Flax/hemp/glass	Epoxy resin	Vacuum infusion process	–	–	218/8	–	12 J	–	105
Bamboo/jute/glass	Epoxy resin	Hand lay-up	–	191/15.57	172/4.8	98.4/5.75	–	–	106
Sisal/glass fiber	Epoxy resin	Hand lay-up	–	171	269	–	18 J	–	107
Kenaf/bamboo/coir	Poly (lactic acid)	Hot-pressing method	–	187/7.2	199/9	–	–	–	78
Jute/glass/carbon	Polyester resin	Vacuum infusion technique	–	329	–	–	205	–	108
Waste paper/jute	Polyester resin	Hand lay-up	–	78/3.1	90/5	–	–		109
Banana/carbon	Epoxy resin	Hand lay-up	–	277	3 kN	–	4.58 J	–	110
Sugar palm/glass	Thermoplastic polyurethanes (60%)	Melt compounding technique	–	21/7	24/4.2	–	20.5	–	111
Jute/kenaf/E-glass	Epoxy resin	Vacuum bag method	–	–	–	–	1078	–	112
Oil palm empty fruit bunch/sugarcane bagasse	Phenolic formaldehyde resin (50%)	Hand lay-up	–	5.2/6.61	–	–	–	–	113
Kenaf/almond/kenaf	Epoxy resin (70%)	Hand lay-up	5% of NaOH	85/6.5	92/0.95	–	5	–	114
Areca/moringa	Polyethylene terephthalate	Micro-injection molding machine	5% NaOH at 80 °C temp. for 1 h	60.77	78.32	–	35.18	33.88 VHN	115
Sisal/kenaf	Epoxy resin (70%)	Compression molding machine	10% of NaOH for 12 h	41.34	–	–	1.88 J	84.8 HD	116
Calotropis gigantea/palmyra	Phenolic formaldehyde resin (60%)	Hand lay-up	–	44.82	53	–	1.28	–	117
Basalt/glass	Unsaturated polyester resin	Hand lay-up	–	270/7.1	946/44	–	–	–	118
Pineapple/sisal	Polyester resin	Injection molding method	–	207/4.07	90/3.47	–	29	83.7 (shore-D)	119
Sugar palm/ramie	Epoxy resin	Hand lay-up	–	52.66/8.34	80.70/4.26	–	–	–	120

Table 2 (continued)

Combination of fibers	Matrix	Fabrication method	Chemical modification	Tensile strength (MPa)/Young's modulus (GPa)	Flexural strength (MPa)/flexural modulus (GPa)	Compressive strength (MPa)/compressive modulus (GPa)	Impact strength (kJ/m^2 or J/m)	Hardness	Ref
Hemp/S-glass	Epoxy resin	Hand lay-up	10% of NaOH	23.5	–	–	7	45 barcol hardness (B)	121
Palm sheath/sugarcane bagasse	Epoxy resin	Hand lay-up	5% NaOH	19.8/0.95	28.79		2	38.02 HD	122
Palm empty fruit bunch/kenaf	Epoxy resin (50%)	Hand lay-up	–	55.7/2.9	116/8.7	–	3 J	–	123
Bamboo mats/fiber glass	Isophthalic polyester resin	Compression molding method	–	60	379	–	–	82 HD	124
Jute/bamboo/glass	Epoxy resin (55%)	Hand lay-up	–	103.46	56.65	–	6.8 J	–	125
Bamboo fiber/ rice husk/MWCNT filler	Epoxy resin	Vacuum lay-up	–	42.66	54.72		50.4	79 (shore-D)	126
Nacha/sisal/glass	Unsaturated polyester resin (70%)	Hand lay-up	5% of NaOH	220	210	308	–	–	127
Bamboo/coconut	Epoxy resin (70%)	Hand lay-up	NaOH	62	48	–	–	48 HRC	128
Kenaf/kapok	Unsaturated polyester resin	Hand lay-up	–	25.25	21/0.9	–	46	–	129
Enset/sisal	Polyester resin	Hand lay-up	–	132	152	–	24	–	130
Glass/kenaf/honeycomb	Epoxy resin (70%)	Hand lay-up	–	147.6/3.39	219/11.47	–	44.6 J	–	131
Kenaf/hemp, multi-walled carbon nanotube	Epoxy	Hand lay-up	–	43.5	55.63		56.6 J/m	87.45 (shore-D)	132

Incorporating flax and sisal, the initial natural fiber–reinforced composites utilized in the E-class Mercedes-Benz resulted in a remarkable decrease in weight of approximately 20% [133], primarily in the inner door panel. After evaluating 13 potential candidates hybridized with glass fiber–reinforced composites for creating a center lever parking brake component in a passenger car, kenaf fiber was identified as a suitable option [134]. In a comprehensive study, Alexander and Churchill [135] scrutinized the performance of sisal/glass, sisal/basalt, and sisal/glass/basalt hybrid composite materials. The remarkable binding strength of sisal and basalt fibers was found to be the key factor behind the exceptional performance of sisal/basalt/epoxy composites, outclassing all other combinations. These results indicate that the application of sisal/basalt/epoxy composites could be immensely advantageous in the realm of aircraft structural engineering. HPFBCs have diverse applications beyond just the automotive industry and structural applications (as shown in Fig. 10).

In recent times, renewable energy sources (wind energy and solar energy) have become the focus of researchers as alternatives to petroleum-based energy sources. Solar energy has gained a lot of attention, and hybridized composites have been increasingly used in solar energy applications as a component of the trough for solar energy gathering, as stated in reference [136]. Reddy and Singla [136] demonstrated the potential of using a woven/jute glass fiber–reinforced polyester hybrid composite material in the construction of parabolic trough collectors (PTCs). Their findings suggest that PTCs made from these hybrid composites could serve as a viable alternative to conventional PTCs. By using these materials, the costs associated with fabricating molds for batch production of parabolic trough reflectors can be effectively offset.

To harness natural energy, wind power is commonly generated by constructing windmills in open regions, often located far from urban areas. However, the challenge lies in optimizing the efficiency while minimizing the costs. One solution is the use of hybrid composite material blades, which can replace traditional wind turbine blades and potentially reduce expenses. A recent investigation [137] focused on enhancing the properties of wind turbine composites by incorporating silica mesoporous, epoxy, and kenaf fibers. The resulting hybrid composites, named SiaK/Ep, exhibited remarkable strength because of the optimal interaction between the matrix and the fillers at a 3.0 vol.% SiaK/Ep composition. This composition achieved a maximum flexural modulus of 1569.48 MPa, indicating its potential in wind turbine applications.

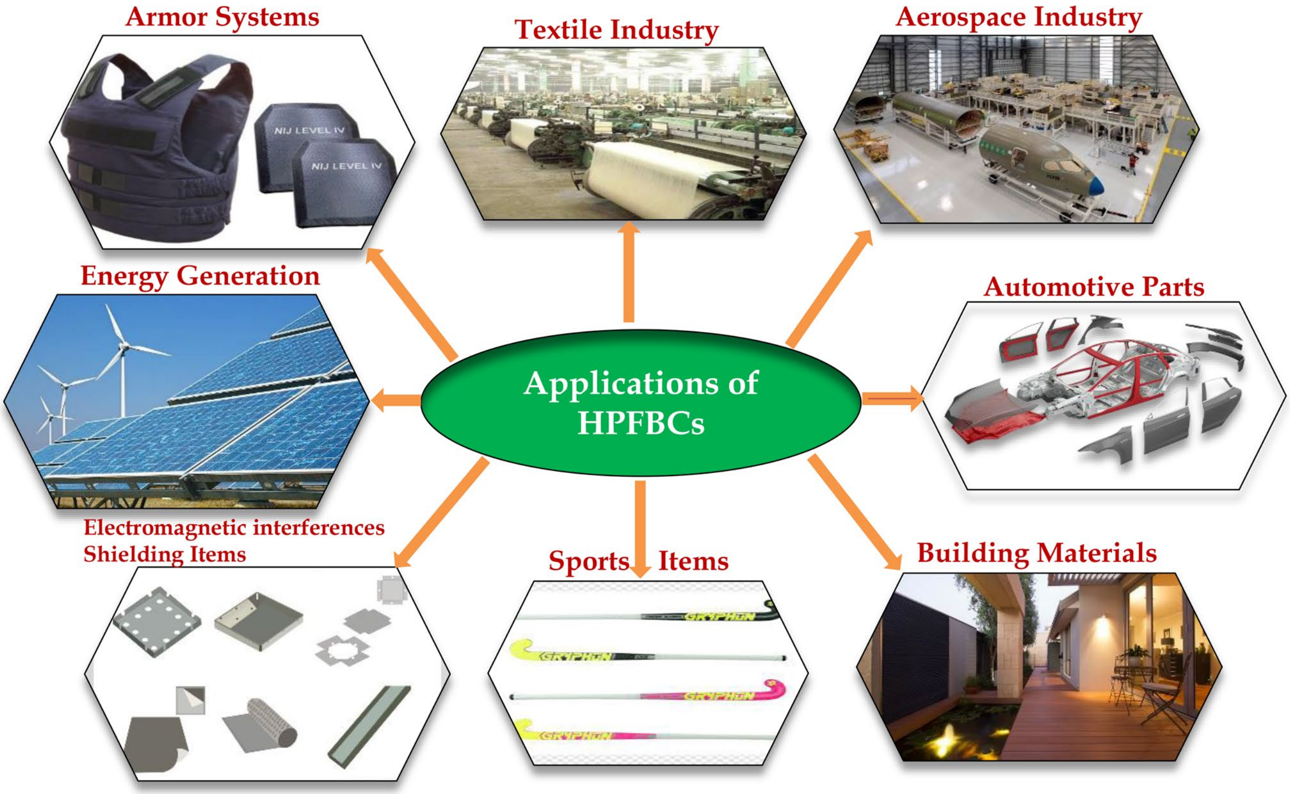


Fig. 10 Different applications of HPFBCs

It has become common practice to use glass, carbon, and aramid fibers as reinforcing materials in resin-based armor systems in order to study their efficacy and potential for useful uses [138]. Interest in the possibility of natural fibers combined with synthetic fibers for use in ballistic applications has grown recently. Ballistic perforation is affected by a few variables, including the order in which the stacks are stacked, the density of the areal or surface layer, the direction, and the thickness. In order to achieve this, Yahaya et al. [139] investigated the efficacy of various stacking sequences, utilizing Kevlar and nonwoven kenaf fiber layers in various configurations (innermost layers, outermost layers, and alternating layers). Their research showed that, when compared to other systems, the hybrid system with kenaf at the outermost layers performed better in terms of V50 (i.e., the velocity of ballistic impact with a 50% probability of penetration and a 50% chance of non-perforation). Results of this study show that it is possible to utilize a combination of synthetic and plant fibers in armor systems.

7 Current research challenges and future directions

In order to gain insight into the existing research gaps and possible avenues for future exploration in this field, it is essential to acknowledge the primary challenges and prospects linked to these materials. Despite extensive research on hybrid biocomposites, numerous research challenges persist. This section will shed light on some of these key challenges, drawing from the aforementioned literature. Additionally, it will explore potential avenues for future research in this field. The first challenge is a restricted understanding of the interaction between fibers and between fibers and matrix when they clubbed in hybrid biocomposites. Research is required to understand how these fibers interact at a microscopic level, affecting the overall performance of the biocomposites. However, in order to improve this interaction, various studies have suggested chemical treatment methods as these methods majorly contribute to improving the compatibility and adhesion and reduce moisture absorption. The second challenge is optimizing the processing techniques for hybrid plant fiber–based biocomposites. Investigations are required to identify effective methods for the preparation of hybrid composites to maintain the desired properties. The third challenge is the long-term durability and aging behavior of hybrid biocomposites under various environmental conditions such as high temperature and moisture, which is critical. Research should be focused on understanding deterioration mechanisms and emerging methods to improve the lifespan of these materials. The fourth challenge is biodegradability and recyclability, although hybrid biocomposites are known as biodegradable materials. Nevertheless, there must be a need for established testing and clarification for determining the authentic biodegradability and environmental impacts. Research should aim to establish industry-wide standards for evaluating biocomposite deterioration. Research on recycling methods and end-of-life options for HPFBCs is lacking. Based on published results and literature, some important future research directions are highlighted in Fig. 11.

8 Conclusion

In the present article, published works on tribo-mechanical performances of plant-based hybrid polymer composites have been reviewed and discussed in detail. In the context of tribo-mechanical performances, hybrid composites reinforced with plant fibers outperform composites made of glass fibers, and they are also more affordable than glass fiber composites. It is notable that the development of hybrid composites made with plant fibers has sparked competition in the market for a range of industrial applications. The major observations and suggestions are as follows:

1. In comparison to hybrid natural fiber/natural fiber–based polymer composites, hybrid composites developed with the combination of natural/synthetic fibers show improved tribo-mechanical performances at high operating conditions.
2. Plant-based hybrid polymer composites filled with filler materials (such as TiO_2 and Al_2O_3) have attracted research toward the fabrication of advanced HPFBCs for structural/non-structural applications. However, significant research is required in this new class of composites by altering the shape, size, and concentration of filler materials.
3. Tribo-performance of HPFBCs using stacking sequences of fibers also exhibits a reduction in friction and wear loss. Furthermore, chemically treated fibers also provided improved wear resistance properties of HPFBCs.
4. Chemical modification techniques applied in the pretreatment of plant fibers have demonstrated enhanced tribo-mechanical characteristics, indicating the potential use of these composites as an alternative material across a broad spectrum of applications.
5. More focus is required on the simulation and theoretical studies on the tribo-mechanical performances of HPFBCs. Also, more tribological studies are required under different lubrication conditions.
6. With the aim of improving the overall performance of composites, it is essential to achieve excellent interfacial adhesion between the matrix and plant fibers because this factor is key in defining the material's final characteristics. HPFBCs have shown greater mechanical

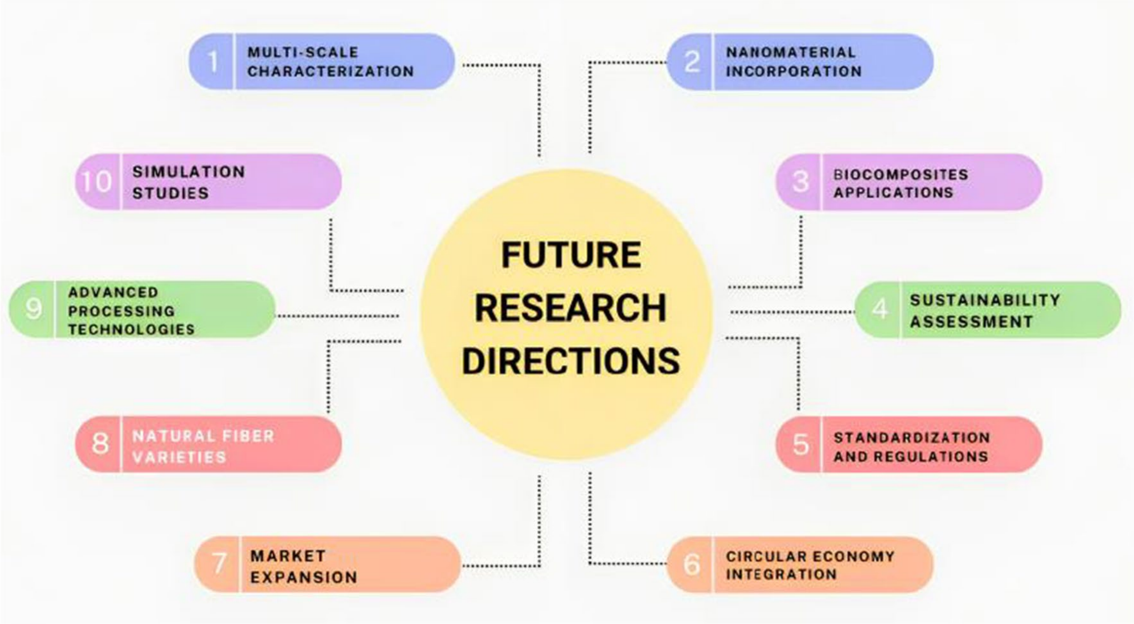


Fig. 11 Some future research directions for HPFBCs

capabilities in contrast to untreated composites using chemical treatments or changes of fibers. This is primarily attributable to the enhanced fiber-matrix bonding in chemically treated composites.

7. HPFBCs have demonstrated remarkable promise for usage in a variety of industries, including pipework, body armor, architectural and structural materials, and automotive components. Nevertheless, by performing more studies to enhance moisture absorption, thermal stability, and durability, usage of bast fibers in hybrid composites can still be expanded. It is probable that bast fibers might someday completely replace synthetic fibers with ongoing breakthroughs in these fields, opening the door for even more diversified and sustainable uses.

Declarations

Conflict of interest The author declares no competing interests.

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