RSC Advances

REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2026, **16**, 1392

Advances in tribological performance of plant–fiber reinforced epoxy composites

Nur Mohammad Mia,[a] M. S. Rabbi, *[a] Mohammad Ashraf Parvez,[a] Mohammad Asaduzzaman Chowdhury,[b] Md. Shifat Hasan Naim, [a] Md Momin Hossain[a] and Md. Mahbubur Rahman [c]

The growing interest in sustainable materials has prompted extensive research into plant fiber reinforced polymer composites as alternatives to synthetic fibers (*e.g.* glass, carbon). This review explores the tribological behavior, wear resistance, and mechanical properties of various plant fibers, like Abaca, Banana, Hemp, Jute, Coir *etc.*, when incorporated into epoxy matrices. It analyzes the chemical compositions, fiber–matrix interactions, and the influence of fiber content, treatment methods and fiber orientations on the tribological performance of the composites. Surface treatments along with the nanoparticles and fillers, have demonstrated lower friction coefficient, increased wear resistance and overall strength of every fiber reinforced epoxy composite. Combining multiple natural fibers or hybrid composites, offers superior durability and wear resistance compared to pure fiber composites. Increasing fiber content enhances the mechanical and tribological properties, with optimum performance observed at 20–30% fiber concentrations. Also, this review highlights the potential of plant fiber/epoxy composites as sustainable substitutes for synthetic fibers in industrial applications like automotive, construction, and aerospace.

Received 14th October 2025
Accepted 16th December 2025

DOI: 10.1039/d5ra07843a

rsc.li/rsc-advances

1. Introduction

The growth of population and industrialization has played a significant role in shaping the demand for high-strength, lightweight materials in construction and building applications, consequently fueling the need for eco-friendly alternatives.[1–3] Natural fiber reinforcements become the best substitute for replacing conventional fibers (glass/carbon) because they are environmentally friendly, biodegradable, and have good mechanical performance and chemical resistance, and are low cost and lightweight.[4–6] Natural fibers are being used extensively in polymer composites nowadays for various applications such as helmets, roofing sheets, postboxes, laminates and panels for multifunctional tables, door frames, seat coverings, glove boxes, seat surface, door panels, back support, trunk panel, and trunk floor.[7–9] The use of synthetic fibers is an important aspect in many different fields because of the properties and characteristics obtained from its production, with widespread types being utilized in numerous contexts.[10–12] Their development has revolutionized sectors such as textiles, automotive, construction and packaging, offering numerous advantages. However, it is important to know that synthetic fibers come with so disadvantages also, specially concerning their effect on environment and health. For example, one of synthetic material, asbestos has been referred to as a "God-given" material for inclusion in friction linings for its good physical and chemical properties that remain stable over the temperature range experienced by friction materials,[13] it has been reported that asbestos has serious health risks. Diseases associated with it include asbestosis, mesothelioma, lung cancer and other cancers.[14] Today plant fibers are widely used in research since they are abundant, cheap, and re-growable in a relatively short period of time. The increasing interest in using natural fibers for environmentally friendly products is attributed to their natural biodegradability (Fig. 1).[15,16]

The mechanical properties of natural fibers depend on some factors like cellulose content and polymerization, microfibril angle.[17] Moreover, significant amount of research works have been carried out on polymer composites employing natural fibers,[18–28] but a clear understanding of their tribological behavior is still missing.

In recent articles showed that fibers such as bamboo, sisal, jute, flax, coir, and abaca can improve friction, wear, and load-bearing performance while offering better sustainability than synthetic fibers.[29–31] Another review reported that nanofillers like nano-silica, nano-clay, metal oxides, and CNC/CNF can increase strength, thermal stability, and bonding when they are well dispersed.[32–34] A number of studies reported that extraction

[a]*Department of Mechanical Engineering, Chittagong University of Engineering & Technology (CUET), Chattogram 4349, Bangladesh. E-mail: rabbi@cuet.ac.bd*

[b]*Department of Mechanical Engineering, Dhaka University of Engineering & Technology (DUET), Gazipur 1707, Bangladesh*

[c]*Department of Mechanical Engineering, Khulna University of Engineering & Technology (KUET), Khulna 9208, Bangladesh*

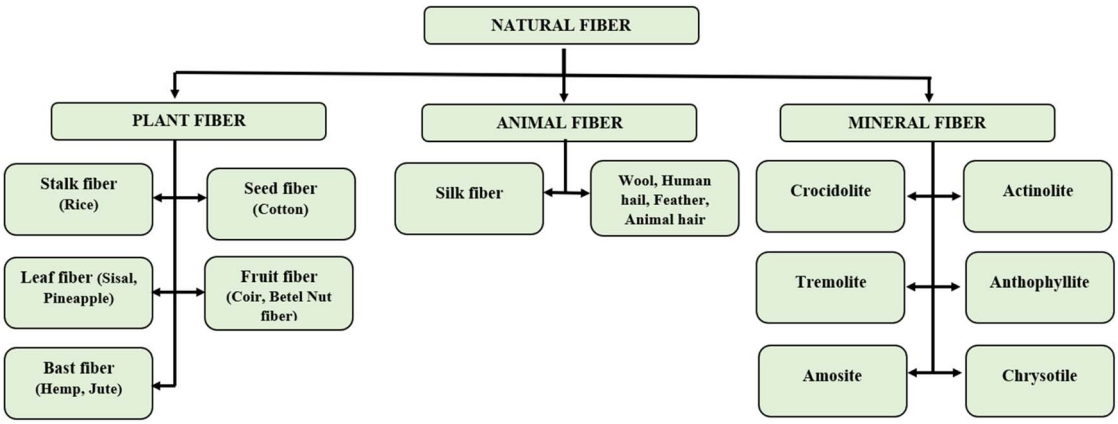

Fig. 1 Type of natural fiber.

procedures and chemical treatments (such alkali, silane) would remove impurity and increase adhesion, therefore decrease the moisture absorption content and improve composite performance.[35–37] Reviews on hybrid composites showed that mixing natural fibers with synthetic ones like glass or carbon gives higher impact resistance, better stiffness, and improved durability, but moisture and bonding issues still exist.[27,38,39]

Some reviews also introduced new plant fibers with good cellulose content and mechanical strength, which could be used for inducing a sustainable composite.[40,41] A fiber-specific review on coir showed that its high lignin content gives good stability and makes it useful for eco-friendly applications.[7,42] One more review on nano-lubricants indicated that friction and wear can be reduced significantly with carbon-based and metal-oxide nanoparticles, provided valuable findings for tribology studies.[43] Overall, these works give important knowledge, but none combine all aspects of fiber structure, treatment, filler addition, and composite design to explain tribological behavior in plant–fiber–reinforced epoxy composites.

Recent studies have explored the tribological behavior of single fiber polymer to hybrid composite (Fig. 2). However, there are noticeable gap in understanding of best fibers reinforced epoxy composites based on tribological behavior, wear, friction co-efficient and mechanical properties by collectively analysis. Also, the effect of fiber loading and external filler content on tribological and mechanical properties. The goal of the current review article is to summarize all recent research papers on natural fiber composite based mechanical and tribological enhancement, including those that address improvement in wear rate, coefficient of friction (COF), anti-wear properties, load-carrying capacity, effects of extraction process and chemical treatments on fiber properties. Also, this paper carried the

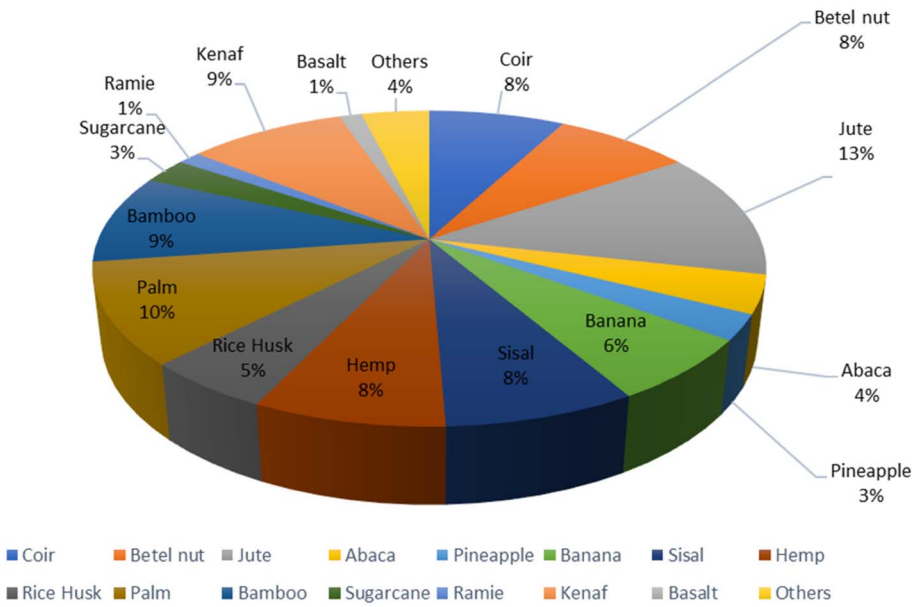

Fig. 2 Available research paper on the topic of plant fiber/epoxy based tribological analysis at Google scholar; (search keywords: tribological properties, fiber name, epoxy).

comparative analysis of hybrid composite to pure fiber polymer on the perspective of mechanical and tribological behavior. This exploration helps us better grasp practical applications. Additionally, this article helps to understand the best performers during reinforcement with epoxy. Ultimately, our goal is to offer a comprehensive understanding of these composites and their behavior under changing of different perimeters.

2. Chemical, and mechanical properties of natural fiber

2.1 Chemical properties

Plant fibers are primarily composed of cellulose, hemicellulose, and lignin. These fibers possess intricate structures and contain a diverse range of organic compounds, such as cellulose, hemicellulose, wax, pectins, fatty acids, and ash.[44] Numerous studies have examined the properties of various fibers.[45–78] The composition of these components in fibers varies depending on factors such as the fiber source, age, extraction methods, conditions, and environmental factors *e.g.* soil, weather.[79] The average proportion of chemical constituents in the plant fibers are provided in Table 1.

From Table 1 it can show that, the cellulose content varies widely, with pineapple, ramie exhibiting the highest at approx. 80–85%, while piassava has the lowest at 31.6%. Hemicellulose content is highest in kapok (49.3%) and lowest in ramie (3–4%), indicating a greater presence of structural components like cellulose in some fibers. Lignin content is notably high in piassava (48.4%) and coir (38–40%), while ramie has the lowest at 0.5%, which may contribute to the fiber's superior strength and durability.

In terms of ash content, rice straw having highest ash content (of 9.9%), and fibers like *Luffa cylindrica*, sisal having lower value indicates the presence of impurities in them along with some mineral content. The density in these fibers varies from 0.6 g cm^{-3} (bamboo) to 1.6 g cm^{-3} (pineapple); thus, making them more suitable for varied applications depending on weight requirements.

The cellulose crystallinity index (CI) shows a strong positive relationship with the mechanical performance of natural-fiber composites.[40] The crystallinity index also differs significantly fiber to fiber; flax offers 86.1%, offering great structural integrity and strength,[61] while kapok has relatively low values-up to 35.3% (ref. 66) – possibly limiting its applicability in high-strength applications. In general, higher CI increases tensile and flexural strength by 20–60%, because highly crystalline regions improve fiber stiffness and load transfer to the matrix. Fibers with CI above 70% (such as flax, hemp, ramie) typically produce composites with 30–50% higher tensile modulus

Table 1 Chemical properties of different type of fiber

Natural fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Ashes (wt%)	Density (g cm^{-3})	Crystallinity index (%)	Reference
Abaca	56–63	20–25	7.9	—	1.5	68.7	45and 46
Areca sheath fiber	65.32	15.02	8.46	4.4	1.05–1.25	—	4 and 80
Alfa	45.4	38.5	14.9	—	—	—	47
Bagasse	69.4	21	4.4	0.6	1.25	45.2	48 and 49
Bamboo	33–45	30	20–25	—	0.6–1.1	59.7	45, 46 and 50–52
Banana	60–65	6–8	5–10	1.2	1.5	39	45, 51 and 53
Carauá	70.7	21.1	7.5	0.8	1.4	75.6	54
Coir	43–53	14.7	38–40	—	1.2	44	55–59
Corn straw	39.82	23.19	11.98	—	—	50.3	45 and 60
Cotton stalk	50	28.4	23.1	—	1.5	74	52
Cytostachys renda (leaf stalk)	38.99	19.15	18.24	—	—	—	47
Flax	71	18.6–20.6	2.2	—	1.5	86.1	61 and 62
Hemp	72	10	3	2.3	1.5	79.9	57 and 63
Jute	60	22.1	15.9	1.0	1.3–1.4	58	55 and64
Kapok	50.7	49.3	13.4	—	—	35.3	65 and 66
Kenaf	72	20.3	9	4	1.5	72.1	57, 67 and 68
Luffa cylindrica	62	20	11.2	0.4	0.82	59.1	69 and 70
Sisal	74–75	10–13.9	7.6–7.9	0.4	1.5	72.2	45 and 58
Sleeve	55	20.6	23.8	—	—	—	71
Oil palm	65	10.12	17.5	—	—	—	47
Piassava	31.6	—	48.4	—	—	—	59
Pineapple	83	—	12	—	0.8–1.6	38	45, 55, 56 and 72
Raffia	44.6	13.5	2.7	—	—	64	52
Ramie	80–85	3–4	0.5	—	1.5	62.9	50,53 and 73
Rice straw	43.2	31.7	16.9	9.9	—	77	52 and 60
Weed	69	—	17	—	—	74.1	74
Wheat straw	43.2	34.1	22	4.99	—	54.4	48 and 75–77
Wood (soft density)	30–60	20–30	21–37	<1	—	—	78
Wood (hard density)	31–64	25–40	14–34	<1	—	71.6	60 and 78

compared to fibers with moderate crystallinity (50–60%).[81] Abaca, flax and hemp have the highest cellulose and crystallinity, they offer the best mechanical properties as shown in our results for making strong durable composite materials.

Another promising fiber for high strength applications is Carauá, which can contain up to 70.7 of cellulose and has quite good crystallinity ≈75.6%. Despite the high cellulose content (69.4%) in bagasse, its crystallinity (45.2%) is less, and this can lead to lower wear resistance. Jute and rice straw have a moderate amount of cellulose and crystallinity that can balance in many composite applications; hence they are both considered useful fibers. By contrast, fibers such as Piassava and Kapok with relatively more lignin may be better used in certain applications requiring resistance to wear and degradation.

2.2 Mechanical properties

The mechanical properties of the natural fibers in the table, shows significant variation, making them suitable for a wide range of applications. The density of these fibers Table 2 varies from 0.55 g cm^{-3} (bagasse) to 1.60 g cm^{-3} (pineapple), which reflect their weight and compactness properties. Fibers with higher density, such as abaca (1.5 g cm^{-3}) and cotton (1.50–1.60 g cm^{-3}), tend to offer better mechanical properties. Besides, lighter fibers like bagasse (0.55–1.25 g cm^{-3}) are more suited for lightweight applications. Elongation at break strongly affects how natural-fiber composites fail under tensile, impact, and fatigue loading because it determines how much strain the material can withstand before breaking. The coir fibers have the highest elongation at break 47% whereas pineapple fibers are start form only 0.8%. Coir exhibits an elongation percentage significantly greater, representing lower Young's modulus, that provides much desired flexibility 7. Fibers with low elongation at break (flax (1.2–4.0%),[82] hemp (1.5–4.0%),[83] jute (1.3–3.0%),[84] ramie (1.2–4.0%)[31]) make composites stiff but brittle, leading to early matrix cracking, sudden fiber breakage in tension, low impact energy absorption, and faster fatigue crack growth. Bagasse and pineapple fibers are significantly more rigid; this means that they have a lesser yield load they can take before breaking point.

According to its tensile strength, which is the power of a fiber not to break when it stretches, fibers go from 20 MPa (bagasse) up until 1830 MPa (flex). High tensile strength fibers like flex (345–1830 MPa), pineapple (170–1627 MPa), abaca, 400–980 MPa, hemp (310–1110 MPa) and banana (500–914 MPa) are used when high strength, strong and durable composites are required. On the other hand, fiber such as bagasse (20–290 MPa) and coconut (83–222 MPa) have a low tensile strength which limited them to high-strength application. Young's modulus (E) for the fiber stiffness, ranges from 1.44 GPa (pineapple) to 128 GPa (ramie). Ramie stands out with exceptionally high stiffness, followed by flex (27.6–82 GPa) and hemp (23.5–9 GPa), making these fibers ideal for reinforcing materials that need to resist deformation. Coir (3–6 GPa) have lower moduli which make this more flexible but less stiff than other fibers. Ramie has very high stiffness because of its special microstructure. It has thick cell walls and a very low microfibril angle, meaning the cellulose microfibrils are almost straight along the fiber axis.[95] This alignment helps the fiber carry load easily and reduces deformation. Ramie also has high cellulose content, high crystallinity, and very low lignin, which make it even stiffer.[73,96] Fibers like Ramie, Flex, and Banana offer a combination of high tensile strength and stiffness, that making them excellent candidates for applications where requiring both durability and structural integrity.[95,96]

3. Tribological properties

3.1 Friction co-efficient (COF)

The coefficient of friction (COF) is a measure of the resistance experienced when two surfaces are moving against each other. The frictional force that occurs relative motion the two surfaces to remain as a ratio form of normal force pressing one material against the other. Natural fiber reinforced epoxy composites face wear, efficiency, and overall performance issues which this parameter significantly influence. Composites developed using natural fibers and epoxy matrices render a set of fascinating

Table 2 Mechanical property ranges of natural fibers

Serial	Fiber	Density, ρ (g cm^{-3})	Elongation at break (%)	Tensile strength (MPa)	Young's modulus, E (GPa)	Reference
1	Abaca	1.5	3–12	400–980	12–72	85–90
2	Bagasse	0.55–1.25	0.90–1.1	20–290	2.7–27.1	82, 85, 87, 89 and 91
3	Bamboo	0.6–1.1	1.3–7.0	140–575	11–35.9	87 and 92–94
4	Banana	1.30–1.35	3–10	500–914	7.7–32.0	85, 89 and 83–98
5	Coconut	0.81–1.10	—	83–222	12–32	91 and 93,94,97
6	Coir	1.15–1.25	15–47	106–304	3–6	87 and 99–102
7	Cotton	1.50–1.60	3–10	200–800	5.50–12.6	82, 83 and 31–105
8	Flex	1.40–1.50	1.2–4.0	345–1830	27.6–8	42, 82, 83 and 87
9	Hemp	1.4–1.5	1.5–4.0	310–1110	23.5–9	42, 83, 87, 103 and 104
10	Jute	1.30–1.50	1.3–3.0	187–800	3–55	42, 84, 90, 101 and 103
11	Pineapple	0.8–1.6	0.8–14.5	170–1627	1.44–82	82, 83, 88, 90, 98 and 104
12	Ramie	1.0–1.55	1.2–4.0	220–938	23.0–128	31, 82, 99 and 101
13	Sisal	0.7–1.5	2.0–14.0	350–840	9.0–38.0	87, 83–98 and 101

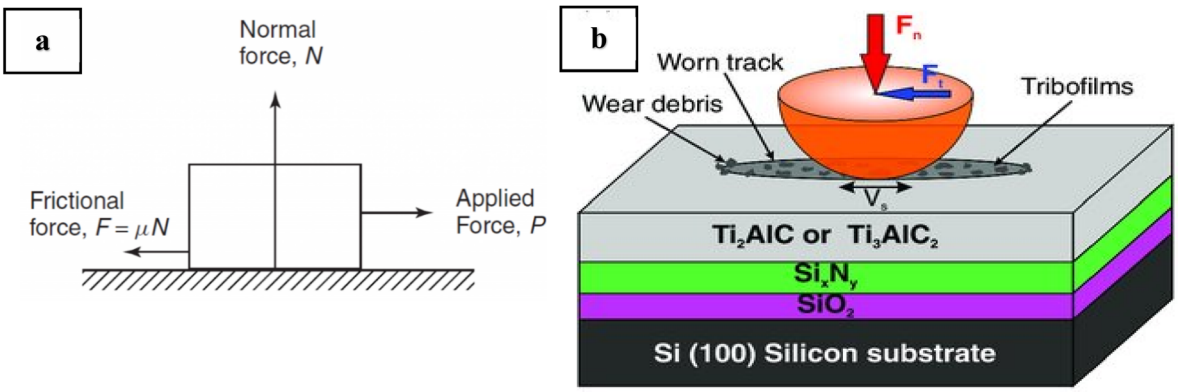

Fig. 3 Tribological elements. (a) Coefficient of performance. Reproduced from ref. 108 with permission from Elsevier, Copyright 1993; (b) Turbo films. Reproduced from ref. 109 with permission from Wiley, Copyright 2022.

tribological behaviors, owing to the inter fiber–matrix interaction governing their applicability in diverse field for tribology.[106,107]

The coefficient of friction varies depending on normal load, sliding velocity, surface roughness and other lubrication conditions. The normal load/force is one of the main influencing factors on frictional behavior of natural fiber composites. With the increase in average load, the contact area between two surfaces increases thereby making a reduction in coefficient of friction possible (Fig. 3).

The friction coefficient depends on the sliding velocity as well as normal load. For natural fiber composites, increasing the sliding velocity typically leads to a decrease in the COF. This reduction in wear is owing to the formation of a tribo-film: a thin layer of either wear debris or lubricant that develops on sliding surfaces. The tribo-film acts as a separator so the surfaces are not in direct contact, which results in lower friction coefficient. It is because in boundary lubricated condition the lubricant film is very thin that it could not create full separation between surfaces, therefore the tribo-films are generated. Yet, this behavior could be changed with the addition of nanoparticles or friction modifiers which can assist in a formation of more stable tribo-film resulting in lower COF and better wear resistance. For example, the incorporation of TiO_2 nanoparticles in the composite matrix or lubricants has been shown to significantly reduce the COF, as these nanoparticles serve as a solid lubricant due to the absence of direct material-to-material contact.[110–114]

Natural fiber–reinforced epoxy composites usually show a friction coefficient between 0.2 and 0.5, depending on fiber type, treatment, and loading conditions. Besides, untreated fibers shows higher values of 0.4–0.5 due to rough surfaces. Treatments such as silane and NaOH reduce the friction coefficient nearly to 0.3 by improving fiber–matrix adhesion and smoothing the surface. Hybrid systems that combine natural fibers with basalt fibers, metal fillers, or ceramic fillers can show even lower friction due to tribological effects and the formation of tribo-films. Surface treatments, friction modifiers, and nanoparticles also help further reduce friction and improve overall tribological performance.[115,116]

3.2 Wear rate

In order to evaluate the tribological performance of natural fiber–reinforced composites, wear rate is an important parameter. All of these things combine to influence the wear rate, which can be a function of fiber type and treatment, matrix material, and operating conditions (such as load, sliding speed and temperature). Wear rate often goes up with increasing load though it is not always the same as sliding speed and frictions couple between fibers and matrix depending on fiber nature of matrix material used.[117] When exceeding a certain critical load, wear rates were found to increase dramatically in high-speed applications, sometimes resulting in material adhesion/failure.[113] Wear rate can be decreased by modifications of the fiber surface such as fiber treatments and hybrid fibers, which improves bonding between the fiber and matrix[118] Furthermore, the addition of reinforcement agents, *e.g.* hexagonal boron nitride (h-BN), can improve lubrication effect and significantly thus reduce wear rate.[118] As for metallic glass composites those tend to form the tribo-layer offering better wear resistance at high temperature due to a tribo-layer that formed at the worn surface of some alloys.[119] Moreover, laser cladding, ultrasonic assistance and other processing technologies improved the wear resistance *via* enhancing particle reinforcement uniformity of the surface layer as well as decreasing particle

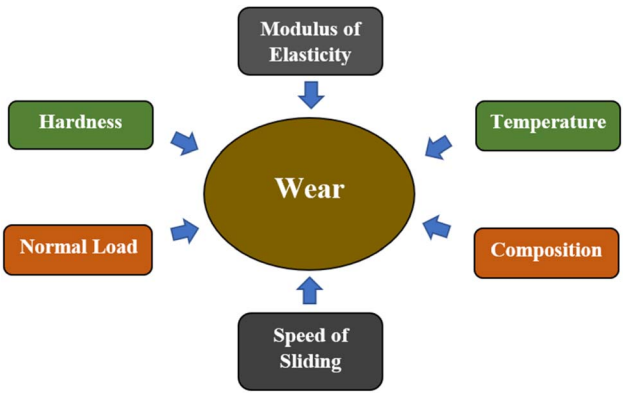

Fig. 4 Factors influence the wear.

agglomeration. The wear rate is also decreased by the formation of a mechanically mixed layer during wear, which makes these composites applicable for high-wear use under different conditions (Fig. 4).[118,119]

3.3 Lubrication

Another perimeter is lubrication, that plays a critical role in enhancing the tribological performance of natural fiber reinforced epoxy composites. The addition of lubricants significantly reduces friction and wear by preventing direct contact between the sliding surfaces. Under boundary and mixed lubrication conditions, where such contact is more likely, lubrication is particularly beneficial. For instance, the addition of Cu nanoparticles to lubricating oil has been studied, and it was found that these nanoparticles form a protective copper film on the worn surface, especially under high temperatures. This film leads to a substantial reduction in both friction and wear.[120]

The presence of a tribo-film formed on the counter-face during sliding further improves the performance of glass fiber reinforced epoxy composites under oil lubrication conditions. The tribo-film acts by separating the friction surfaces, which reduces wear and helps maintain the composite's integrity.[121] The lubrication process itself is aided by the oil, which helps in the transfer of wear debris and provides a protective barrier between the composite and counter-face.[121] Solid lubricants, such as SiO_2 nanoparticles, graphite, and PTFE, also improve wear resistance in these composites without significantly affecting the friction coefficient.[122–124]

Metallic and metal-oxide nanoparticles such as Cu, MoS_2, and ZnO enhance the tribological performance of lubricating oils through several synergistic mechanisms.[43,120,125] During sliding, nanoparticles form protective tribo-films that fill asperities and reduce direct surface contact, thereby lowering friction and wear. Spherical nanoparticles also act as nano ball bearings, transforming sliding friction into partial rolling motion. Certain nanoparticles, particularly Cu and ZnO, participate in surface repair processes by depositing into wear scars and forming smooth, load-bearing layers.[43] Furthermore, metal-oxide nanoparticles improve thermal stability and inhibit oxidative degradation of the lubricant, while lamellar MoS_2 provides exceptional low-shear interlayer sliding.[125]

The resin phase itself plays a significant role in lubrication. Due to its lower heat distortion temperature compared to the fiber phase, the resin softens under frictional heat, allowing it to migrate to the contact surfaces and act as a lubricant. This migration reduces friction and enhances wear resistance by preventing direct fiber-to-fiber contact.[121,126] Fiber orientation, fiber type, and the resin phase act together and strongly influence performance. Surfaces where fiber nodes contact the resin show higher wear, more roughness, and therefore higher friction because they undergo direct frictional contact. In contrast, perpendicular and parallel fiber surfaces give better wear resistance and lower friction because the resin can act as a lubricant between sliding surfaces.[126] The wear resistance is increased by the high fiber content in the composite, however more amount of fibers may lead to debonding causing higher rates of wear.[121,124] The matrix phase, fiber orientation and fiber, filler content also interact to affect the lubrication as well as the wear mechanism, where loading plays an essential role for decreasing friction and wear with coatings involved.[127,128]

3.4 Surface roughness

Surface roughness refers to the microscopic irregularities present on the surface of a material, which can significantly impact its tribological performance.[123] These surface features, including peaks and valleys, influence the contact between two surfaces during sliding or rolling. In the case of natural fiber reinforced epoxy composites, surface roughness plays a crucial role in determining how these materials perform under frictional and wear conditions.[129] The topography of the composite's surface, along with that of the opposing surface, directly affects the friction and wear behavior, with smoother surfaces typically offering better performance due to their ability to promote more uniform interactions.[123]

Rougher surfaces tend to create more contact points between the composite and the opposing material, leading to increased friction and wear. This is because the surface asperities engage more aggressively, causing higher mechanical interactions during the initial sliding stages.[122] Smoother surfaces more easily form a uniform lubricating film that prevents direct contact between sliding pairs, thereby reducing friction and wear. In practice, smooth surfaces promote faster and more stable development of this protective lubricant layer, which significantly minimizes friction-related damage.[123]

In the case of composite materials reinforced with natural fibers, such as hemp, jute, or sisal, surface roughness also depends on the fiber type and the treatment applied to these fibers.[130] Chemical treatments, such as hydrogen peroxide or sodium carbonate, can change the fiber's body structure, which can then affect the surface, opening/twisting up ends and loosening some of the bundles, improving the fiber–matrix interface and the overall wear performance of the composite.[130] As a result, a better fiber–matrix link can help a more effective protective layer to form during the sliding time, and, thus, the material's tribology will also be upgraded.[130,131]

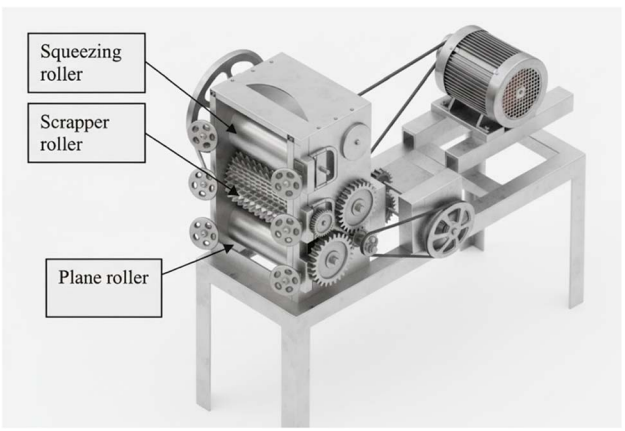

Fig. 5 Schematic diagram of a mechanical decorticator.

4. Chemical, processing, and tribo-chemical influences on natural fiber performance

4.1 Fiber extraction methods

4.1.1 Mechanical extraction. Mechanical extraction relies on physical forces such as shearing, scraping, and ripping to separate fiber bundles from the plant stem, bark, or pseudo-stem without significant chemical or biological intervention.[37] The process typically includes decortication, fiber cleaning, and fiber opening, during which the shive or woody core is mechanically removed and the remaining fiber bundles are refined into finer strands.[132,133] Although mechanical extraction offers rapid processing and is scalable for industrial production, the intense mechanical forces often cause fiber breakage, reduced fiber length, and inconsistent quality.[134–136] Studies on jute, banana, and *Sansevieria cylindrica* fibers show that mechanically extracted fibers retain higher lignin and wax content than retted fibers, resulting in lower flexibility and variable tensile properties.[137] Mechanical extraction is therefore suitable for applications where fast processing is required, but the resulting fibers may require additional retting or chemical treatment to improve their uniformity, cellulose exposure, and mechanical performance (Fig. 5).[134,138]

4.1.2 Biological extraction. Biological extraction uses naturally occurring microorganisms or targeted enzymes to decompose pectin, hemicellulose, and other binding components that hold fiber bundles to plant tissues.[139] This method is slower than mechanical processing but produces cleaner, more

Fig. 6 Water retting process. (A) Retting in the roadside pond, (B) silver color fibers by traditional retting, (C) retting with native microbial inoculum and (D) golden color fibers. Reproduced from ref. 147 with permission from Excellent, Copyright 2020.

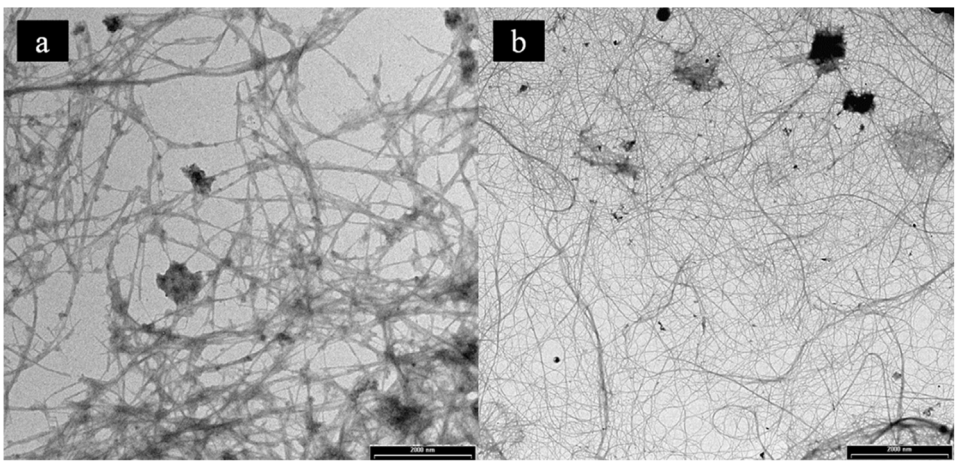

Fig. 7 Image of banana peel cellulose fibers; (a) obtained by chemical treatment and (b) obtained by enzymatic treatment, (scale bar 2000 nm). Reproduced from ref. 152 with permission from Elsevier, Copyright 2014.

uniform fibers with minimal structural damage.[140] Because biological extraction preserves fiber length and reduces harsh mechanical forces, the resulting fibers generally show improved flexibility, higher spinnability, and more consistent mechanical properties.[141]

4.1.2.1 Retting extraction. Retting is the most traditional form of biological extraction, where stems or leaves are placed in water, on the ground, or in controlled microbial baths to allow bacteria and fungi to break down pectin-rich tissues.[140] Water-retted fibers typically display higher cellulose and hemicellulose content and lower lignin content compared to mechanically extracted fibers, resulting in greater flexibility and better tensile performance.[142–145] However, retting is highly dependent on environmental conditions and timing under-retting results in incomplete separation, while over-retting weakens fibers and reduces stiffness. Despite these limitations, retting remains a widely used method for producing high-quality bast fibers.[146] Microbial activators like molasses and fertilizers accelerate retting and it gives golden fiber color in 14–30 days (Fig. 6).[89]

4.1.2.2 Enzyme extraction process. Enzymatic extraction applies controlled mixtures of pectinase, cellulase, and hemicellulase to selectively dissolve the gummy materials that bind fibers, offering more precise control than traditional retting. This method enhances fiber surface cleanliness while minimizing damage to the cellulose structure, leading to fibers with higher stiffness, improved uniformity, and better interfacial bonding in composite applications.[148] Enzyme retting is also environmentally friendly, requiring less water and producing less pollution than conventional retting, while yielding fibers with consistent fineness and mechanical performance.[149]

4.1.3 Chemical extraction. Chemical extraction involves using alkaline, acidic, or oxidative solutions, most commonly sodium hydroxide (NaOH), potassium hydroxide (KOH),

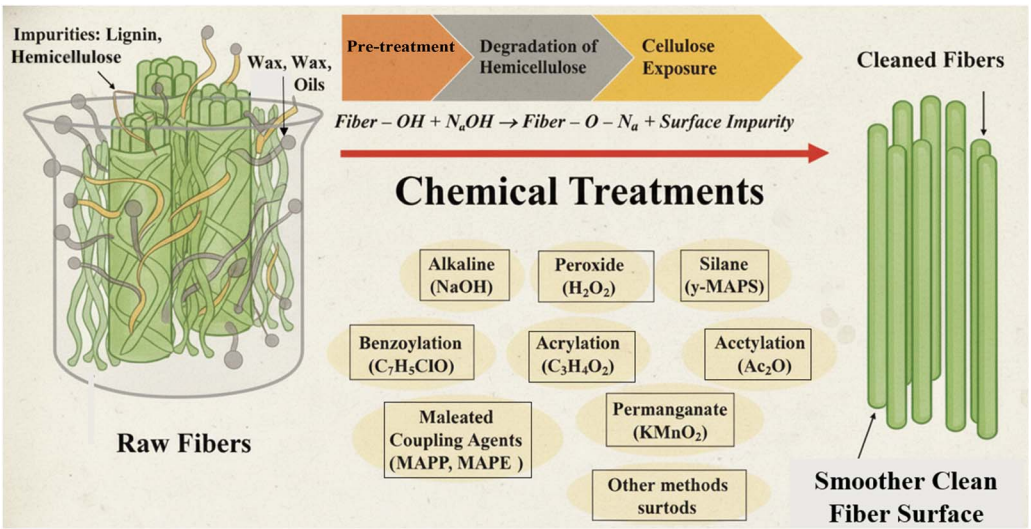

Fig. 8 Schematic illustration of the chemical treatments on natural fiber.

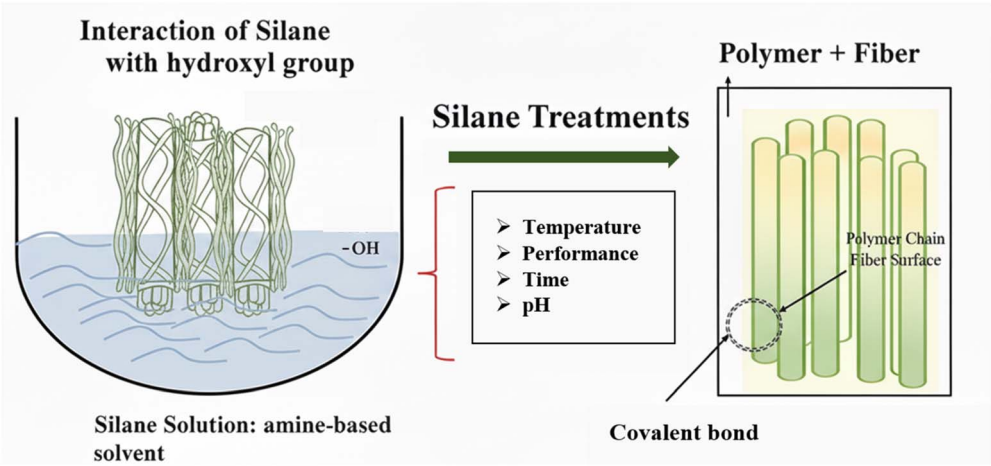

Fig. 9 Schematic representation of the silane treatment on natural fiber.

sodium carbonate (Na_2CO_3), or mild acid systems.[35] This process dissolve pectin, hemicellulose, waxes, and portions of lignin that bind fibers within plant tissues. In a typical process, plant stems or leaves are immersed in an alkali solution at controlled temperature and duration, allowing the chemicals to penetrate the cell wall matrix and selectively remove amorphous

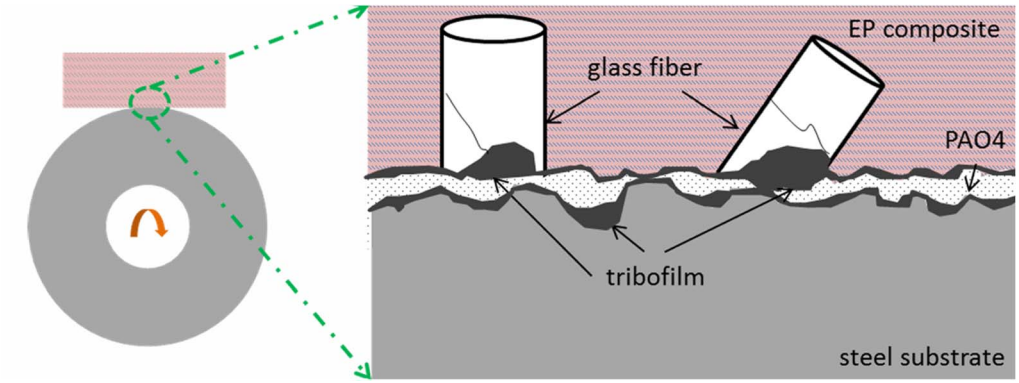

Fig. 10 Schematic of tribological mechanism of short glass fiber/epoxy composites under oil lubrication conditions. Reproduced from ref. 98 with permission from Elsevier, Copyright 2016.

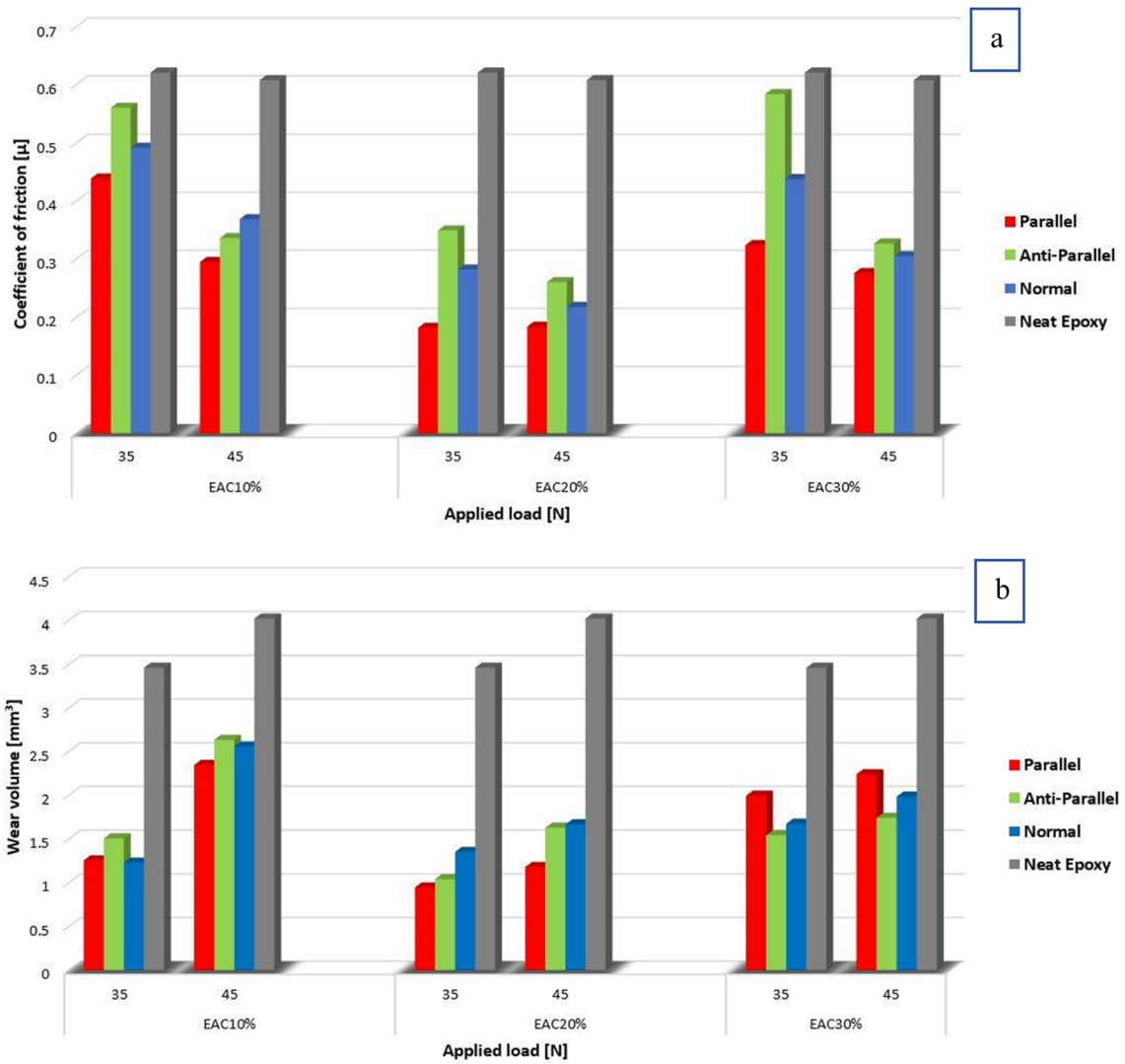

Fig. 11 Tribological properties of epoxy/abaca composite (EAC) after two applied loads, and 800 m of sliding distance. (a) Coefficient of friction; (b) wear volume of the EAC's and NE. Reproduced from ref. 190 with permission from MDPI, Copyright 2022.

Table 3 Tribological properties of abaca fiber reinforced epoxy composites

Fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubrication	Mechanical properties	Key findings	Reference
Abaca fiber	Alkali treatment (6% NaOH); vacuum infusion for composite formation	10%, 20%, 30% fiber content	0.34–0.62	Lowest wear rate observed at 20% fiber content; wear rate increases with higher fiber content	Dry	Tensile strength: 762.36 MPa, elastic modulus: 42.58 GPa, elongation: 1.68% (treated)	- Fiber orientation and content strongly affected abaca–epoxy tribology - Anti-parallel orientation gave the highest friction at high loads - Lowest wear occurred at 20% fiber - Wear resistance improved up to 20%, best in parallel orientation	190
Abaca fiber	NaOH treatment (5% NaOH); compression molding	0–25% fiber content	—	Best wear performance at 25% fiber content; lower wear rate with increased fiber content	Dry	—	- 25% abaca fiber provides the lowest wear rate and best wear resistance - Wear mechanisms include adhesive wear, fatigue, and delamination - SEM analysis shows fewer fiber pull-outs and better interfacial bonding at 25% fiber content	192
Abaca fiber	NaOH treatment (3% NaOH); compression molding	0%, 1%, 2%, 3%, 4% fiber content	—	Lowest wear rate at 3% fiber content; increases beyond 3%	Dry	After NaOH treatment tensile strength increased from 723.65 MPa to 762.36 MPa, elastic modulus increased from 31.24 MPa to 42.58 MPa, and the elongation decreased by ~12.5%	- The best wear resistance was found in the composite with 3% abaca fiber - The wear rate decreased with increasing fiber content up to 3%, after which it increased - SEM analysis revealed better surface morphology with fewer fiber pull-outs at 3% fiber content	191

Table 4 Tribological properties of pineapple fiber reinforced epoxy composites

Fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubrication	Mechanical properties	Key findings	Reference
Pineapple leaf fiber	NaOH treatment (5% NaOH); hand lay-up; different fiber orientations (45°, 60°, 75°, 90°)	10–30% fiber content	0.33–0.56	Wear rate is lowest at 90° fiber orientation; highest wear at 45° orientation	Dry	Tensile strength: 40.42 MPa at 90° orientation Flexural strength: 126.42 MPa at 90° orientation	- Optimal performance at 90° orientation for wear resistance and friction - Lower wear rate at 90° fiber orientation, showing improved durability and higher mechanical properties - Worst performance at 45° orientation with the highest wear rate and lower mechanical strength	193

components, after which the fibers are washed and neutralized to restore pH balance. This treatment effectively increases fiber purity and exposes more cellulose microfibrils, resulting in improved surface roughness, better fibrillation, and enhanced fiber–matrix adhesion in composite applications.[36,150] Mechanically, the removal of hemicellulose and lignin increases cellulose crystallinity and stiffness, while the reduction of amorphous regions generally lowers fiber elongation due to decreased flexibility.[141] If treatment is excessively strong, however, chemical degradation of cellulose may occur, leading to reduced tensile strength and fiber brittleness. Therefore, optimized chemical extraction is crucial for producing high-performance natural fibers with balanced stiffness, strength, and elongation characteristics (Fig. 7).[151]

4.2 Different type of treatments

Chemical treatments are used to make natural fibers more compatible with polymer matrices. They remove surface impurities, change chemical groups, and help the fibers bond better with the resin. The quality of the natural fibers relies on the extraction techniques and different processing methods.[35] Alkali, silane, and enzymatic treatments are especially effective because they clean the fiber surface and expose more cellulose for bonding.[36] NaOH increases surface roughness and removes hemicellulose and lignin. Silane forms strong chemical bridges between the fiber and the polymer.[153] Enzymes remove pectin and waxes without damaging the cellulose. These treatments improve interfacial bonding, stiffness, and the overall mechanical performance of composites. However, too much treatment can damage the cellulose and weaken the fibers (Fig. 8).

4.2.1 Sodium hydroxide treatment (NaOH). Alkaline treatment is a simple, low-cost, and effective method used to improve the water resistance, adhesion, and mechanical, thermal, and acoustic properties of natural fibers in thermoplastic and thermoset composites.[154–157] This treatment changes the size, shape, and strength of the fibers.[35] It causes fibrillation, where fiber bundles separate into smaller units. As a result, the aspect ratio increases, and more cellulose surfaces become exposed for bonding with the polymer matrix. These effects improve surface wetting and lower water absorption. Sodium hydroxide is widely used because it converts cellulose-I to cellulose-II more effectively than other chemicals.[36] In a research by Bar and Chaudhary, stem fibers subjected to alkali treatment showed an increase in cellulose content from 55% to 64%, significantly enhancing their crystallinity and tensile strength.[158]

During alkaline treatment, fibers are soaked in a NaOH or KOH solution. The concentration, temperature, soaking time, and applied tension control the swelling of the fibers and the changes in their structure, morphology, dimensions, and mechanical behavior. The treatment also creates a rougher surface, which strengthens the fiber–matrix bond and further enhances mechanical properties.[159] In addition, mercerization increases active bonding sites on the fiber surface and removes non-cellulosic materials such as lignin, hemicellulose, pectin,

Table 5 Tribological properties of sisal fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process & fabrication method	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Sisal	—	Stearic acid, sodium citrate treatment	25 wt% fiber	0.233	1.423 mm^3 N^{-1} m^{-1}	Tensile strength: 45.67 MPa, flexural strength: 160.54 MPa, ILSS: 10.23 MPa	Chemical treatments (sodium citrate and stearic acid) reduce surface impurities and enhance fiber–matrix adhesion, improving wear resistance, friction, and mechanical properties. Sodium citrate treatment showed the best performance	195
Sisal	—	Hand lay-up method	30 wt% fiber	0.30–0.50	74.86, 60.85, 49.46 mg (at 10, 20, 30 wt% fiber)	Tensile strength: 45.67 MPa	Sisal fiber composites show improved wear resistance and friction coefficient reduction. Wear rate decreases by 43.07–40.57% compared to neat epoxy at various load conditions	196
Short sisal	—	Hand lay-up method	30% wt of fiber 10 mm length	—	—	—	- The specific wear rate and coefficient of friction of sisal reinforced epoxy composite decrease with reinforcement in epoxy - The wear rate increases with load, sliding velocity, and sliding distance - Friction force increases with load, sliding velocity, and sliding distance, while the coefficient of friction decreases with these factors	198
Sisal	—	Vacuum-assisted resin transfer molding (VARTM) technique	56% sisal fiber	0.233	1.423 mm^3 N^{-1} m^{-1}	Tensile strength: 45.91 MPa; modulus of elasticity 1.69 GPa	Sisal showed the highest modulus of elasticity; have moderate wear rate compare to coir and cotton with epoxy	20
Sisal	—	Compression molding process	20% to 80%	—	—	—	Normal fiber direction (TT) orientated sisal fiber–epoxy composites exhibited minimum wear rate	199
Sisal	—	Silane treatment	30 wt% sisal	0.39 (bi-directional)	0.032 mg min^{-1} (10 N, 0.1 m s^{-1}); 0.039 mg min^{-1} (40 N, 0.7 m s^{-1})	Flexural strength: 58.54 MPa, tensile strength: 39.15 MPa	(70 wt% epoxy, 30 wt% sisal) showed lower wear rate and friction coefficient than bi-directional composites. The fiber orientation influenced the	200

Table 5 (*Contd.*)

Fiber	Filler with fiber	Treatment process & fabrication method	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
							composite's flexural strength, which decreased with bi-directional fiber formation	
Sisal	Coconut shell powder	Compression molding	10, 20, 30 wt% fiber	—	74.86, 60.85, 49.46 mg (for 10, 20, 30 wt% fiber)	Compression strength: 21% higher than 15 wt% fiber	Sisal fiber composites show the highest wear loss compared to jute and hybrid composites. Increased fiber content improves strength and hardness, with wear resistance improving as fiber percentage rises	197

wax, and oil. Removing lignin and hemicellulose, which bind microfibrils, can reduce tensile stress in natural fiber composites.[160]

4.2.2 Potassium per manganate treatment ($KMnO_4$). Permanganate treatment is used to improve the bonding between natural fibers and polymer matrices. Potassium permanganate reacts with cellulose and lignin, creating new hydroxyl, carbonyl, and carboxyl groups that enhance adhesion and reduce water absorption. As an oxidizing agent, $KMnO_4$ etches the fiber surface, removes amorphous regions, and increases surface roughness. This roughness provides more mechanical anchoring points, improves load transfer, and strengthens interfacial bonding. Functional groups formed during oxidation also promote covalent and secondary interactions with the polymer matrix, improving wettability and fiber–matrix compatibility.

Kudva *et al.*[161] showed that bamboo fibers treated with 0.5% $KMnO_4$ had higher tensile strength, along with alkali-treated fibers. The treatment cleaned the surface and produced slight fibril separation. Abisha *et al.*[162] found that $KMnO_4$-treated *Butea parviflora* fibers had increased tensile strength (92–198 MPa), higher Young's modulus (2.16–4.40 GPa), and thermal stability up to 240 °C. SEM and FTIR analyses confirmed improved roughness and changes in cellulosic functional groups. $KMnO_4$ treatment is usually applied for 1–3 minutes after alkaline pretreatment. Increasing $KMnO_4$ concentration reduces hydrophilicity and water absorption, but concentrations above 1% can degrade fibers. The formation of cellulose–manganate complexes supports graft copolymerization and enhances interfacial chemical bonding.

Kulandaiyappan *et al.*[163] reported higher tensile and impact strength in nanocomposites made from palm leaf stalk fibers treated with 5% $KMnO_4$. Acharya *et al.*[164] found that $KMnO_4$-treated *Helicteres isora* fibers showed the best physical properties, highest thermal stability, and lowest water absorption. Studies also show notable improvements in mechanical strength, modulus, impact resistance, thermal stability, and durability after permanganate treatment.[165–170]

4.2.3 Benzoylation treatment. Benzoyl chloride or benzoic anhydride is an effective chemical method for improving the thermal stability, mechanical strength, fiber–matrix adhesion, and hydrophobicity of natural fibers. It also reduces water absorption in composites.[171–175] The process begins with alkali pretreatment, which removes extractives such as waxes, oils, and lignin and exposes more hydroxyl groups. These exposed groups then react with benzoyl chloride during benzoylation. The reaction replaces hydrophilic hydroxyl groups with hydrophobic benzoyl groups, creating a rougher surface and promoting fibrillation. This modification improves fiber–matrix compatibility and increases the hydrophobic behavior of the fibers. Benzoylation also enhances interaction with aromatic polymer matrices because the benzoyl group contains a benzene ring capable of electron interactions with polymer aromatic structures.

While the treatment improves water resistance, strength, and durability, it also has disadvantages, including toxicity, environmental hazards, higher processing cost, and the risk of

fiber degradation. Benzoyl chloride is highly corrosive and poses serious risks to the skin, eyes, and respiratory system. Its reaction with fibers produces hydrochloric acid, which must be handled and disposed of as hazardous waste to prevent environmental damage.

Sheeba *et al.*[176] reported that benzoyl chloride treatment of *Acacia pennata* fibers improved tensile strength, thermal stability, modulus, microfibrillar angle, and elongation at break. These improvements depended on benzoyl chloride concentration, fiber loading, and immersion time. XRD and SEM confirmed higher crystallinity and smoother surfaces in treated fibers. Thamarai Selvi *et al.*[177] found similar benefits for *Agave americana* fibers treated with NaOH followed by benzoylation. The treatment reduced cellulose (3.49%), lignin (13.46%), and moisture content (11.61%), while increasing fiber strength (12.16 N mm) and thermal stability. Surface morphology also showed clear modification after treatment.

4.2.4 Silane treatment (SiH_4). Silanes are inorganic compounds with the formula Si_nH_{2n+2} and are closely related to silicon alkoxides. They are hydrophilic and contain functional groups attached to silicon. Silane treatment usually begins by dissolving an amine-based silane derivative in an acetone or alcohol solution. When natural fibers are immersed in this solution, they develop stronger interactions with polymer matrices than fibers treated only with alkali. This leads to improvements in thermal stability, flexural stiffness, tensile strength, and tensile modulus.[178] In this process, the alkoxysilane end of the coupling agent reacts with hydroxyl groups on natural fiber surfaces, while the opposite end bonds with the polymer, creating better adhesion and reducing water absorption.[153]

Silane coupling agents lower the number of cellulose hydroxyl groups at the interface. In the presence of water, alkoxy groups hydrolyze to form silanols. These silanols then bond with fiber hydroxyl groups, creating covalent linkages that strengthen the fiber surface. Fig. 9 presents the method of treatment of natural fibers by silane. Research[179] showed that silane modification of coconut fibers (GLYMO, VTMS, TEOS) increased interaction with a PLA matrix and raised PLA crystallinity from 48.95% to over 60%. Matykiewicz *et al.*[180] also reported that silane-treated composites using 3-chloropropylmethyldimethoxysilane and *N*-(2-aminoethyl)-3-aminopropyltrimethoxysilane improved impact strength and flexural modulus. Another study[181] found similar benefits in hemp fiber composites, including higher glass transition temperatures (79.9–90.8 °C), elastic moduli above 3400 MPa, and reduced water absorption (49% to 38%).

Silane performance depends on factors such as hydrolysis time, pH, temperature, and silane functionality. The treatment mechanism occurs in four stages: (a) hydrolysis of silane monomers to form silanols, (b) limited self-condensation of silanols to maintain reactivity, (c) adsorption of silanol monomers or oligomers onto fiber surfaces through hydrogen bonding, and (d) grafting at elevated temperatures, where hydrogen bonds convert into strong Si–O–C linkages with water released during condensation.[36]

4.2.5 Maleated coupling agents. A coupling agent acts as a bridge between the hydroxyl groups of natural fibers and the polymer matrix. It contains two reactive groups: one that bonds with cellulose –OH groups and another that reacts with the polymer. Maleic anhydride is particularly effective because it modifies both the fiber surface and the polypropylene (PP) matrix, resulting in stronger interfacial bonding and better mechanical performance. Maleic anhydride–grafted polypropylene, poly-diphenylmethane diisocyanate, and modified polyethylene are commonly used to enhance mechanical properties by improving adhesion and reducing water absorption. Frequently used coupling agents include isocyanates,[182] silanes,[183] and copolymer anhydrides such as PP grafted with maleic anhydride[184] and acetic anhydride.

Maleic anhydride reacts with fiber hydroxyl groups to form covalent ester bonds, which significantly strengthen the fiber–matrix interface. This strong chemical attachment improves load transfer from the polymer to the fibers, increasing tensile strength and modulus. Better adhesion also distributes applied stress more evenly throughout the composite, resulting in enhanced impact resistance.

4.3 Tribo-chemical mechanisms

Tribo-chemical mechanisms describe how chemical reactions and surface interactions during sliding affect friction and wear in natural fiber composites.[29] Chemical treatments such as alkali and silane increase the number of reactive hydroxyl or silanol groups on the fiber surface, which improves bonding with epoxy through covalent or hydrogen bonding. Stronger fiber–epoxy interfaces reduce fiber pull-out and create smoother load transfer during friction.[185] During sliding, treated fibers and epoxy can also form thin tribo-films made of polymer debris, oxidized material, or compacted cellulose fragments. These films act as protective layers that reduce direct contact and help lower friction.[186] Oxidative wear can occur at high temperatures or long sliding durations, causing degradation of lignin and epoxy, which produces more brittle wear debris. The chemistry of cellulose and lignin strongly affects friction behavior: cellulose-rich fibers tend to form stable, smooth tribo-layers that reduce friction, while lignin-rich surfaces generate harder, more brittle debris that increases roughness and friction.[29] Overall, tribo-chemical interactions, surface chemistry, and film formation play key roles in controlling friction, wear, and long-term performance of natural fiber composites (Fig. 10).[121]

5. Tribological behavior of epoxy-natural fiber reinforced composite

5.1 Single fiber reinforced epoxy composites

5.1.1 Leaf fibers. Leaf fibers are obtained from the long, stiff vascular bundles found in the leaves of monocot plants.[150] Common leaf fibers include sisal, abaca, pineapple leaf fiber (PALF), and agave fibers. These fibers usually contain high amounts of cellulose and lignin, making them strong, coarse, and highly durable.[187] Leaf fibers often show higher tensile

strength and stiffness than many seed and fruit fibers because of their thick cell walls and high microfibril alignment.[150,187] However, they are typically less flexible than bast fibers due to high elongation at break.[187] Their natural rigidity, moisture resistance, and abrasion strength make them suitable for rope, cordage, bio-composites, automotive parts, and structural panels.[187,188] Compared with stem fibers such as bamboo or banana, leaf fibers often provide better consistency and higher strength-to-weight ratio, but they may require more surface treatment to achieve strong bonding with polymers.[187]

5.1.1.1 Abaca. Abaca fiber, a relative of the banana plant, is useful for reinforcement in composites due its high mechanical properties.[189] After alkali treatment with 6% NaOH, the fiber's tensile strength is recorded at 762.36 MPa, with an elastic modulus of 42.58 GPa, and an elongation of 1.68%.[190] Additionally, the mechanical strength of fiber after NaOH treatment is improved obviously; tensile strength from 723.65 MPa grows to 762.36 MPa and elastic modulus from 31.24 MPa elevates to 42.58 MPa.[191]

The tribological and mechanical properties of abaca fiber–reinforced epoxy composites are highly sensitive to fiber content and chemical treatment.[189] For the best wear performance, composites with 20% fiber content exhibit the lowest wear rate and optimal wear resistance Fig. 11. The performance improves with increased fiber content up to 20%, after which it declines with higher content. SEM analysis further corroborates these findings, highlighting the importance of fiber pull-out and interfacial bonding in the overall wear resistance. For lower fiber contents (3%), wear rates are significantly reduced, making abaca fiber composites a viable option for applications requiring both strength and wear resistance.[190–192] The summarized data of tribological properties of abaca reinforced epoxy composite are listed at Table 3.

5.1.1.2 Pineapple. Pineapple leaf fiber is a natural fiber obtained from the leaves of the pineapple plant (*Ananas comosus*). The fiber is known for its strength and durability, making it an ideal material for composite applications. It is a sustainable and eco-friendly alternative to synthetic fibers, often used in textiles, bio-composites, and industrial products. Pineapple leaf fibers are so rich in cellulose, which contributes to their excellent mechanical properties, such as high tensile and flexural strength. Due to its natural origin, pineapple fiber is biodegradable and offers an environmentally friendly option for various industrial applications (Table 4).[31]

There is less research on pineapple fibers tribological behavior. The key findings from the tribological analysis of pineapple leaf fiber composites show that the fiber orientation significantly impacts the wear rate and friction properties. The lowest wear rate and optimal performance for both wear resistance and friction are achieved at a 90° fiber orientation. This orientation provides improved durability and mechanical properties. In contrast, the worst performance is observed at a 45° fiber orientation, where the wear rate is highest, and mechanical strength is reduced.[193]

5.1.1.3 Sisal. Sisal fiber, derived from the agave plant, shows improved mechanical and tribological properties when treated with sodium citrate and stearic acid (Table 5). These chemical treatments reduce surface impurities and enhance fiber–matrix adhesion, leading to significant improvements in wear resistance and friction. According to Venkatesh R. *et al.*[194] epoxy hybrid composite with effective incorporations of 20 wt% sisal fiber and 5 wt% of nano-size SiC recorded superior tensile and flexural, and fracture toughness of 62.5 MPa, 54 MPa, and 1.55 MPa. At 25 wt% fiber content, treated sisal composites exhibit the lowest wear rate and friction coefficient, with sodium citrate treatment showing the best performance.[195] Sisal composites with 30 wt% fiber content also demonstrate improved wear resistance, with wear rates decreasing by 43.07–40.57% compared to neat epoxy at various load conditions.[196] The tribological performance of sisal fiber composites are influenced by fiber content, load, sliding velocity, and distance. The wear rate increases with load, sliding velocity, and distance, indicating the importance of these factors in performance. Sisal composites fabricated with compression molding and coconut shell powder show enhanced mechanical properties, including

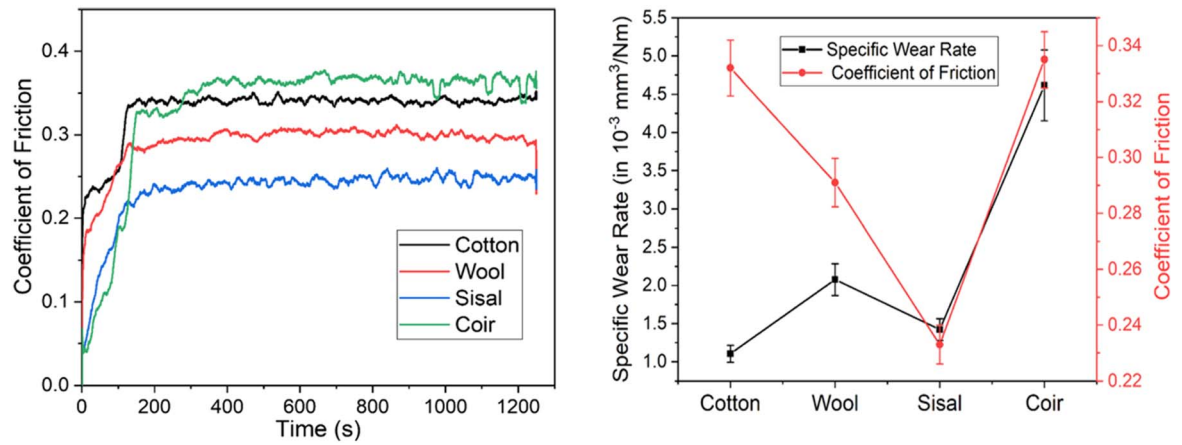

Fig. 12 Comparison of specific wear rate and coefficient of friction for some different fiber with sisal. Reproduced from ref. 20 with permission from Springer, Copyright 2024.

Table 6 Tribological properties of hemp fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Hemp	—	5% NaOH treated	2.5, 5, 7.5% and 10 wt% hemp filler	2.5 wt% filler: 0.20–0.25 (at 5 N load, 1000–3000 m); 5 wt% filler: 0.23–0.28 (at 5 N load, 1000–3000 m); 7.5 wt% filler: 0.25–0.30 (at 5 N load, 1000–3000 m)	—	Tensile strength: 2.5 wt% filler: 24.3 MPa 7.5 wt% filler: 38.2 MPa flexural strength: 2.5 wt% filler: 36.9 MPa 7.5 wt% filler: 59 MPa	2.5% and 7.5 wt% hemp filler composite has generated the minimum wear and better mechanical characterization; 2.5 wt% filler content provide best wear performance due to a homogeneous filler–matrix interface, while wear increases with higher filler loading due to particle agglomeration	204
Hemp fiber	—	2% NaOH solution for 24 h	5, 10, 15, 20 wt% fiber; fiber length of 1–5 mm	0.544 (5 wt% hemp fiber) to 0.389 (20 wt% hemp fiber)	5 wt% hemp fiber: 1.08 g wear, 20 wt% hemp fiber: 1.69 g wear	Density: Decreases with hemp fiber addition (2.53 g cm^{-3} to 2.21 g cm^{-3}). Porosity: Increases with fiber content	The 5 wt% hemp fiber demonstrates the best friction performance (0.544), superior fade resistance (30.33%), excellent friction stability (0.93), minimal wear (1.08 g), and the lowest friction variability (0.38)	205
Hemp powder	—	$KMnO_4$ for 3 min	5% hemp powder	500 rpm: 0.18–0.23 750 rpm: 0.19–0.25 1000 rpm: 0.20–0.26	—	Hardness: 45.4 ± 5.4 HV	- Wear increased with higher load, speed, and test time, highest at 30 N, 1000 rpm, 30 min - Friction coefficient was 0.18–0.26, lowest at 500 rpm. - High wear caused micro-cracks, delamination, and craters	206
Hemp	Carbon fiber	Pyrolysis at 1000 °C	2.5 wt%, 5 wt%, 7.5 wt%, 10 wt% HFB	0.23–0.30 (at 2.5 wt% HFB)	2.5 wt% HFB: 80% reduction compared to unfilled epoxy resin. 10 wt% HFB: 3.88 × 10^{-5} mm^3 N^{-1} m^{-1}	Storage modulus: 2310 MPa (at 10 wt% HFB) at 40 °C, flexural strength: 91.7 shore *D* (at 10 wt% HFB)	HFB reduced the wear rate by 80% and friction coefficient by 21% at 2.5 wt% HFB compared to unfilled epoxy. The electrical conductivity reached 6 mS m^{-1} at 10 wt% HFB. Adding HFB improved the thermal stability and mechanical properties, especially at higher loadings (5–10 wt%)	207
Hemp	Polyamide 1010 (PA1010)	Alkaline ($NaClO_2$) treatment, ureidosilane, epoxy resin (EP)	20 vol% fiber	0.19–0.24 ($NaClO_2$ + A-1160 + EP)	Specific wear rate: Reduced by 1/3 compared to $NaClO_2$ treatment	Tensile strength: Increased; bending modulus: +48% ($NaClO_2$ + A-1160 + EP)	Surface treatment with epoxy resin significantly improved wear rate and friction coefficient. The combination of $NaClO_2$ + A-1160 + EP enhanced fiber–matrix interaction, increasing bending modulus and specific wear rate by 48%	208

increased compression strength and improved wear resistance as fiber content increases (Fig. 12).[197]

5.1.2 Bast fibers. Bast fibers come from the inner bark (phloem) of dicot plant stems, making them one of the strongest natural fiber categories.[201] Typical bast fibers include jute, flax, hemp, kenaf, and ramie, all known for their high cellulose content, long fiber length, and superior tensile strength.[202,203] Bast fibers usually have excellent stiffness, moderate flexibility, and low density, giving them a very high reinforcement potential for polymer composites. Among all natural fiber groups, bast fibers are often considered to have the best mechanical performance, especially in tensile strength and modulus.[201–203] Their balanced combination of strength and flexibility makes them widely used in packaging, textiles, automotive interior parts, construction boards, and biodegradable composites.[188] Compared with leaf, fruit, and stem fibers, bast fibers typically offer the best fiber–matrix bonding performance after treatment because of their high cellulose purity and uniform microfibrillar structure.[201–203]

5.1.2.1 Hemp. Hemp fiber, derived from the *Cannabis sativa* plant, known for its good strength, durability, and versatility. It has been around for thousands of years in textiles, ropes, and numerous composite materials. Because of its sustainable nature, hemp fiber is becoming more widely used in green composites. Hemp fiber composites show improved wear resistance and friction performance with increasing fiber content and treatment. The incorporation of hemp fiber into the epoxy composites improves their wear properties and generally maximum effect occurs at 5 wt% fiber content. NaOH is treated and other treatments of chemical removal can improve the mechanical properties, wear resistance were significantly increased. In addition of fillers such as carbon or polyamide, increases the mechanical stability and wear resistance of the composites (Table 6).

Hemp fiber composites treated with 5% NaOH and reinforced with 2.5% or 7.5% hemp filler exhibit the minimum wear and superior mechanical characterization.[204] For composites with varying fiber content, 5 wt% hemp fiber shows the highest friction performance, the lowest wear, and the least friction variability, while 20 wt% fiber composites show a reduction in friction performance.[205] Hemp composites reinforced with carbon fiber or pyrolyzed at 1000 °C reduce wear rates by 80% and friction coefficients by 21%, improving thermal stability and mechanical properties.[207] For optimal wear resistance and friction performance, hemp fiber composites should be reinforced with 5 wt% hemp fiber, particularly for composites treated with NaOH. The addition of carbon fiber or pyrolysis at high temperatures offers significant improvements in wear resistance and thermal stability, making it ideal for applications requiring high mechanical properties. For composites using polyamide and $NaClO_2$ treatments, enhanced wear performance is achieved through better fiber–matrix interaction, which improves both wear rate and friction coefficient.[208]

5.1.2.2 Jute. Another common fiber of Asian subcontinent is jute. Jute fiber has a cellulose content ranging from 60–70%, with hemicellulose at 22.1% and lignin at 15.9%. It has a density of approximately 1.3–1.4 g cm^{-3} and a crystallinity index of 58%. Its mechanical properties include a tensile strength range of 187–800 MPa and an elongation at break of 1.3–3% [Table 2]. With a Young's modulus ranging from 3 to 55 GPa, jute fiber is considered to be a stiff and relatively strong natural fiber.

Jute fiber's tribological performance is influenced by factors such as fiber content, treatment processes, and filler materials.[30] For example, short jute fiber reinforced in epoxy resin exhibits a friction coefficient ranging from 0.0930 to 0.2700. The wear rate of jute composites varies between 1.81×10^{-5} (low fiber content at 144 cm s^{-1} velocity) and 2.84×10^{-5} (high fiber content at 144 cm s^{-1} velocity), with the wear rate decreasing at higher fiber content and velocity.[209] Alkali-treated jute fibers (25% fiber, 75% epoxy) show improved wear resistance with varying fiber orientations, with the best wear resistance observed at a 90° fiber orientation.[210] The wear rate increases with load, and the best performance is seen at a 10 N load.[211] Additionally, the introduction of nano fly ash as a filler (up to 3%) significantly improves wear resistance, with the lowest wear rate observed at 3% nano fly ash content.[212] The inclusion of TiO_2 as a filler also affects the wear performance of jute composites. Composites with TiO_2 show a significant increase in flexural strength, particularly at 2% TiO_2 content, and demonstrate the lowest wear rate at a 90° fiber orientation.[213] Similarly, the addition of SiC filler improves wear resistance, with the highest erosion rates observed at 60° and 75° angles.[214]

In summary, jute fiber composites perform best with a higher fiber content (30–40%) and are particularly sensitive to fiber orientation and filler material. Fiber loading and treatment methods, such as alkali treatment and the addition of fillers like nano fly ash and TiO_2, play significant roles in enhancing the wear resistance and mechanical properties of jute composites. These composites show potential for applications requiring moderate strength and wear resistance. The summarized data of tribological properties of jute reinforced epoxy composites are listed at Table 7.

5.1.2.3 Kenaf. Kenaf (*Hibiscus cannabinus*) is a fast-growing, renewable plant that has gained popularity as a source of natural fiber in various applications, including textiles, composites, and bioplastics.[38] Native to tropical and subtropical regions, kenaf is known for its high cellulose content and impressive mechanical properties, making it a suitable alternative to synthetic fibers. Moreover, Kenaf's fast growth cycle and ability to thrive in diverse climatic conditions make it an eco-friendly and sustainable resource.

Kenaf fiber composites exhibit strong mechanical properties, which improve with fiber loading. This fiber has also great tribological properties. There are many researches upon the fiber. From the common findings of the research it can be say that, the best wear performance is often achieved with 30–35% fiber content, especially in composites treated with NaOH. The addition of carbon nanotubes or silane coupling agents further enhances wear resistance and friction reduction. From other research, kenaf fiber composites treated with 6% NaOH and with 30–35% fiber content exhibit the best wear performance, particularly in normal orientation (N–O) composites, where wear resistance significantly improves.[218] When treated with

Table 7 Tribological properties of jute fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Short jute fiber	—	Reinforced in epoxy resin; hand lay-up technique	12–48% fiber, 52–88% epoxy	0.0930–0.2700	Wear rate varies between 1.81×10^{-5} (low fiber, 144 cm s^{-1} velocity) to 2.84×10^{-5} (high fiber, 144 cm s^{-1} velocity)	Improved tensile and flexural strength with increasing fiber content, especially at 36% fiber loading	Higher fiber content (36%) exhibited the lowest wear rate; wear rate increases at higher velocities; significant wear reduction observed at 90° fiber orientation	209
Jute fiber	—	Alkali-treated with 6% NaOH for 24 hours, air-dried, then fabricated using hand lay-up	25% jute fiber, 75% epoxy	—	Wear rate higher at 30 N load, lower with increasing fiber orientation	Increased wear resistance with parallel and anti-parallel fiber orientation	Fiber orientation significantly influences wear performance; best wear resistance in anti-parallel orientation	210
Jute fiber	—	Alkali-treated; hand lay-up with epoxy matrix	25 wt% jute fiber, 75 wt% epoxy	—	Wear rate increases with load; best performance at 10 N load	Friction force decreases at 10 N load for jute/epoxy; flexural and tensile strength better with jute reinforcement	Best performance for wear resistance and friction at 10 N load; jute/epoxy composites outperform hemp and flax composites; significant effect of applied load on friction force and wear rate	211
Jute fiber	—	Alkali-treated; hand lay-up method with epoxy resin	25% jute fiber, 75% epoxy	—	Wear rate decreases with increasing NWP content; lowest wear rate at 50 N load for D4 composite	Improved wear resistance with 10% NWP; highest wear rate in composite B2	As NWP content increases, wear rate decreases; D4 composite with 10% NWP has the lowest friction and wear rate, whereas B2 composite shows the highest wear rate at higher load	214
Jute fiber	—	—	20–40% fiber, 60–80% epoxy	0.0490–0.2110	Wear rate increases with fiber content; highest wear rate at 40% fiber loading	Higher tensile and flexural strength at 40% fiber loading; better wear resistance at 40% fiber	The erosion rate increases with fiber loading; peak erosion observed at 60° impingement angle; performance improved with 40% fiber loading	215
Jute fiber	Coconut shell powder 10%, calcium carbonate 2%, barium sulphate, Al_2O_3%, Gr 2%, antimony sulphate 1%	—	10–30 wt% jute fiber, 70–90 wt% epoxy	—	Wear rate increases with fiber content; higher at 10% fiber loading	Improved compression strength and hardness with increasing fiber content; higher strength at 30% fiber	Wear rate decreases with increased fiber content; specific wear rate decreases at higher fiber loading; best performance at 30% fiber loading	216

Table 7 (*Contd.*)

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Jute fiber	TiO2	Woven jute fiber reinforced with TiO_2 filler; epoxy resin matrix	20–40% fiber, 60–80% epoxy	—	Highest wear rate at 60° angle with TiO_2 filler at 5 N load	Flexural strength increased by 38.44% with 2% TiO_2 filler at 90° orientation	Erosion rate increases at 45° and 60° fiber orientations with TiO_2 filler; 90° fiber orientation shows the lowest wear rate	213
Jute fiber	SiC	Jute fiber reinforcement in epoxy with SiC filler; air jet erosion test	20–40% fiber, 60–80% epoxy, 10–20% SiC	—	Erosion rate increases at 60° and decreases at 75° with higher SiC content	Improved tensile and flexural strength with SiC addition	Maximum erosion at 60° angle for unfilled composites, and at 75° for SiC-filled composites; SiC content improves wear resistance	214
Jute fiber	TiO_2	Hand lay-up method; TiO_2 filler loading at 2.5%, 5%, 7.5%, and 10%	55 wt% jute fiber, 45–35 wt% epoxy, 2.5–10 wt% TiO_2 filler	—	Wear rate improves at 5 wt% TiO_2, 7.5 wt% TiO_2 composites show the highest tensile and flexural strength	Flexural and tensile strength increase with TiO_2 content up to 7.5%; 10 wt% TiO_2 filler reduces strength	The wear rate decreases with TiO_2 up to 5 wt%; the highest tensile and flexural properties found with 7.5 wt% TiO_2; wear rate is highest for unfilled composites and improves with TiO_2 content up to 5%	217
Jute fiber	Nano fly ash	Waste jute fiber; alkali treatment with 5% NaOH	25 wt% jute fiber, 75 wt% epoxy	0.40–0.49	Wear rate decreases with increasing nano fly ash content up to 3%	Best wear resistance observed with 3% nano fly ash filler	Nano fly ash improves the tribological properties; the highest wear resistance and lowest friction coefficient observed at 3% nano fly ash content; wear rate increases with load and sliding velocity	212

Table 8 Tribological properties of kenaf fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubri-cation	Surface roughness	Mechanical properties	Key findings	Reference
Kenaf fibre	—	Hand lay-up method	48 vol% fiber	0.52–0.68 (depending on orientation)	—	—	At normal orientation (N–O), $R_a = 0.72 \times 10 \times 10^{-6}$ m	Density: 850 ± 2 kg m^{-3}; modulus of elasticity: 14.5 ± 2 GPa; tensile strength: 135 ± 2 MPa; thermal conductivity, 0.11 W (m^{-1} K^{-1})	Kenaf fiber reinforced epoxy composite showed significant wear resistance improvement, especially in N–O (normal orientation) with an 85% improvement over neat epoxy. Friction coefficient decreased with fiber orientation, and wear was reduced under higher applied loads (50–100 N)	218
Kenaf fibre	—	Silane treatment	30 wt% fiber	0.44 (sample 2, bi-directional)	0.034 mg min^{-1} (10 N, 0.1 m s^{-1}) 0.041 mg min^{-1} (40 N, 0.7 m s^{-1})	—	—	Flexural strength: 59.61 MPa, tensile strength: 39.8 MPa	(70 wt% epoxy, 30 wt% kenaf) exhibited lower friction coefficient and wear rate compared to unidirectional composites. The bi-directional fiber orientation resulted in reduced flexural strength (59.61 MPa) compared to unidirectional orientation	200
Kenaf fibre	—	6% NaOH at 26 ± 2 °C for 48 h	30 wt%, 50 wt% and 70 wt% fiber	—	—	—	—	For 70%, 50% & 30% fiber, hardness 6.62, 6.57 & 6.21 (GPa); density 1.256, 1.245 & 1.186 g cm^{-3}; water absorption 60.4, 61.7 & 63.1% respectively	Higher fiber compositions in the KF/E composite led to improved wear performance, while an increase in temperature caused a reduction in the coefficient of friction (COF) and an increase in wear rate	22
Kenaf long fiber	—	Alkali treated, hand layup method	10, 20, 30, and 40 wt% fiber	—	—	—	—	—	The 30% wt fiber loading has best wear resistance both in adhesive and abrasive wear compared to rest of the composites	220

Table 8 (*Contd.*)

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubri-cation	Surface roughness	Mechanical properties	Key findings	Reference
Kenaf fiber	—	NaOH treatment (6%)	48 vol% fiber	0.03–0.045 (at wet contact conditions)	50 N load: High wear; 100 N load: Moderate wear; 200 N load: low wear (improved with higher load)	Wet contact	—	Density: 1.28 g cm^{-3} Flexural strength: 55 MPa Tensile strength: 40 MPa	- N–O kenaf composite improved wear by 35–57% over other orientations - Water reduced heat and debris, lowering friction - Composite is suitable to replace glass fiber in wet tribology	221
Kenaf	—	NaOH treatment (6%)	20% fiber	0.44 (5 N load) to 0.39 (20 N load)	5 N load: 1.0 mg min^{-1}; 20 N load: 1.1 mg min^{-1}; 30 N load: 1.3 mg min^{-1}	Dry sliding	Roughness decreased with wear	Density: 1.15 g cm^{-3}; flexural strength: 50 MPa	Kenaf epoxy composite showed higher wear rate compared to carbon fiber composites. Wear rate increased with applied load, with a 25% increase at 30 N load. The friction coefficient decreased with fiber loading. Surface roughness was observed to decrease due to cyclic deformation during wear	222
Kenaf	0.5 wt%, 0.75 wt%, 1 wt% multi walled carbon nanotubes	Acid treatment (H_2SO_4, HNO_3) and silane modification for MWCNT	—	PMWCNT 0.5 wt%: 0.47 PMWCNT 1 wt%: 0.44 SMWCNT 0.5 wt%: 0.39 SMWCNT 1 wt%: 0.38	- 0.5 wt% PMWCNT: 0.0004 mm^3 N^{-1} m^{-1} - 1 wt% PMWCNT: 0.0003 mm^3 N^{-1} m^{-1} - 0.5 wt% SMWCNT: 0.0002 mm^3 N^{-1} m^{-1} - 1 wt% SMWCNT: 0.0002 mm^3 N^{-1} m^{-1}	—	—	- Density: 1.14 g cm^{-3} (0.5 wt% PMWCNT), 1.12 g cm^{-3} (1 wt% PMWCNT) - Flexural strength: 65 MPa - Tensile strength: 52 MPa	- 1% PMWCNT composite showed the best wear resistance - Acid-treated MWCNT increased wear due to poor bonding - Silane improved dispersion but created rough debris, raising wear - Small debris formed a protective layer, reducing wear and friction	219

ilane, kenaf fiber composites show reduced wear and friction coefficients, especially in bi-directional orientations.[200] NaOH-treated composites with up to 70% fiber content show good mechanical properties, but higher fiber loading may increase wear due to fiber agglomeration.[22] The addition of carbon nanotubes improves wear resistance, with 1 wt% PMWCNT composites showing the best results.[219] The summarized data of tribological properties of kenaf reinforced epoxy composites are listed at Table 8.

5.1.3 Fruit/seed fibers. Fruit and seed fibers originate from the husk, shell, or seed hairs of fruits and seeds. Major examples include coconut coir (fruit husk), cotton (seed hair), and kapok (seed floss). These fibers often have lower stiffness and strength than bast and leaf fibers but offer unique properties such as high elasticity, excellent moisture resistance (coir), and very low density (kapok) 9. Cotton is soft and flexible with very high cellulose content, making it ideal for textiles but less suitable as a structural reinforcement. Coir, in contrast, contains more lignin, giving it excellent impact resistance and damping properties.[223] Fruit and seed fibers generally perform best in lightweight composites, cushioning materials, thermal and acoustic insulation, and impact-absorbing applications, but are rarely used for high-strength structural purposes.[224] Compared to stem and leaf fibers, fruit/seed fibers offer better thermal stability and resilience, but lower stiffness.[9,223]

5.1.3.1 Areca nut. Areca nut, commonly known as betelnut is a well-known fiber, is a significant agricultural resource in South and Southeast Asia with strong tribological relevance.[225] The areca nut fiber and areca sheath fiber has strong potential as a reinforcement material in polymer composites, particularly for low-strength applications, such as artistic furniture and automobile interiors.[4,26] Areca nut fiber is short length fiber but has a great impact resistance.[226] Treated with NaOH, betel nut fiber exhibits significant improvements in tensile, flexural strengths and hardness as fiber surface improvement makes.[227] Researches by Srinivasa C. V. showed that alkali (NaOH), or other treatments improve fiber–matrix bonding and mechanical properties.[80,228] In multi-layered composites, 10% NaOH-treated ALS-epoxy showed peak tensile strength of 20.51 MPa and flexural strength of 115.27 MPa.[228] Best wear performance is often achieved at 20–36% fiber loading, and excessive fiber content leads to a reduction in mechanical properties.[227,229] The tensile strength peaks with higher fiber content, demonstrating the fiber's contribution to the composite's structural integrity. The wear resistance also improves with higher fiber content (Fig. 13).[230]

Treated with 5% NaOH and processed using a hand lay-up method, areca-nut fiber exhibits improvements in tensile strength (20.20–28.5 MPa) and flexural strength (42.35 MPa) with increasing fiber content, peaking at 20%.[231] The material's

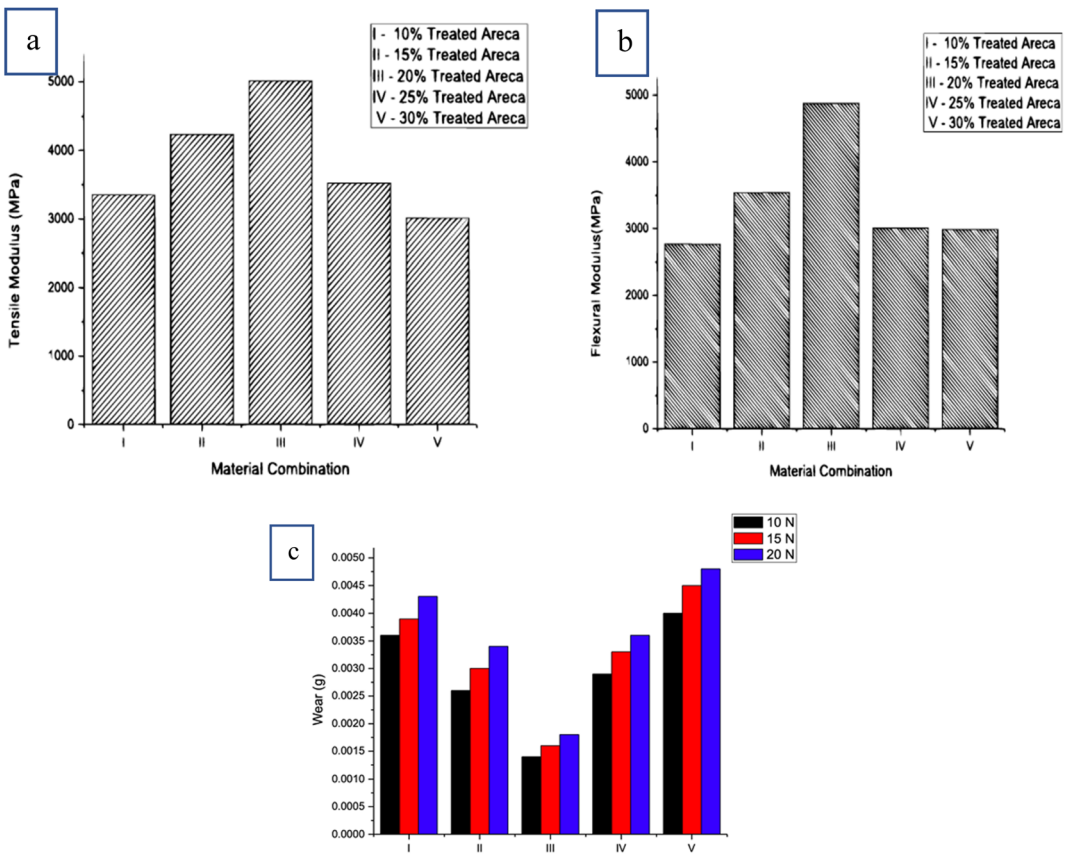

Fig. 13 Mechanical and tribological properties of various percentile loaded areca nut fiber composites. (a) Tensile properties, (b) flexural properties, (c) wear rate at different load. Reproduced from ref. 231 with permission from Elsevier, Copyright 2021.

Table 9 Tribological properties of betel nut fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Wear rate	Lubrication	Mechanical properties	Key findings	Reference
Areca sheath fiber (10 mm short fibers)	—	Untreated	0, 12, 24, 36, 48 wt% fiber content	Lowest wear rate at 36 wt% fiber and high sliding velocity ($\approx$1.2 m s^{-1})	Dry three-body abrasion (silica sand, no lubricant)	- Hardness (↑) with fiber content (max at 48 wt%) - Tensile & flexural strength (↓) with fiber content - Young's modulus & impact strength (↑) with fiber content	−36 wt% fiber gives optimal tribological performance - High velocity reduces wear; low load reduces wear - COF and wear strongly influenced by sliding velocity, fiber fraction, and abrasive size	229
Betel nut fiber	—	Alkali treatment (5% NaOH)	0%, 2%, 3%, 4%, 6%, 8% fiber content	5.92×10^{-3} mm^3 N^{-1} m^{-1}	Dry	Tensile strength: improved with fiber reinforcement; highest at 8 wt% fiber content Flexural strength: improved with fiber content	- The tensile and flexural strengths increase with fiber content up to 8 wt% - Wear resistance improves with the increase in fiber content - The wear rate is optimized for composite samples with 6% fiber content	230
Areca nut fiber	—	Alkali treatment, chopped fiber, hand lay-up method	0%, 5%, 10%, 15%, 20%, 25%, 30% fiber content	Wear rate decreases as fiber content increases, optimal wear performance at 20% fiber content	Dry	- Tensile strength: 20.20 MPa (for 10% treated fiber) - Flexural strength: 42.35 MPa	- Tensile strength and flexural strength improved with fiber content up to 20% fiber composition - Best wear performance observed at 20% fiber content - Excessive fiber content leads to reduced mechanical properties due to poor fiber–resin adhesion	231
Areca nut husk fiber	—	Alkali treatment (5% NaOH), chopped fibers; compression molding	10%, 15%, 20%, 25%, 30% fiber content	Wear rate decreases with 20% fiber content; increases beyond 20%	Dry	Tensile strength: 28.5 MPa Flexural strength: 42.35 MPa Impact strength: 3.34 kJ m^{-2}	- Composites with 20% fiber content have the best wear resistance - Tensile, flexural, and impact strength are highest with 20% fiber content - Increased fiber content improves wear resistance, but too much fiber (30%) reduces mechanical properties	227

Table 10 Tribological properties of coir fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Coir fiber	10% Al_2O_3	Hand lay-up technique; epoxy matrix; coir fiber reinforcement; Al_2O_3 filler	5–20 wt% coir fiber, 70–85 wt% epoxy	—	Varies with fiber content and length; higher at higher impact velocities (48–109 m s^{-1})	Fiber content and length significantly influence wear resistance. Composites with 12 mm fiber length show better resistance. Al_2O_3 filler enhances wear resistance	Al_2O_3-filled coir fiber composites show better wear resistance compared to unfilled composites, with best performance at 15 wt% fiber. Filler presence improves wear resistance, especially at high impact velocities and 75° impingement angle	235
Coir filler	—	Alkali-treated coir filler; epoxy resin matrix	2.5–12.5 wt% coir filler, 87.5–97.5 wt% epoxy	Varies with filler content; lowest at 2.5 wt% filler (0.25–0.48)	Higher wear rates at 10–12.5 wt% coir filler, best wear resistance at 5 wt% filler	Increased tensile strength at 2.5 wt% filler; max tensile modulus at 5 wt% filler	Best wear performance observed at 5 wt% coir filler; increased wear and COF at 10–12.5 wt% filler; volume loss decreases with increased sliding velocity; best tribological properties at 2.5–5 wt% filler	236
Coir fiber (white/brown)	—	Alkali treatment with 6% NaOH for 12 h; vacuum infusion	20 wt% coir fibers, 80 wt% epoxy	—	Wear rate for brown coir at 5 mm fiber length: 0.0703 g at 5 N, white coir: 0.0666 g at 5 N	Brown coir has higher tensile strength (123 MPa) *vs.* white coir (115 MPa); increased tensile strength post-alkali treatment (brown coir: 58 MPa increase, white coir: 36 MPa increase)	Brown coir has higher porosity (50.77%) and larger average pore diameter (0.2128 μm) than white coir (46.64%, 0.1163 μm); alkali treatment increases tensile strength and modulus, and improves interfacial interaction with epoxy matrix	237
Coir fiber	—	Alkali-treated coir fiber; epoxy resin matrix	5–25% coir fiber, 75–95% epoxy	—	Highest wear rate: 0.0695 at 10 mm fiber length, 10 N load; lowest wear rate: 0.012 at 15 mm fiber length, 5 N load	Increased tensile strength at 5% coir fiber; max tensile modulus at 5% coir fiber	Wear rate increases with higher coir fiber content; best performance at 5% coir fiber; highest wear rate at 10 mm fiber length and 10 N load; wear rate decreases with longer fiber lengths	238
Coir fiber	—	Alkali treatment and surface modification with 3-aminopropyltriethoxysilane; vacuum-assisted resin transfer molding (VARTM)	36% coir fiber, 64% epoxy	0.335	4.615 mm^3 N^{-1} m^{-1}	Tensile strength: 15.34 MPa; modulus of elasticity: 0.47 GPa	Highest wear rate among fibers tested due to coarse fiber nature; coir composite is less thermally conductive (0.187 W m^{-1} K^{-1}) but has high specific heat (26.313 MJ m^{-3} K^{-1}), suitable for insulation	20

Table 11 Tribological properties of bamboo fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubrication	Mechanical properties	Key findings	Reference
Bamboo fiber	—	Hydrolytic alkalization and multi-phase bleaching; epoxy resin matrix	25–35% bamboo fabric, 65–75% epoxy	0.4–0.5	Wear increases at higher applied loads and temperatures; lowest wear under lubricated conditions	Lubricated and dry conditions tested	Tensile and flexural strength improves with fiber orientation and resin impregnation	Wear rate is lower under lubricated conditions; fabric orientation significantly affects mechanical and tribological performance. Best wear resistance found at 0° and 90° orientations	241
Bamboo fiber	—	Alkali treatment; hand lay-up; post-curing	10–30% bamboo fiber, 70–90% epoxy	—	Wear rate increases with higher load and sliding distance	—	Tensile strength and flexural properties improve with fiber loading	- AP-O bamboo composite showed the best wear and friction performance - Wear improved by 60% and friction by 46.4% *vs.* neat epoxy - Fiber orientation strongly affected wear - AP-O also lowered interface temperature by 34.7%	240
Bamboo fiber	SiO_2	Silane coupling agent (KH550 and KH570), nano-SiO_2 surface modification	5–20% bamboo fiber, 3% SiO_2	—	Decreases as SiO_2 content increases, improved by 15 wt% bamboo fiber	—	Significant increase in tensile and flexural strength with SiO_2 content; highest impact strength at 15 wt% bamboo fiber	Wear resistance improves with increasing SiO_2 and bamboo fiber content; the maximum depth of the wear pit is shallowest with 15 wt% bamboo fiber and 3 wt% SiO_2 filler; improved erosion resistance with increased fiber and filler content	242
Bamboo fiber	Red mud	Alkali treatment; hand lay-up method; post-curing	10–20% bamboo fiber, 0–20% red mud	—	Wear rate improves with red mud content; highest wear at 20% red mud	No lubrication used in the experiments	Increased flexural strength with red mud; improved hardness and tensile modulus at 10–20% red mud	Erosion wear resistance improves significantly with red mud addition; the wear rate decreases with increasing red mud content; highest wear resistance at 10–20% red mud content	243

Table 11 (*Contd.*)

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Lubrication	Mechanical properties	Key findings	Reference
Bamboo fiber	—	NaOH treatment; silane coupling agent KH550 and KH560; epoxy resin matrix	30–35% bamboo fiber, 65–70% epoxy	—	Wear rate improves with increased bamboo fiber content	—	Increased tensile, flexural, and impact strength with surface modification of fibers	Improved wear resistance and mechanical properties observed with the surface modification of bamboo fibers; the composites show good impact strength and toughness when treated with coupling agents KH550 and KH560	244
Bamboo fiber	SiC	Hand lay-up technique; SiC filler mixed with epoxy resin	50 wt% bamboo fiber, 0–20% SiC	—	Wear rate improves with increasing SiC filler content	—	Flexural strength increases with 10 wt% SiC; maximum tensile strength at 10 wt% SiC	Erosion resistance improves with SiC filler; wear rate decreases as SiC content increases; maximum erosion resistance at 10 wt% SiC; impact strength improves at 10 wt% filler	245
Bamboo fiber	Bamboo dust	Alkali treatment, resin transfer molding (RTM), post-curing	30–35% bamboo fiber, 65–70% epoxy	0.1609	0.00073 mm^3 N^{-1} m^{-1}	—	Density: 1.375 g cm^{-3}, void content: 0.22%; specific tensile strength improved with filler content	Excellent wear resistance with low friction coefficient; wear rate remains low at higher applied loads and velocities. The composite exhibits improved toughness and mechanical properties with bamboo dust	246

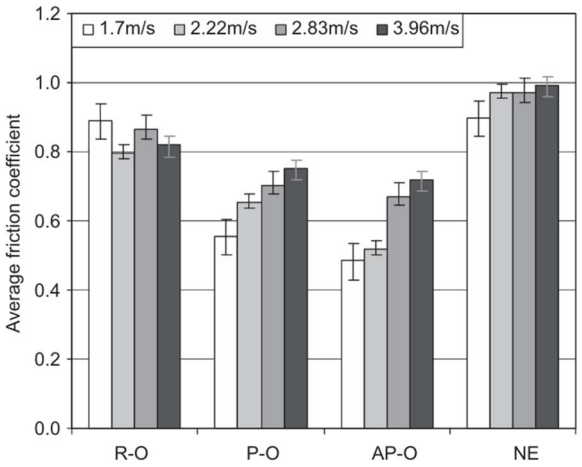

Fig. 14 Average friction coefficient for the three different bamboo fibre orientations (R, P and AP) and neat epoxy (NE) at 30 N of normal load at different counter face sliding velocities. Reproduced from ref. 240 with permission from Elsevier, Copyright 2012.

limitations, such as potential degradation temperatures around 200 °C, necessitate chemical modification.[225] The summarized data of tribological properties of betel nut reinforced epoxy composites are listed at Table 9.

5.1.3.2 Coir. Coir is classified as a cellulose-based natural vegetable fiber.[232,233] It offers several advantages, including high strength, significant strain at break, medical safety, and availability, all of which contribute to its low cost (approximately 0.50 USD per kg).[234] The chemical composition of coir consists of 43–53 wt% cellulose, 14.7 wt% hemicellulose, and 38–40 wt% lignin, contributing to its unique structural characteristics. With a density of 1.2 g cm^{-3} and a crystallinity index of 44%, coir exhibits a relatively high degree of rigidity compared to other natural fibers, which supports its use in composite materials Table 2. In terms of mechanical properties, coir fiber demonstrates a tensile strength range of 106–304 MPa, elongation at break between 15 and 47%, and a Young's modulus ranging from 3 to 6 GPa. These properties indicate that coir has moderate strength and flexibility, making it suitable for applications where durability and stiffness are required, particularly in composite materials.

The key findings from the tribological studies on coir fiber composites highlight the significant role of fiber content, length, and treatment processes in influencing wear resistance and mechanical performance Table 10. Coir fiber composites reinforced with 10% Al_2O_3 filler show enhanced wear resistance, especially at higher impact velocities, with the best performance observed at a fiber length of 12 mm. This suggests that the combination of coir fiber with Al_2O_3 filler offers a promising solution for improving the durability of the composite under dynamic conditions.[235] In terms of filler content, alkali-treated coir fibers demonstrate the best wear resistance at 5 wt% filler, although higher filler content (10–12.5 wt%) results in increased wear rates. This indicates that the fiber–matrix interaction and filler content play crucial roles in optimizing wear properties. Additionally, the tensile strength of the composites improves with alkali treatment, with brown coir exhibiting a more significant increase in strength compared to white coir.[236,237]

From a performance standpoint, coir composites containing 5–25% fiber content yield the best results, particularly at 5% fiber, where wear resistance is optimized. Interestingly, wear rates decrease as fiber lengths increase, suggesting that longer fibers improve the composite's durability. On the other hand, coir composites with high fiber content (36%) show a significantly higher wear rate due to the coarse nature of the fiber, yet these composites are advantageous in thermal insulation applications due to their low thermal conductivity.[20,238]

5.1.4 Stem fibers. Stem fibers come from the structural tissues of plant stems, especially from monocot species that do not produce true bast fibers.[38] Well-known stem fibers include bamboo culm fibers, banana pseudo-stem fibers, rice straw fibers, and rattan fibers.[146] These fibers are made of vascular bundles surrounded by parenchyma, resulting in variable mechanical properties depending on plant species and growing conditions. Many stem fibers have high stiffness and good rigidity, especially bamboo. This is one of the stiffest natural fibers due to its high silica and cellulose content.[146] Banana and straw fibers tend to be less stiff but more flexible, which make them suitable for lightweight or semi-structural composites. Stem fibers generally perform better than fruit/seed fibers in terms of strength and modulus but are less uniform and less flexible than bast fibers. They are often used in construction

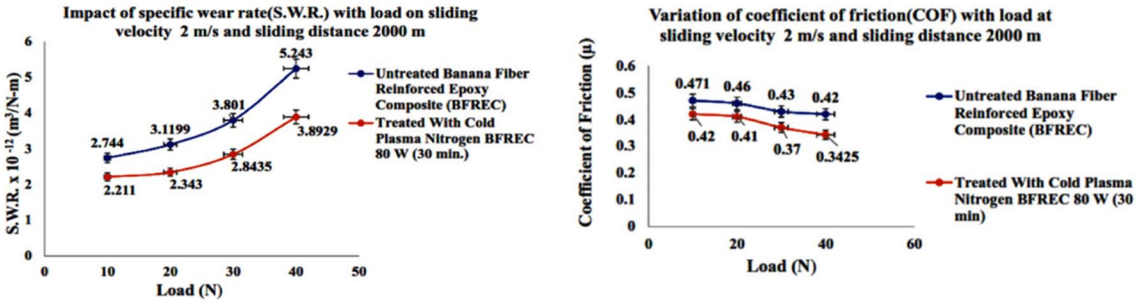

Fig. 15 Variation of specific wear rate and COF with load (N) on 2 m s^{-1} and S.D. 2000 m for untreated banana fiber reinforced epoxy composites (BFREC) and low-pressure N_2-modified BFREC. Reproduced from ref. 118 with permission from Elsevier, Copyright 2025.

Table 12 Tribological properties of banana fiber reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Surface roughness	Mechanical properties	Key findings	Reference
Banana fiber	—	Alkali treatment (5% NaOH); compression molding	10%, 15%, 20%, 25% fiber content	0.0121 at 30 N, 3.96 m s^{-1} sliding speed	Best wear resistance observed at 25% fiber content; lowest wear rate	—	Tensile strength: Increased with fiber content; flexural strength: Increased with fiber content	- The lowest wear rate and friction coefficient (0.0121) were observed at 25% fiber content in anti-parallel orientation (AP-O) - Wear resistance improved by 29.4% and friction coefficient decreased by 48.9% compared to neat epoxy - SEM analysis showed minimal fiber pull-out and improved wear morphology at 25% fiber content	23
Banana fiber	—	Low-pressure nitrogen treatment (80 W, 0.5 h)	30% fiber content	0.429–0.468 (depending on load and velocity)	Wear rate reduced by 24.10–43.14% for treated samples	—	Tensile strength: 24.58 MPa; flexural strength: 35.21 MPa	- Wear rate decreased significantly with nitrogen treatment (up to 43.14% reduction) - Friction coefficient was lowered by up to 26.47% with treated samples - Best wear performance at 30% fiber content with significant improvement in surface morphology (SEM shows minimal fiber pull-out)	248
Banana fiber	—	Treatment not mentioned; hand lay-up; compression molding		—	Wear is lowest at 90° orientation. Wear increases by 235% at 20 N and 2801% at 50 N from 0° to 90° orientation	—	Tensile strength: 23.79 MPa at 0° orientation; flexural strength: 42.35 MPa at 0° orientation; impact strength: 9.89 kJ m^{-2}	- Tensile strength decreases from 23.79 MPa (0°) to 7.58 MPa (90°) - Wear is more at 0° orientation due to higher fiber contact and tensile stress - Wear increases by 235% at 20 N load and 2801% at 50 N load when transitioning from 0° to 90° orientation	247

Table 12 (*Contd.*)

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Surface roughness	Mechanical properties	Key findings	Reference
								- Young's modulus decreases from 851.4 MPa at 0° to 424.9 MPa at 90° orientation	
Banana fiber	Nano-clay	Nano-clay infusion; alkali treatment (5% NaOH); compression molding	20%, 40%, 60% fiber content	20 wt% NC-BF: 0.468 at 10 N40 wt% NC-BF: 0.445 at 20 N60 wt% NC-BF: 0.42 at 30 N	20 wt% NC-BF: improved by 40–50% compared to UT-BF	- Before (AP): R_a = 0.578 μm	**Hardness**	- Nano-clay-infused banana fiber composites exhibit better wear resistance than untreated fiber composites	249
						- After (AP): R_a = 1.122 μm	- 49 ± 1 HB (20 wt% NC-BF)	- Friction coefficient decreases with increasing fiber content	
						- Before (P): R_a = 0.386 μm	- 56 ± 1 HB (40 wt% NC-BF)	- A transfer layer improves wear resistance, with the lowest wear rate observed in 20 wt% NC-BF composites	
						- After (P): R_a = 0.677 μm	- 60 ± 2 HB (60 wt% NC-BF)	- Improved hardness and braking performance with nano-clay infusion	
						- Before (NE): R_a = 0.126 μm - After (NE): R_a = 0.221 μm	**Braking performance** - NC-BF 20 wt%: deceleration = 1.9 m s^{-1} - NC-BF 40 wt%: deceleration = 1.9 m s^{-1} - NC-BF 60 wt%: deceleration = 2.1 m s^{-1}		

Table 13 Tribological properties of palm fiber reinforced epoxy composites

Fiber	Filler with fiber	Fiber treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Date palm fibre	—	6% NaOH, 26 ± 2 °C for 48 h	30%, 50%, 70% fiber	—	—	—	- Hardness, density, and water absorption decreased as fiber content decreased - Higher temperature lowered friction but increased wear - OPF/E showed lower wear than KF/E at high temperatures	22
Date palm	—	Washed with tap water (2% detergent solution), treated with 6 wt% sodium hydroxide (NaOH) for 24 h	35% fiber	0.51	1.9×10^{-5} mm^3 N^{-1} m^{-1}	Tensile strength: 67 MPa Elastic modulus, $E = 1.38$ GPa	The inclusion of date palm fiber improved the wear and frictional properties of the epoxy composites	250
Date palm	Graphite wt 3%	Washed with tap water (2% detergent solution), treated with 6 wt% sodium hydroxide (NaOH) for 24 h	35% fiber	0.47	1.35×10^{-5} mm^3 N^{-1} m^{-1}	Tensile strength: 63 MPa Elastic modulus, $E = 1.29$ GPa	Additionally, incorporating 3 wt% of graphite into the date fiber/epoxy composites enhances their performance	250
Palm kernel fiber	Carbon	—	70 wt%; (size ≤ 1 mm)	At 27 °C = 0.21–0.24; at 90 °C = 0.30–0.34; at 150 °C = 0.55–0.74	For sliding speed 2.7 m s^{-1}; load 49 N; at 27 °C: (0.05–0.085 × 10^{-5} mm^3 N^{-1} mm^{-1}); at 90 °C: (0.08–0.14 × 10^{-5} mm^3 N^{-1} mm^{-1}); at 150 °C: (0.2–0.395 × 10^{-5} mm^3 N^{-1} mm^{-1})	Hardness 8.8 (GPa); density 1.35 g cm^{-3}; porosity 1.21%	The coefficient of friction (COF) shows no significant change with sliding distance. Palm kernel activated carbon–epoxy (PKAC–E) is considered a highly potential self-lubricating material for use at temperatures below 90 °C	251
Palm kernel	Carbon	—	60 wt% carbon + fiber	—	—	Young modulus, $E = 7.61$ GPa; hardness, $H = 8.36$ GPa	-Friction and wear rose sharply with higher pressure -High speed (500 rpm) reduced wear through self-lubrication -Pressure caused severe wear; speed improved performance -Mild wear showed cracks; severe wear showed delamination -Activated carbon–epoxy had better wear resistance	253

Table 13 (*Contd.*)

Fiber	Filler with fiber	Fiber treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Palm (bunches fiber)	Carbon, barium sulfate, silica, metallic powders and phenol formaldehyde	—	10–25%; fiber length less than 5 mm	0.56	The wear resistance of composites containing bunch fibers and aluminum was the lowest compared to composites with corn and bunch fibers	—	The highest friction values were observed with 25 wt% bunch fibers and 20 wt% aluminum. Copper particles slightly improved the friction coefficient, with the highest value (0.56) at 30 wt% copper and 25 wt% bunch fibers	252

boards, particle composites, packaging, furniture, and medium-strength polymer composites.[188] Compared with leaf fibers, stem fibers show greater variability but often provide better specific strength-to-density ratios in properly processed composites.[146,239]

5.1.4.1 Bamboo. Bamboo is a fast-growing, renewable plant which is well known for its strength, flexibility, and sustainability. It has been used for centuries in various applications, from construction and furniture to textiles. Bamboo fibers from the bamboo stem are currently applied in composites as a natural reinforcement material owing to their high mechanical properties and environmental friendliness. Bamboo fiber composites present a sustainable option to the hazardous synthetic materials, since bamboo is widespread everywhere, it is biodegradable and has low carbon footprints. In composite material research, bamboo fiber show improved wear resistance and reduced friction when treated with chemical treatments like alkali treatment or surface modifications [Table 11]. With addition of fillers such as red mud, SiC, or carbon, the mechanical properties like tensile and flexural strength with wear resistance improving as fiber content and filler concentration increase.[32] The fiber orientation also has very significant effect on performance, different orientations of fibers exhibit the enhanced wear and friction performance like anti-parallel orientations (AP-O) (Fig. 14).[240]

Composites with a bamboo fiber content of approximately 30–35% are found to exhibit the most efficient wear performance, particularly when they are treated utilizing anti-parallel orientations.[240] Addition of SiO_2 increases wear resistance and tensile & flexural strength.[242] The addition of red mud improves the wear resistance and bender strength, with optimal performance obtained at 10–20% red mud incorporation.[243] Furthermore, bamboo composites reinforced with SiC fillers show improved wear resistance, especially at 10 wt% SiC content.[245] The summarized data of tribological properties of bamboo reinforced epoxy composites are listed at Table 11.

5.1.4.2 Banana. Banana fiber, derived from the banana plant, is known for its high tensile and flexural strength, making it an ideal material for reinforcement in composite applications. After alkali treatment with 5% NaOH, banana fiber shows an increase in tensile strength and flexural strength with higher fiber content. The tensile strength and flexural strength increase with higher fiber content, with a tensile strength of 23.79 MPa at 0° orientation and 7.58 MPa at 90° orientation, showing reduced mechanical strength at the 90° position due to increased fiber contact and tensile stress (Fig. 15).[247]

The tribological properties of banana fiber composites depend on fiber content, orientation, and treatment processes. The lowest wear rate and friction coefficient (0.0121) are observed at 25% fiber content in anti-parallel orientation (AP-O), where wear resistance improves by 29.4%, and the friction coefficient decreases by 48.9% compared to neat epoxy.[23] Nitrogen treatment significantly reduces wear rate (4%) and friction coefficient (up to 26.47%) at 30% fiber content, with SEM analysis showing improved surface morphology and minimal fiber pull-out.[248] The wear rate increases by 235% at

Table 14 Tribological properties of rice husk reinforced epoxy composites

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Surface roughness	Mechanical properties	Key findings	Reference
Rice husk	—	Benzoylation treatment	(5, 10, 15, 20 wt%)	—	—	—	—	Rice husk fiber improves wear resistance in epoxy composites, with 10 wt% fiber showing the best wear performance. Benzoylation treatment improves fiber compatibility with the matrix, reducing friction coefficient and wear rate. Higher fiber loadings beyond 10 wt% lead to agglomeration and increased wear	254
Rice husk char	—	Carbonization (850 °C, 900 °C, 950 °C)	10, 20, 30 and 40 wt% fiber	0.65 for 10%; 0.75 for 20%; 0.82 for 30%; 0.89 for 40% at 15 N applied normal load, 0.62832 m s^{-1} sliding velocity, temperature 950C	-	—	—	The wear rate decreases with increasing fiber content up to 30 wt%, beyond which it increases due to insufficient fiber–matrix interaction. 950 °C carbonization temperature produced the best wear performance, with lower wear rates and improved tribological properties	255
Rice husk ash	—	Functionalization with orange juice, alkaline treatment	0 & 2 wt% ash	Epoxy-0 wt% RHAnp: 0.40 Epoxy-2 wt% RHAnp: 0.35 Epoxy-2 wt% modified RHAnp: 0.05	- Epoxy-0 wt% RHAnp: 0.000576 mm^3 m^{-1} - Epoxy-2 wt% RHAnp: 0.000345 mm^3 m^{-1} - Epoxy-2 wt% modified RHAnp: 0.000189 mm^3 m^{-1}	78.07% reduction in surface roughness with 2 wt% P-A-RHAnp	-	- Coating thickness increased by 70.23% with 2% modified RHAnp - Surface roughness decreased by 78.07% - Hardness and adhesion increased by 68.12% and 72.06% - Wear resistance improved by 67.19% - Modified RHAnp greatly enhanced adhesion and wear performance	256

Table 14 (*Contd.*)

Fiber	Filler with fiber	Treatment process	Fiber–epoxy ratio	Friction co-efficient	Wear rate	Surface roughness	Mechanical properties	Key findings	Reference
Rice husk	Al_2O_3, and Fe_2O_3	Hand layup method	Rice husk, Al_2O_3, and Fe_2O_3, 20 wt%, 15 wt%, and 15 wt% respectively	-	8.665×10^{-7} mm^2 kg^{-1}	-	Density, hardness, flexural strength, and flexural modulus were 1.23 g cm^{-3}, 81.2 Vickers (HV), 57.24 MPa, and 4.08 GPa respectively	- BP-6 had the best overall performance - It showed the highest density, hardness, and flexural strength - Friction decreased with more rice husk and ceramics - Wear rate dropped by 4% *vs.* BP-1 - Thermal stability improved, highest in BP-6	257

a 20 N load and 2801% at a 50 N load when transitioning from 0° to 90° orientation.[247] The addition of nano-clay improves wear resistance, reduces friction, and enhances the mechanical properties, with the lowest wear rate observed in 20 wt% NC-BF composites.[249] In summary, for the best wear resistance and friction performance, 25% fiber content in anti-parallel orientation is recommended. Nitrogen treatment improves wear performance at 30% fiber content, while nano-clay infusion enhances wear resistance and mechanical properties, especially in 20 wt% NC-BF composites. The summarized data of tribological properties of banana reinforced epoxy composites are listed at Table 12.

5.1.4.3 Palm. Palm fiber, obtained from the palm tree, is a natural fiber widely used in composite materials due to its strength, durability, and environmental sustainability. It comes from different parts of the palm tree, such as date palm, palm kernel, and palm bunch fibers. Palm fiber composites demonstrate improved wear resistance and friction properties when treated with NaOH or infused with graphite or carbon. The addition of graphite and activated carbon has a significant impact on enhancing the wear and friction properties of date palm and palm kernel fiber composites. Moreover, increasing fiber content typically leads to improved mechanical properties, although it may also result in higher wear rates under certain conditions.

In terms of key findings, date palm fiber composites show improved wear rate and friction coefficient with the addition of fiber, especially when 3% graphite is incorporated, which further enhances wear properties.[250] For palm kernel fiber composites, particularly those with activated carbon, there is no significant effect on the coefficient of friction at temperatures below 90 °C, but they have great potential as self-lubricating materials.[251] Palm bunch fiber composites exhibit the highest friction at 25 wt% bunches and 20 wt% aluminum, with slight improvements in friction when copper is included.[252]

Based on the data, for optimal performance in wear resistance and friction, date palm fiber composites with 35% fiber content and the addition of 3% graphite should be considered. Palm kernel composites with activated carbon show promise as self-lubricating materials, especially in environments below 90 °C. For palm bunch fiber composites, increasing fiber content improves strength; however, careful selection of filler materials is crucial to maintain a balance between wear performance and friction. The summarized data of tribological properties of palm reinforced epoxy composites are listed at Table 13.

5.1.5 Other filler

5.1.5.1 Rice husk. Rice husk fiber as an agricultural waste obtained from the husk of rice during milling and it is a natural fiber. However, owing to its high cellulose content, eco-friendliness and availability rice husk is finding utility in the reinforcement material of composites applications.[226] With the help of different treatment techniques such as benzoylation, carbonization and functionalization, mechanical properties of fiber can be improved which helps to increase its overall alignment with matrix materials and eventually results in advance wear resistance, strength and friction performance. With the incorporation of rice husk, epoxy composites show an

Table 15 Tribological properties of jute/banana/epoxy hybrid composite

Fiber	Filler with fiber	Treatment process & fabrication method	Jute/Banana/Epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Jute/banana	Molybdenum disulphide (weight fractions of 5%, 10% and 15%)	—	—	—	For S5 (5%): 2.486 × 10–3 $mm^3\ N^{-1}\ m^{-1}$; for S10 (10%): 2.206 × 10–3 $mm^3\ N^{-1}\ m^{-1}$; for S15 (15%): 1.785 × 10^{-3} $mm^3\ N^{-1}\ m^{-1}$	The tensile modulus of S5 and S10 composites was 1183 MPa and 1971 MPa, respectively. The S15 composite had a tensile modulus of 2293 MPa, showing a 41.28% increase compared to the no filler (SN) hybrid composite	Among all the composites, the S15 composite showed the lowest abrasion loss of 0.2729 g, which is 31.62% lower than that of the SN composite. This suggests that incorporating molybdenum sulphide into the resin matrix significantly improved the wear resistance of the composites	258
Jute/banana	—	—	30 wt% banana pseudo stem fiber (BPSF) + 20 wt% jute fiber (JF) + 50 wt% epoxy resin (C1); 30 wt% BPSF + 30 wt% JF + 40 wt% epoxy resin (C2); 30 wt% BPSF +10 wt% JF + 60 wt% epoxy resin (C3)	—	C1: 0.003 mg min^{-1} (at 10 N, 0.5 m s^{-1}) C3: 0.004 mg min^{-1} (at 10 N, 0.5 m s^{-1})	**Flexural strength** C1: 69.66 MPa C2: 73.66 MPa C3: 68.82 MPa **Tensile strength** C1: 24.28 MPa C2: 27.02 MPa C3: 22.88 MPa **Impact strength** C1: 2.40 joules C2: 4.56 joules C3: 2.17 joules	The C2 composite exhibited the best mechanical performance with highest flexural strength and impact resistance. The wear rate was the lowest for this composition at 10 N load, and the composite exhibited balanced properties for wear, impact, and mechanical strength	260
Jute/banana hybrid	—	Hand lay-up method, epoxy resin (LY-556), hardener HY-951	EP8 (8 wt% jute + banana) EP16 (16 wt% jute + banana) EP24 (24 wt% jute + banana) EP32 (32 wt% jute + banana)	EP8: 0.45 EP16: 0.42 EP24: 0.40 EP32: 0.38	EP8: 35 mm^3 EP16: 32 mm^3 EP24: 48 mm^3 EP32: 40 mm^3 (under 180 grit SiC)	Density: 1.16 g cm^{-3} (EP16) Tensile strength: 98 MPa (EP16) Flexural strength: 130 MPa (EP16)	- EP16 (16% jute–banana) showed the highest wear resistance - Wear volume reduced by 56% *vs.* neat epoxy - EP8 performed better than EP24 and EP32 - High fiber content caused agglomeration and reduced wear resistance	259

Table 16 Tribological properties of jute/coir/epoxy hybrid composite

Fiber	Filler with fiber	Treatment process	Jute/Coir/Epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Jute/ Coconut coir	Graphite (0–5%)	NaOH treatment for jute, graphite nano-powder, mechanical interlocking	75% jute, 20% coir	Sample 4 (75% jute, 20% coir, 5% graphite): 0.043	Sample 4: 0.043 cm^3 (40 N, 0.25 m s^{-1}); sample 1 (no graphite): 0.049 cm^3 (40 N, 0.25 m s^{-1})	Tensile strength: 51.69 MPa (sample 4) Hardness: 27.41 ± 0.99 Hv (sample 4)	- Sample 4 (75% jute, 20% coir, 5% graphite) showed the lowest wear - Wear reduced by 12% compared to sample 1 - Tensile strength increased by 44.5% - Flexural strength increased by 25.55% - Graphite improved hardness and tribological behavior - Composite is suitable for automotive parts	27

increased wear resistance performance with high value usually obtained at 10–30% fiber content. Incorporation of carbon or ceramic fillers with rice husk fiber, this adds a higher mechanical stability and wear resistance. In combination with functionalization as stated RHAnp provides a pronounced effect on surface properties and abrasion resistance on composites (Table 14).

For rice husk fiber composites, the benzoylation treatment reduces friction and wear rates, with 10 wt% fiber showing the best performance. Carbonization at 950 °C produces the best wear performance, with lower wear rates and improved tribological properties at fiber contents up to 30 wt%.[254,255] The addition of 2 wt% modified RHAnp significantly reduces surface roughness by 78.07%, while improving hardness and wear resistance.[256] When combined with Al_2O_3 and Fe_2O_3 fillers, rice husk fiber composites show improved thermal stability and wear resistance, with a reduced wear rate of 4% compared to pure epoxy.[257]

5.2 Natural fiber reinforced epoxy hybrid composites

5.2.1 Jute/banana fiber reinforced epoxy composites. Jute and banana fibers are natural fibers known for their sustainability, low cost, and strong mechanical properties. These fibers are increasingly used in composite materials, particularly in combination with epoxy resins, to create hybrid composites that offer superior performance compared to individual fibers. Hybrid composites take advantage of the unique properties of each fiber, enhancing the overall mechanical strength, wear resistance, and environmental benefits.[39] Jute and banana fibers, when combined in varying ratios with epoxy, create composites with improved properties for diverse applications, including automotive and construction materials. For optimal wear resistance and friction performance, jute/banana hybrid composites with 15–20% fiber content, particularly with molybdenum disulfide fillers, should be used.[258] These composites show the best balance of wear resistance, friction, and mechanical strength, especially with fiber orientations such as AP-O. Additionally, composites with 16 wt% jute and banana fibers (EP16) provide superior performance, making them suitable for applications requiring high durability and wear resistance.[259] The summarized data of tribological properties of jute/banana fiber reinforced epoxy composites are listed at Table 15.

5.2.2 Jute/coir fiber reinforced epoxy composites. The widely used natural fibers: jute & coconut coir have good mechanical properties and sustainability. Jute: a natural bast fiber derived from the *Corchorus* plant that is strong and 100% biodegradable. Coconut coir: a natural fiber extracted from the husk of coconuts which is known for its toughness and elasticity. Combining with epoxy resin, these fibers form hybrid composites that offer a balance of strength, stiffness, and environmental friendliness. It presents that 75% of jute/20% of coconut coir and 3% graphite is an ideal combination for better wear resistance and friction performance when reinforced with epoxy as a hybrid composite. It offers the best mechanical and tribological performance for that matter.[27] Tribological

Table 17 Tribological properties of jute/glass/epoxy hybrid composite

Fiber	Filler with fiber	Treatment process	Jute/Glass/Epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Jute-glass hybrid	—	Hand lay-up, NaOH treated fibers	80% jute/20% glass; 60% jute/40% glass; 40% jute/60% glass	S1 (80% jute, 20% glass): 0.46 S2 (40% jute, 60% glass): 0.42 S3 (60% jute, 40% glass): 0.45	S1: 0.016 $mm^3\ g^{-1}$ (10 N load, 2.5 m s^{-1}) S2: 0.012 $mm^3\ g^{-1}$ (10 N load, 2.5 m s^{-1}) S3: 0.015 $mm^3\ g^{-1}$ (10 N load, 2.5 m s^{-1})	—	S2 composite (40% jute, 60% glass) showed higher wear resistance compared to S1 (80% jute, 20% glass) and S3 (60% jute, 40% glass). The stacking sequence significantly impacted the wear rate, with S2 offering best performance due to higher glass fiber content	261
Glass/jute hybrid	Sawdust, SiC; filler 0–9% varied	—	50% glass, 50% jute	Glass/Jute (0% filler): 0.55 (at 2 m s^{-1}, 20 N) SiC filler (9%): 0.41 (at 4 m s^{-1}, 35 N) Sawdust filler (9%): 0.46 (at 3 m s^{-1}, 30 N)	—	Flexural strength: 90 MPa (for 9% SiC filler) Tensile strength: 60 MPa (for 9% SiC filler)	- Sawdust-filled composite had the lowest wear (2.1 mg) *vs.* unfilled (3.5 mg) - SiC fillers showed the best wear and lowest friction - Friction decreased with higher filler; lowest at 9% SiC - Water absorption increased with filler; sawdust reached 7.85% at 9%	28
Jute/Glass hybrid	—	NaOH treatment, hand lay-up method	40 wt% jute, 60 wt% glass	0.38 (average for hybrid composite)	—	Flexural strength: 85 MPa (hybrid composite) Tensile strength: 60 MPa	Jute–glass hybrid showed 30% better wear resistance than jute Friction decreased due to glass fibers Wear increased with load, but hybrids stayed lower across speeds Hybridization improved overall tribological performance	215

properties of jute/coir fiber reinforced epoxy composites summarized at Table 16.

5.2.3 Jute/glass fiber reinforced epoxy composites. Jute and glass fibers are two of the best choices for reinforcement materials in composite applications, especially due to their excellent mechanical properties, low cost, and renewable nature.[33] If these fibers combine with epoxy resin, they create hybrid composites that offers advantages of both the materials: economical green nature of jute and mechanical properties performance from glass and simultaneously same property modification being made to resins also improve significantly tribological properties of the composites. Jute/glass/epoxy hybrid composites can achieve best wear resistance and friction performance at 40% jute/60% glass fiber content.[261] The addition of fillers SiC enhances the wear resistance and these composites are suitable for high-wear applications.[28] Tribological properties of jute/glass fiber reinforced epoxy composites summarized at Table 17.

5.2.4 Jute/sisal fiber reinforced epoxy composites. Jute/Sisal/Epoxy hybrid composites show significant improvements in wear resistance, friction performance, and mechanical strength.[262] When combined with appropriate fillers there are a rapid enhancement of mechanical and tribological properties of this composites.[263] These composites generally exhibit lower friction coefficients and wear rates compared to individual fiber composites (jute/epoxy, and sisal/epoxy). The jute–sisal hybrid composite with 20 wt% fiber content shows the best performance in terms of wear resistance and mechanical strength. The wear rate decreases proportionally with increased fiber content, with the 20 wt% hybrid composites exhibiting the lowest wear.[197] For the sisal/jute/E glass composites, increasing filler content results in improved friction performance and wear resistance.[263] From Fig. 16, the combination of jute, sisal, and fillers like coconut shell powder offers an eco-friendly alternative to conventional materials like asbestos.[264] The summarized data of tribological properties of jute/sisal fiber reinforced epoxy composites are listed at Table 18.

6. Applications of natural fiber reinforced composites

Natural fiber reinforced composites have achieved extensive use across diverse industries, demonstrating its adaptability and capacity to reduce environmental effect.[265–268] Hybrid fiber design follows several established rules that enable tailoring of composite performance for automotive, aerospace, and construction applications. Stiff, high-crystallinity fibers such as flax, hemp, and ramie are commonly combined with high-elongation fibers like coir, banana, or sisal to create a balanced synergy of strength, stiffness, and impact

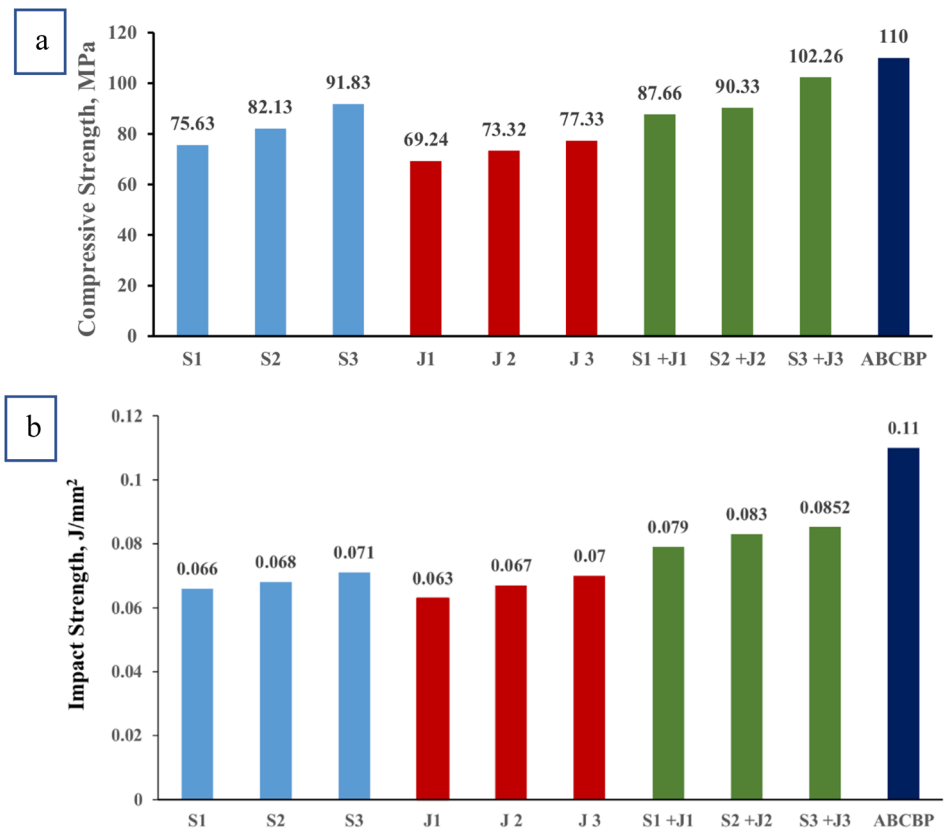

Fig. 16 Mechanical properties of pure jute/epoxy, pure sisal/epoxy, sisal/jute/epoxy reinforcement composite, and asbestos-based commercial brake pads (ABCBP). (a) Compressive strength of asbestos free brake friction material (AFBFM); (b) impact strength of AFBFM. Reproduced from ref. 264 with permission from Springer, Copyright 2024.

Table 18 Tribological properties of jute/sisal/epoxy hybrid composite

Fiber	Filler with fiber	Jute/sisal/epoxy ratio	Friction co-efficient	Wear rate	Mechanical properties	Key findings	Reference
Jute-sisal hybrid	Coconut shell powder 10%, calcium carbonate 2%, barium sulphate, Al_2O_3%, Gr 2%, antimony sulphate 1%	5%/5%/60%; 10%/10%/50; 15%/15%/40	0.38	56.26 mg (10 wt%), 32.43 mg (20 wt%), 28.87 mg (30 wt%)	Compressive strength: hybrid composite increased by 16.65% compared to 15 wt% fiber composites Flexural strength: hybrid composites showed the best performance	- Jute–sisal hybrid showed better compression strength and wear resistance - Wear decreased with higher fiber content; 20% showed the lowest wear - Reinforcement level strongly affected braking performance - Hybrid fibers gave the best balance of wear and strength	197
Sisal/jute/E glass	(3–9)% nano clay	Fiber: 10%/10%/15%; rest are epoxy	—	—	—	The results suggest that filler content has a greater impact on both the friction coefficient and specific wear rate of the developed hybrid composites compared to other factors. The optimal response is observed at the maximum filler content level	263
Jute-sisal hybrid	Coconut shell powder 10%, calcium carbonate 2%, barium sulphate, Al_2O_3%, Gr 2%, antimony sulphate 1%	5%/5%/60%; 10%/10%/50; 15%/15%/40	0.31	—	—	- Sisal–jute hybrid showed better wear resistance and lower friction than single-fiber composites - Performance was close to commercial brake pads - Coconut shell powder improved wear and compressive strength - Composite is a promising eco-friendly brake pad alternative	264

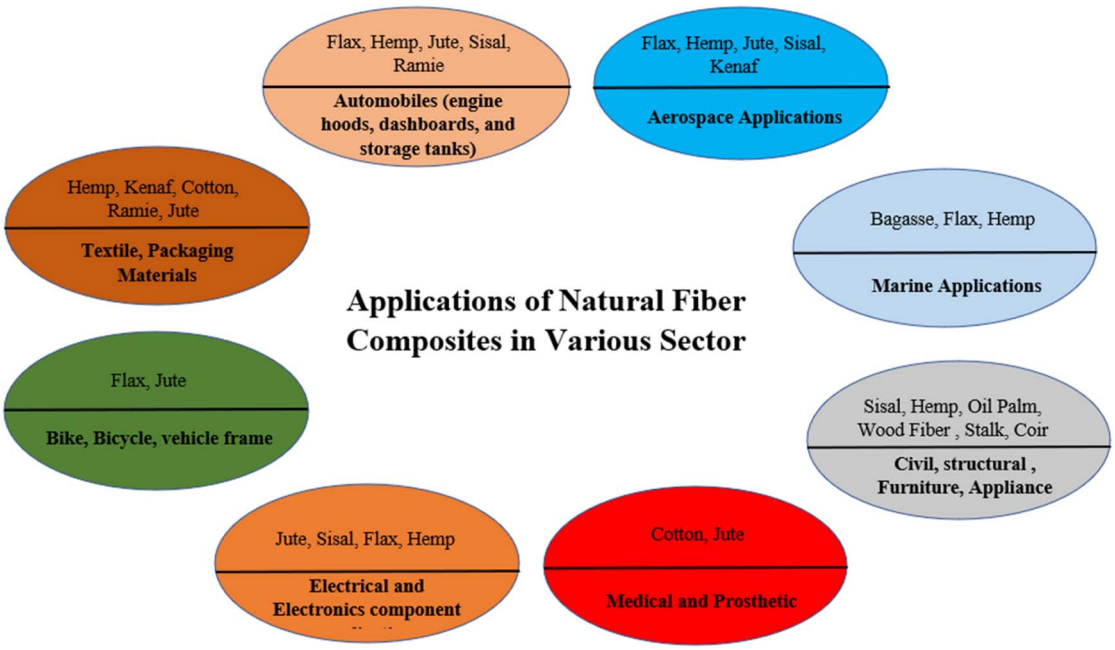

Fig. 17 Application of plant fiber reinforced composites at various industrial sectors.

tolerance.[187] Fibers with complementary chemical compositions, high-cellulose fibers for load-bearing capacity and high-lignin fibers for damping and moisture resistance, are paired to achieve multifunctional behavior. Multilayer stacking designs place stiff fibers on the outer skins and tougher fibers in the core, improving bending strength and controlling failure modes.[208] Environmental durability can be tuned by integrating thermally stable fibers (basalt, treated flax)[269] with moisture-resistant fibers (coir or bamboo). In high-performance sectors, natural-synthetic hybrids such as carbon/flax or glass/jute are preferred to reduce weight while maintaining structural integrity (Fig. 17).[188,261,270]

Products like animal bedding, laptop and mobile cases, insulating materials, soilless potting mixes, packaging materials, and clothing-grade fabrics, for instance, frequently use kenaf fiber reinforced composites.[271] Similarly, ramie fiber reinforced composites are utilized in paper products, fishing nets, filter cloths, sewing threads, and household furnishings.[272] In packaging, Enkev has employed coir fiber reinforced in natural latex rubber composites for items like trays, containers, and packaging boxes. Flexform Technologies combines natural fibers such as hemp, kenaf, and jute with thermoplastic polymers to create shields for trucks and cars, containers for shipping and storage, and office and home furnishings. Tech Wood International incorporates wood-plastic composites for modular house construction.[273,274] In the automotive industry, composites made from flax, sisal, hemp, wood, and other natural fibers are used in components such as headliner panels, floor mats, seat backs, and boot liners for vehicles like the Volkswagen Passat, Bora, Golf, A4, and BMW 3, 5, and 7 series.[275] Additionally, oil palm fiber reinforced composites are used in building materials like fencing, door frames, and roofing.[276] Hemp fiber composites are also applied in a variety of products, including geotextiles, furniture, textiles, and construction materials.[277]

Natural fiber epoxy bio-composites are particularly prominent in the automotive industry, where they are used in parts like door panels, engine and transmission covers, seat backrests, and underbody panels. Specific components such as engine hoods, dashboards, and storage tanks are made using natural fibers like flax, hemp, jute, sisal, and ramie.[278–282] The automotive sector has made considerable progress in using these materials to address economic and environmental challenges, aiming to reduce mass, fuel consumption, and emissions.[283] Areca sheath fibers can be considered as a very promising material for locomotive parts, packaging industry and office furniture.[284] In aerospace, fiber–reinforced epoxy composites are essential due to their mechanical strength and lightweight nature, making them ideal for aircraft interiors.[283,285] Marine applications include the use of these composites in constructing ship hulls, propeller blades, and wind and tidal turbine blades,[286] while in the oil and gas industry, they are applied in underground pipes and boat building.[287]

Innovative developments have led to the creation of specialized composite materials. For instance, Sumesh *et al.*[282] investigated the use of pineapple, banana, and coir fiber ash as fillers in epoxy-based bio-composites, which improved mechanical properties and suitability for lightweight automotive applications. Likewise, Rajeshkumar *et al.*[288] developed sodium hydroxide-treated Phoenix Sp fiber/epoxy composites with enhanced impact properties, making them ideal for automotive panels. Hybrid composites using bacterial cellulose from coconut fibers and Kevlar have been found to exhibit

exceptional strength and impact resistance, making them suitable for marine and ballistic applications.[289] In thermal insulation, Chowdari *et al.*[290] showed that areca/coconut shell powder epoxy composites provide excellent thermal insulation. Furthermore, hemp fiber/epoxy composites, especially those containing 20–30 wt% hemp fibers, are highly effective in ballistic applications.[277]

Epoxy-based bio-composites are also finding use in the construction sector. Jawaid *et al.*[291] created hybrid date fiber/bamboo epoxy composites that offer impressive mechanical properties and thermal stability, making them suitable for building materials. Additionally, rice husk and sawdust epoxy bio-composites, known for their excellent acoustic properties, are ideal for sound absorption applications in ceilings and walls.[292] Natural fiber–reinforced epoxy composites have expanded their reach to several other fields, including civil engineering for structural elements like roofs, pipes, and tanks, sporting goods like golf club shafts, tennis rackets, and bicycle frames, and medical applications such as prosthetic devices and imaging.[293]

7. Conclusion

The development of plant fiber-based polymer hybrid composite has drawn a considerable interest from some decade, although several issues still exist. Thus, an attempt is taken in this review to explore the issues related to the tribological behavior of epoxy polymer composite with various plant fibers. The key findings of this review can be shortlisted as follows:

• The studies of plant fiber reinforced epoxy composite show that the tribological and mechanical properties of composites are significantly depending on fiber loading. In general, increasing fiber content enhances the tensile strength, wear resistance, and stiffness of the composite, with optimum performance observed at 20–30% fiber concentrations. Beyond this threshold, excessive fiber content leads to decreased matrix adhesion, agglomeration, and an increase in wear rates. Therefore, hence, balanced fiber loading is key to getting the best of the behavior in term of mechanical property and durability.

• Surface treatments substantially improve the tribological and mechanical characteristics of plant fiber–reinforced epoxy composites with an aid to enhance the fiber–matrix interface. Common methods include alkali treatment (NaOH), which removes surface impurities, increases fiber roughness, enhancing interfacial bonding and ultimately wear resistance; silane treatment drives the fibers closer to the matrix due adhesion improvement resulting in tensile strength enhancement and reducing friction; and nanoparticle incorporation, such as silica (SiO_2), carbon nanotubes (CNTs), and titanium dioxide (TiO_2), significantly reduce wear thickness and hence coefficient of friction while improving thermal stability by formation of a protective tribo-film.

• Fillers can be incorporated into fiber composites to improve the overall tribological behavior such as friction coefficient and wear resistance. Metal fillers, such as aluminum or graphite, or others fillers like SiC, TiO_2, Al_2O_3, carbon nano tubes, or graphene, fly ash *etc.* contribute to a stronger, more durable composite by reducing the void spaces as well reinforcing the fiber–matrix interface.

• Hybrid composites have been reported to give sprouts to increased wear resistance, strength and applicability as against plain fiber composites. These hybrid systems take advantage of the individual properties of each fiber, offering a synergistic enhancement in overall performance. For instance, jute/banana and jute/coir hybrid composites significantly decrease wear rates, reduce the frictional force, and improve the mechanical strength.

• Abaca, palm, sisal and banana are the best overall fibers identified in this review, with respect to combined superior mechanical properties, excellent wear resistance, and environmental benefits. These fibers provide exceptional performance in terms of tensile strength, wear resistance, and durability particularly when treated and incorporated in hybrid composites because of their high cellulose and crystallinity. They show promise in replacing conventional synthetic materials.

• The current review further strengthened that the plant fiber composites are an efficient substitute for synthetic fibers like glass and asbestos due to their deleterious influence on human health and environment. Although synthetic fibers have been the dominant reinforcement in composites for several years, natural fibers like jute, banana, abaca and coir do not only have similar mechanical properties than synthetic one but sometimes even better when used as reinforcement providing also an environmentally friendly way to recycle vegetal wastes with reduced cost. These fibers have shown the prospect of offering innovative solutions for performance and sustainability in expensive applications such as automotive parts, mounting materials, and construction components.

Overall, this review highlights that plant–fiber–reinforced epoxy composites consistently benefit from proper fiber selection, optimized treatment, and balanced fiber or filler loading. A unified trend observed across studies is that improved interfacial bonding, higher cellulose content, and appropriate reinforcement levels directly enhance friction reduction, wear resistance, and mechanical stability. Future research should focus on multi-scale modeling, advanced hybridization strategies, nano-modified interphases, and durability assessments under thermal, moisture, and fatigue loading. Such efforts will help establish reliable design guidelines and unlock broader industrial applications for sustainable plant–fiber/epoxy tribocomposites.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

References

1 R. Punyamurthy, D. Sampathkumar, R. P. G. Ranganagowda, B. Bennehalli and C. V. Srinivas, Mechanical properties of abaca fiber reinforced polypropylene composites: effect of chemical treatment by benzenediazonium chloride, *J. King Saud Univ., Eng. Sci.*, 2017, **29**(3), 289–294.

2 G. Demircan, M. Ozen, M. Kisa, *et al.*, The effect of nano-gelcoat on freeze-thaw resistance of glass fiber-reinforced polymer composite for marine applications, *Ocean Eng.*, 2023, **269**, 113589.

3 M. Sienkiewicz, H. Janik, K. Borzędowska-Labuda and J. Kucińska-Lipka, Environmentally friendly polymer-rubber composites obtained from waste tyres: a review, *J. Cleaner Prod.*, 2017, **147**, 560–571.

4 B. Bennehalli, S. Nagaraja, S. S. Poyil, M. R. Reddy, A. R. Banagar, S. Kumaraswamy, S. V. Chikkol and M. I. Ammarullah, Surface modification of sustainable bio-derived areca sheath fibers for enhanced mechanical and thermal properties in epoxy-based biocomposites: spectroscopic, thermogravimetric, and crystallographic insights, *J. Nat. Fibers*, 2025, **22**(1), 2497914.

5 V. P. Cyras, S. Iannace, J. M. Kenny and A. Vázquez, Relationship between processing and properties of biodegradable composites based on PCL/starch matrix and sisal fibers, *Polym. Compos.*, 2004, **22**(1), 104–110.

6 E. Chiellini, P. Cinelli, F. Chiellini and S. H. Imam, Environmentally degradable bio-based polymeric blends and composites, *Macromol. Biosci.*, 2004, **4**, 218–231.

7 M. Nissar, N. CK, Y. A. Birjerane, S. Patil, S. Shetty and A. Das, Coconut coir fiber composites for sustainable architecture: a comprehensive review of properties, processing, and applications, *J. Compos. Sci.*, 2025, **9**(10), 516.

8 D. H. Mueller and A. Krobjilowski, New discovery in the properties of composites reinforced with natural fibers, *J. Ind. Text.*, 2003, **33**(2), 111–130.

9 B. Xue, G. Wu, J. Li, D. Wei, J. Li, C. Ji, Y. Wang and F. Sun, Recent advances in fiber pretreatment for plant fiber-reinforced PLA biocomposites: interfacial tailoring, properties, and applications, *J. Ind. Text.*, 2025, **55**, 1–43.

10 G. Demircan, M. Kisa, M. Ozen, *et al.*, Nano-gelcoat application of glass fiber reinforced polymer composites for marine application: structural, mechanical, and thermal analysis, *Mar. Pollut. Bull.*, 2023, **194**, 115412.

11 H. R. Pakravan and T. Ozbakkaloglu, Synthetic fibers for cementitious composites: a critical and in-depth review of recent advances, *Constr. Build. Mater.*, 2019, **207**, 491–518.

12 G. Demircan, M. Kisa, M. Ozen and B. Aktas, Surface modified alumina nanoparticles-filled aramid fiber-reinforced epoxy nanocomposites: preparation and mechanical properties, *Iran. Polym. J.*, 2020, **29**, 253–264.

13 H. Smales, Friction materials: black art or science?, *Proc. Inst. Mech. Eng., Part D*, 1995, **209**(3), 151–157.

14 R. L. Norton. *Machine Design*. Prentice Hall, London, 2010.

15 M. Boumaaza, A. Belaadi and M. Bourchak, Systematic review on reinforcing mortars with natural fibers: challenges of environment-friendly option, *J. Nat. Fibers*, 2022, **19**, 14262–14286.

16 M. Ozen, G. Demircan, M. Kisa and Z. Ilik, Investigation of usability of waste textile fabrics in composites, *Emerging Mater. Res.*, 2020, **9**, 1–6.

17 A. K. Mohanty, M. Misra and G. Hinrichsen, Biofibres, biodegradable polymers and biocomposites: an overview, *Macromol. Mater. Eng.*, 2000, **276**(1), 1–24.

18 T. Sathishkumar, S. Satheeshkumar and J. Naveen, Glass fiber-reinforced polymer composites—A review, *J. Reinf. Plast. Compos.*, 2014, **33**, 1258–1275.

19 S. Ojha, R. Gujjala and S. K. Acharya, Effect of filler loading on mechanical and tribological properties of wood apple shell reinforced epoxy composite, *Adv. Mater. Sci. Eng.*, 2014, **2014**, 538651.

20 Y. Tasgin, G. Demircan, S. Kandemir and A. Acikgoz, Mechanical, wear and thermal properties of natural fiber-reinforced epoxy composite: cotton, sisal, coir, and wool fibers, *J. Mater. Sci.*, 2024, **59**, 10844–10857.

21 H. Manjulaiah, S. Dhanraj, Y. Basavegowda, L. N. Lamani, M. Puttegowda, S. M. Rangappa and S. Siengchin, A novel study on the development of sisal-jute fiber epoxy filler-based composites for brake pad application, *Biomass Convers. Biorefin.*, 2023, **14**, 23411–23423.

22 F. F. Shuhimi, M. F. B. Abdollah, M. A. Kalam, M. Hassan, A. Mustafa and H. Amiruddin, Tribological characteristics comparison for oil palm fibre/epoxy and kenaf fibre/epoxy composites under dry sliding conditions, *Tribol. Int.*, 2016, **101**, 247–254.

23 U. Nirmal, Adhesive wear and frictional performance of banana fibre reinforced epoxy (BaFRE) composite, *Polymers*, 2022, **14**(17), 3700.

24 S. Kumar, P. Shyamala, P. R. Pati and P. K. Gandla, Wear and frictional performance of epoxy composites reinforced with natural waste fibers and fillers for engineering applications, *Fibers Polym.*, 2024, **25**, 1429–1442.

25 B. F. Yousif, U. Nirmal and K. J. Wong, Three-body abrasion on wear and frictional performance of treated betelnut fiber reinforced epoxy (T-BFRE) composite, *Mater. Des.*, 2010, **31**, 4514–4521.

26 M. G. Madhu and K. Buddha, Mechanical evaluation of epoxy polymer composites reinforced with areca leaf sheath fiber, *ACS Omega*, 2025, **10**, 25663–25674.

27 R. Venkatesh, P. C. S. Kumar, A. Senthilkumar, J. P. Krishna, P. Chandramohan, V. N. Aneesh, A. Malladi, C. B. Priya and E. Ramaraj, Mechanical interlocking approaches to the prediction of mechanical and tribological behavior of natural fiber-reinforced polymer hybrid nanocomposites for automotive applications, *Adv. Polym. Technol.*, 2023, **2023**, 6685060.

28 P. Borah and S. Samanta, Wear behaviour of glass/jute hybrid epoxy composites with addition of fillers, *Adv. Mater. Processes Technol.*, 2020, **6**, 465–476.

29 A. R. Bhat, R. Kumar and P. K. S. Mural, Natural fiber reinforced polymer composites: a comprehensive review of tribo-mechanical properties, *Tribol. Int.*, 2023, **189**, 108978.
30 M. Rabbi, T. Islam and M. Bhuiya, Jute fiber-reinforced polymer composites: a comprehensive review, *Int. J. Mech. Prod. Eng. Res. Dev.*, 2020, **10**, 3053–3072.
31 M. Asim, K. Abdan, M. Jawaid, M. Nasir, Z. Dashtizadeh, M. R. Ishak and M. E. Hoque, A review on pineapple leaves fibre and its composites, *Int. J. Polym. Sci.*, 2015, **2015**, 1–16.
32 M. S. Rabbi, S. Das, T. Tasnim, M. M. Billah and A. Hasan, Effect of nano-filler on the manufacturing and properties of natural fiber-based composites: a review, *J. Eng. Adv.*, 2023, **4**(4), 101–115.
33 M. S. Rabbi, T. Islam and G. M. S. Islam, Injection-molded natural fiber-reinforced polymer composites: a review, *Int. J. Mech. Mater. Eng.*, 2021, **16**, 15.
34 N. Sienkiewicz, M. Dominic and J. Parameswaranpillai, Natural fillers as potential modifying agents for epoxy composition: a review, *Polymers*, 2022, **14**(2), 265.
35 P. Jagadeesh, M. Puttegowda, S. M. Rangappa and S. Siengchin, A review on extraction, chemical treatment, characterization of natural fibers and its composites for potential applications, *Polym. Compos.*, 2021, **43**(1), 6245–6267.
36 M. Mohammadi, M. R. Ishak and M. T. H. Sultan, Exploring chemical and physical advancements in surface modification techniques of natural fiber reinforced composite: a comprehensive review, *J. Nat. Fibers*, 2024, **21**(1), 2408633.
37 G. Y. Farag, E. M. A. Abou Taleb and T. Hamouda, Natural fibers extraction methods and properties: a review, *Egypt. J. Chem.*, 2025, **68**(3), 445–464.
38 J. Kaufmann, A. G. Temesgen and H. Cebulla, A comprehensive review on natural fiber reinforced hybrid composites processing techniques, material properties and emerging applications, *Discover Mater.*, 2025, **5**, 227.
39 M. Razzaq, S. Moma and M. Rabbi, Mechanical properties of biofiber/glass reinforced hybrid composites produced by hand lay-up method: a review, *Mater. Eng. Res.*, 2021, **3**(1), 144–155.
40 Y. Seki, F. Selli, Ü. H. Erdoğan, M. Atagür and M. Ö. Seydibeyoğlu, A review on alternative raw materials for sustainable production: novel plant fibers, *Cellulose*, 2022, **29**, 4877–4918.
41 A. Balea, E. Fuente, Á. Blanco and C. Negro, Nanocelluloses: natural-based materials for fiber-reinforced cement composites. A critical review, *Polymers*, 2019, **11**(3), 518.
42 T. Vaisanen, A. Haapala, R. Lappalainen and L. Tomppo, Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: a review, *Waste Manage.*, 2016, **54**, 62–73.
43 Y. Z. N. Htwe, A. S. Al-Janabi, Y. Wadzer and H. Mamat, Review of tribological properties of nanoparticle-based lubricants and their hybrids and composites, *Friction*, 2024, **12**(4), 569–590.
44 M. A. S. Siddiqui, M. S. Rabbi and S. Dewanjee, Low-velocity impact response of natural fiber reinforced composites: a comprehensive review on influential parameters, *Compos., Part C: Open Access*, 2023, **12**, 100422.
45 Z. N. Azwa, B. F. Yousif, A. C. Manalo and W. Karunasena, A review on the degradability of polymeric composites based on natural fibres, *Mater. Des.*, 2013, **47**, 424–442.
46 K. Liu, H. Takagi, R. Osugi and Z. Yang, Effect of physicochemical structure of natural fiber on transverse thermal conductivity of unidirectional abaca/bamboo fiber composites, *Composites, Part A*, 2012, **43**(8), 1234–1241.
47 S. Chokshi, V. Parmar, P. Gohil and V. Chaudhary, Chemical composition and mechanical properties of natural fibers, *J. Nat. Fibers*, 2020, **25**(1), 9–22.
48 N. Cordeiro, M. Omelas, A. Ashori, S. Sheshmani and H. Norouzi, Investigation on the surface properties of chemically modified natural fibers using inverse gas chromatography, *Carbohydr. Polym.*, 2012, **87**(4), 7367–7375.
49 P. Anselmo Filho and C. Bahr, Biomass resources for energy in North-Eastern Brazil, *Appl. Energy*, 2004, **77**(1), 51–67.
50 K. G. Satyanarayana, J. L. Guimarães and F. Wypych, Studies on lignocellulosic fibers of Brazil. Part I: source, production, morphology, properties and applications, *Composites, Part A*, 2007, **38**(7), 1694–1709.
51 J. L. Guimaraes, E. Frollini, C. G. Da Silva, F. Wypych and K. G. Satyanarayana, Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil, *Ind. Crops Prod.*, 2009, **30**(3), 407–415.
52 Y. Habibi, W. K. El-Zawawy, M. M. Ibrahim and A. Dufresne, Processing and characterization of reinforced polyethylene composites made with lignocellulosic fibers from Egyptian agro-industrial residues, *Compos. Sci. Technol.*, 2008, **68**(7–8), 1877–1885.
53 M. Sarikanat, Y. Seki, K. Sever and C. Durmuskahya, Determination of properties of *Althaea officinalis* L. (marshmallow) fibres as a potential plant fibre in polymeric composite materials, *Composites, Part B*, 2014, **57**, 180–186.
54 W. Hoareau, W. G. Trindade, B. Siegmund, A. Castellan and E. Frollini, Sugar cane bagasse and curaua lignins oxidized by chlorine dioxide and reacted with furfuryl alcohol: characterization and stability, *Polym. Degrad. Stab.*, 2004, **86**(3), 567–576.
55 S. Hattalli, A. Benaboura, F. Ham-Pichavant, A. Nourmamode and A. Castellan, Adding value to alfa grass (*Stipa tenacissima* L.) soda lignin as phenolic resins. I. Lignin characterization, *Polym. Degrad. Stab.*, 2002, **76**(2), 259–264.
56 K. G. Satyanarayana, K. K. Ravikumar, K. Sukumaran, P. S. Mukherjee, S. G. K. Pillai and A. G. Kulkarni, Structure and properties of some vegetable fibres, *J. Mater. Sci.*, 1986, **21**(1), 57–63.
57 K. Majeed, M. Jawaid, A. Hassan, A. Abu Bakar, H. P. S. Abdul Khalil, A. A. Salema and I. Inuwa, Potential

materials for food packaging from nanoclay/natural fibres filled hybrid composites, *Mater. Des.*, 2013, **46**, 391–410.
58 A. V. Ratna Prasad and K. M. Rao, Mechanical properties of natural fibre reinforced polyester composites: jowar, sisal and bamboo, *Mater. Des.*, 2011, **32**(8–9), 4658–4663.
59 J. R. M. D'Almeida, R. C. M. P. Aquino and S. N. Monteiro, Tensile mechanical properties, morphological aspects and chemical characterization of piassava (*Attalea funifera*) fibers, *Composites, Part A*, 2006, **37**(9), 1473–1479.
60 F. Xu, Y. C. Shi and D. Wang, X-ray scattering studies of lignocellulosic biomass: a review, *Carbohydr. Polym.*, 2013, **94**(2), 904–917.
61 N. Le Moigne, M. Longerey, J. M. Taulemesse, J. C. Bénézet and A. Bergeret, Study of the interface in natural fibres reinforced poly(lactic acid) biocomposites modified by optimized organosilane treatments, *Ind. Crops Prod.*, 2014, **52**, 481–494.
62 V. Tserki, N. E. Zafeiropoulos, F. Simon and C. Panayiotou, A study of the effect of acetylation and propionylation surface treatments on natural fibres, *Composites, Part A*, 2005, **36**(8), 1110–1118.
63 M. P. M. Dicker, P. F. Duckworth, A. B. Baker, G. Francois, M. K. Hazzard and P. M. Weaver, Green composites: a review of material attributes and complementary applications, *Composites, Part A*, 2014, **56**, 280–289.
64 P. Saha, S. Manna, S. R. Chowdhury, R. Sen, D. Roy and B. Adhikari, Enhancement of tensile strength of lignocellulosic jute fibers by alkali-steam treatment, *Bioresour. Technol.*, 2010, **101**(9), 3182–3187.
65 J. Wang, Y. Zheng and A. Wang, Effect of kapok fiber treated with various solvents on oil absorbency, *Ind. Crops Prod.*, 2012, **40**, 178–184.
66 Y. Y. Tye, K. T. Lee, W. N. Wan Abdullah and C. P. Leh, Potential of *Ceiba pentandra* (L.) Gaertn. (kapok) fiber as a resource for second generation bioethanol: parametric optimization and comparative study of various pretreatments prior enzymatic saccharification for sugar production, *Bioresour. Technol.*, 2013, **140**, 10–14.
67 O. Faruk, A. K. Bledzki, H. P. Fink and M. Sain, Biocomposites reinforced with natural fibers: 2000–2010, *Prog. Polym. Sci.*, 2012, **37**(11), 1552–1596.
68 S. Karimi, P. M. Tahir, A. Karimi, A. Dufresne and A. Abdulkhani, Kenafbast cellulosic fibers hierarchy: a comprehensive approach from micro to nano, *Carbohydr. Polym.*, 2014, **101**, 878–885.
69 J. M. R. Almeida, C. A. Boynard and S. N. Monteiro, Effect of chemical treatments on the surface morphology of sponge gourd (*Luffa cylindrica*) fibers, in *Proc 3rd Int Symp Natural Polymers and Composites (ISNaPol)*, Embrapa Instrumentação Agropecuária, São Pedro, 2000. p. 27.
70 V. O. A. Tanobe, T. H. D. Sydenstricker, M. Munaro and S. C. Amico, A comprehensive characterization of chemically treated Brazilian sponge-gourds (*Luffa cylindrica*), *Polym. Test.*, 2005, **24**(4), 474–482.
71 M. P. Elizalde-González and V. Hernández-Montoya, Characterization of adsorbent materials prepared from avocado kernel seeds: natural, activated and carbonized forms, *Biochem. Eng. J.*, 2007, **36**, 730–738.
72 B. L. L. Sipiéo, R. L. M. Paiva, S. A. S. Goulart and D. R. Mulinari, Effect of chemical modification on mechanical behaviour of polypropylene reinforced pineapple crown fibers composites, *Procedia Eng.*, 2011, **10**, 2028–2033.
73 X. Li, L. He, H. Zhou, W. Li and W. Zha, Influence of silicone oil modification on properties of ramie fiber reinforced polypropylene composites, *Carbohydr. Polym.*, 2012, **87**(3), 2000–2004.
74 M. A. Henrique, H. A. Silvério, W. P. Flauzino Neto and D. Pasquini, Valorization of an agro-industrial waste, mango seed, by the extraction and characterization of its cellulose nanocrystals, *J. Environ. Manage.*, 2013, **121**, 202–209.
75 A. Alemdar and M. Sain, Biocomposites from wheat straw nanofibers: morphology, thermal and mechanical properties, *Compos. Sci. Technol.*, 2008, **68**(4), 557–565.
76 L. Chen, F. Hong, X. X. Yang and S. F. Han, Biotransformation of wheat straw to bacterial cellulose and its mechanism, *Bioresour. Technol.*, 2013, **135**, 464–468.
77 A. Kaushika, M. Singh and G. Verma, Green nanocomposites based on thermoplastic starch and steam exploded cellulose nanofibrils from wheat straw, *Carbohydr. Polym.*, 2010, **82**(2), 337–345.
78 M. Jawaid and H. P. S. Abdul Khalil, Cellulosic/synthetic fibre reinforced polymer hybrid composites: a review, *Carbohydr. Polym.*, 2011, **86**(1), 1–18.
79 P. H. F. Pereira, M. F. Rosa, M. O. H. Cioffi, K. C. C. C. Benini, A. C. Milanese, H. J. C. Voorwald and D. R. Mulinari, Vegetal fibers in polymeric composites: A review, *Polímeros*, 2015, **25**(1), 9–22.
80 C. V. Srinivasa, A. Arifulla, N. Goutham, T. Santhosh, H. J. Jaeethendra, R. B. Ravikumar, S. G. Anil and D. G. Santhosh Kumar, Static bending and impact behaviour of areca fibers composites, *Mater. Des.*, 2011, **32**(4), 2469–2475.
81 J. Hindi, K. Muralishwara and B. M. Gurumurthy, Comparative analysis of physical, morphological, tensile and thermal stability characteristics of raw and alkali treated novel Tinospora cordifolia natural fiber, *Sci. Rep.*, 2025, **15**, 18596.
82 M. R. Sanjay, G. R. Arpitha and B. Yogesha, Study on mechanical properties of natural-glass fibre reinforced polymer hybrid composites: A review, *Mater. Today: Proc.*, 2015, **2**(4–5), 2959–2967.
83 J. George, M. S. S. Sreekala and S. Thomas, A review on interface modification and characterization of natural fiber reinforced plastic composites, *Polym. Eng. Sci.*, 2001, **41**(9), 1471–1485.
84 P. Wambua, J. Ivens and I. Verpoest, Natural fibres: Can they replace glass in fibre reinforced plastics?, *Compos. Sci. Technol.*, 2003, **63**(9), 1259–1264.
85 J. Biagiotti, D. Puglia and J. M. Kenny, A review on natural fibre-based composites-part I: Structure, processing and

properties of vegetable fibres, *J. Nat. Fibers*, 2004, **1**(2), 37–68.
86 A. K. Bledzki and A. Jaszkiewicz, Mechanical performance of biocomposites based on PLA and PHBV reinforced with natural fibres–A comparative study to PP, *Compos. Sci. Technol.*, 2010, **70**(12), 1687–1696.
87 L. Yan, N. Chouw and K. Jayaraman, Flax fibre and its composites–A review, *Composites, Part B*, 2014, **56**, 296–317.
88 O. S. Abiola, W. K. Kupolati, E. R. Sadiku and J. M. Ndambuki, Utilisation of natural fibre as modifier in bituminous mixes: A review, *Constr. Build. Mater.*, 2014, **54**, 305–312.
89 S. Ramakrishnan, K. Krishnamurthy, M. M. Prasath, R. S. Kumar, M. Dharmaraj, K. Gowthaman, P. S. Kumar and R. Rajasekar, Theoretical prediction on the mechanical behavior of natural fiber reinforced vinyl ester composites, *Appl. Sci. Adv. Mater. Int.*, 2015, **1**(3), 85–92.
90 O. Onuaguluchi and N. Banthia, Plant-based natural fibre reinforced cement composites: A review, *Cem. Concr. Compos.*, 2016, **68**, 96–108.
91 H. Danso, D. B. Martinson, M. Ali and J. B. Williams, Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres, *Constr. Build. Mater.*, 2015, **101**, 797–809.
92 T. P. Sathishkumar, P. Navaneethakrishnan and O. Shankar, Tensile and flexural properties of snake grass natural fiber reinforced isophthallic polyester composites, *Compos. Sci. Technol.*, 2012, **72**(10), 1183–1190.
93 W. Sujaritjun, P. Uawongsuwan, W. Pivsa-Art and H. Hamada, Mechanical property of surface modified natural fiber reinforced PLA biocomposites, *Energy Procedia*, 2013, **34**, 664–672.
94 W. Nuthong, P. Uawongsuwan, W. Pivsa-Art and H. Hamada, Impact property of flexible epoxy treated natural fiber reinforced PLA composites, *Energy Procedia*, 2013, **34**, 839–847.
95 M. H. Shakir and A. K. Singh, Ramie fiber and its composites: A review, *Polym. Compos.*, 2024, **46**, 6813–6841.
96 Q. Tang, Y. Chen, M. Du, J. Yu, Z. Li and B. Ding, Research progress in Ramie fiber extraction: Degumming method, working mechanism, and fiber performance, *Ind. Crops Prod.*, 2024, **222**(Part 3), 119876.
97 D. Chandramohan and K. Marimuthu, A review on natural fibers, *Int. J. Res. Rev. Appl. Sci.*, 2011, **8**(2), 194–206.
98 M. F. M. Alkbir, S. M. Sapuan, A. A. Nuraini and M. R. Ishak, Fibre properties and crashworthiness parameters of natural fibre-reinforced composite structure: A literature review, *Compos. Struct.*, 2016, **148**, 59–73.
99 H. Ku, H. Wang, N. Pattarachaiyakoop and M. Trada, A review on the tensile properties of natural fiber reinforced composites, *Composites, Part B*, 2011, **42**(4), 856–873.
100 H. Hargitai, I. Racz and R. D. Anandjiwala, Development of hemp fiber reinforced polypropylene composites, *J. Thermoplast. Compos. Mater.*, 2008, **21**(2), 165–174.
101 G. Cristaldi, A. Latteri, G. Recca and G. Cicala, Composites based on natural fibre fabrics, *Woven Fabr. Eng.*, 2010, **17**, 317–342.
102 Y. S. Munde and R. B. Ingle, Theoretical modeling and experimental verification of mechanical properties of natural fiber reinforced thermoplastics, *Procedia Technol.*, 2015, **19**, 320–326.
103 K. L. Pickering, *Properties and Performance of Natural-Fibre Composites*, Woodhead Publishing Limited, Boca Raton, FL. 1st edn,2008.
104 R. Mahjoub, J. M. Yatim, A. R. M. Sam and S. H. Hashemi, Tensile properties of kenaf fiber due to various conditions of chemical fiber surface modifications, *Constr. Build. Mater.*, 2014, **55**, 103–113.
105 P. P. Gohil and A. A. Shaikh, Experimental investigation and micro mechanics assessment for longitudinal elastic modulus in unidirectional cotton-polyester composites, *Int. J. Eng. Technol.*, 2010, **2**(2), 111–118.
106 P. J. Blau, The significance and use of the friction coefficient, *Tribol. Int.*, 2001, **34**(7), 585–591.
107 T. Thankachan, K. S. Prakash and V. Kavimani, Investigating the effects of hybrid reinforcement particles on the microstructural, mechanical, and tribological properties of friction stir processed copper surface composites, *Composites, Part B*, 2019, **174**, 107057.
108 J. O. Bird and P. J. Chivers. Friction. in *Newnes Engineering and Physical Science Pocket Book*, ed. Bird J. O. and Chivers P. J. Newnes, 1993, pp. 235–237.
109 R. Quispe Dominguez, C. Torres, L. Eggert, G. Ccama, M. Kurniawan, M. Hopfeld, J. Zárate, M. Camargo, A. Rosenkranz, J. Acosta, A. Bund, P. Schaaf and R. Grieseler, Tribological and Mechanical Performance of Ti_2AlC and Ti_3AlC_2 Thin Films, *Adv. Eng. Mater.*, 2022, **24**(10).
110 H. Qi, G. Zhang, Z. Zheng, J. Yu and C. Hu, Tribological properties of polyimide composites reinforced with fibers rubbing against Al2O3, *Friction*, 2021, **9**(2), 301–314.
111 C. Birleanu, B. Paul, R. Udroiu, M. Cioaza and M. Pustan, Impact of CuSn10 powder on mechanical properties and tribological performance of novel basalt fiber-reinforced hybrid composites, *Polymers*, 2025, **17**(11), 1161.
112 R. Venkatesh, A. Agrawal, K. Malarkodi, H. Ramakrishnan, C. B. Priya, A. A. Alothman and A. Ghosh, Features of nano TiO2 on metallographic and optical performance of polyvinyl alcohol nanocomposite film, *Opt. Quantum Electron.*, 2024, **56**, 733.
113 H. Liu, J. Hao, Q. Niu, Q. Du, X. Zheng, H. Liu and H. Yang, Influence of ultrasonic assistance on the microstructure and friction properties of laser cladded Ni60/WC composite coatings, *J. Alloys Compd.*, 2025, **1010**, 177149.
114 C. Birleanu, M. Pustan, M. Cioaza, F. Popa and G. Contiu, Effect of TiO2 nanoparticles on the tribological properties of lubricating oil: An experimental investigation, *Sci. Rep.*, 2022, **12**, 5201.
115 B. Mylsamy, V. Chinnasamy, S. K. Palaniappan, S. Pavayee Subramani and C. Gopalsamy, Effect of surface treatment on the tribological properties of Coccinia Indica cellulosic fiber reinforced polymer composites, *J. Mater. Res. Technol.*, 2020, **9**(6), 16423–16434.

116 C. Birleanu, M. Pustan, G. Pop, M. Cioaza, F. Popa, L. Lazarescu and G. Contiu, Experimental investigation of the tribological behaviors of carbon fiber reinforced polymer composites under boundary lubrication, *Polymers*, 2025, **17**, 1161.
117 M. B. Swathi, D. P. Girish, M. H. Dinesh, R. Keshavamurthy and K. Manjunatha, Taguchi-based analysis of wear performance in SLA printed boron nitride composites, *J. Bio- Tribo-Corros.*, 2025, **11**, 63.
118 K. Gabrysiak, A. V. Boehm, T. Gustmann, C. Leyens and U. Kühn, Elevated-temperature strength and wear behavior of Al80Mn11Ce9 processed by laser powder bed fusion, *J. Mater. Res. Technol.*, 2025, **37**(6), 2327–2337.
119 C. H. Lai, K. H. Cheng, S. J. Lin and J. W. Yeh, Mechanical and tribological properties of multi-element (AlCrTaTiZr)N coatings, *Surf. Coat. Technol.*, 2008, **202**(11), 3732–3738.
120 H. L. Yu, Y. Xu, P. J. Shi, B. S. Xu, X. L. Wang and Q. Liu, Tribological properties and lubricating mechanisms of Cu nanoparticles in lubricant, *Trans. Nonferrous Met. Soc. China*, 2008, **18**(5), 637–645.
121 F. Zhao, G. Li, W. Österle, I. Häusler, G. Zhang, T. Wang and Q. Wang, Tribological investigations of glass fiber reinforced epoxy composites under oil lubrication conditions, *Tribol. Int.*, 2016, **105**, 296–305.
122 B. Chen, X. Li, X. Li, Y. Jia, J. Yang and C. Li, Hierarchical carbon fiber–SiO2 hybrid/polyimide composites with enhanced thermal, mechanical, and tribological properties, *Polym. Compos.*, 2017, **39**, E1626–E1634.
123 P. Johansson, P. Marklund, M. Björling and Y. Shi, Effect of roughness on the running-in behavior and tribofilm formation of carbon fiber reinforced PTFE composite in trace moisture environment, *Wear*, 2022, **500–501**, 204367.
124 S. C. Ho, J. H. C. Lin and C. P. Ju, Effect of fiber addition on mechanical and tribological properties of a copper/phenolic-based friction material, *Wear*, 2005, **258**(5), 861–869.
125 X. Wang, C. Li, K. Gong and X. Wu, Surface-modified MoS2 nanoparticles as tribological additives in a glycerol solution, *ACS Appl. Nano Mater.*, 2023, **6**(8), 6662–6669.
126 S. Li, C. Dong, C. Yuan and X. Bai, Study of the synergistic effects of fiber orientation, fiber phase and resin phase in a fiber-reinforced composite material on its tribological properties, *Wear*, 2019, **426–427**, 1047–1055.
127 F. Dong, G. Hou, H. Liu, L. Liu, F. Cao, J. Wang and F. Yan, An investigation on the mechanical and tribological properties of carbon fiber/polyimide composites at elevated temperatures, *Polym. Compos.*, 2017, **39**, E869–E882.
128 H. Xu, Z. Feng, J. Chen and H. Zhou, Tribological behavior of the carbon fiber reinforced polyphenylene sulfide (PPS) composite coating under dry sliding and water lubrication, *Mater. Sci. Eng., A*, 2006, **416**(1), 66–73.
129 F. Chegdani, S. Mezghani, M. El Mansori and A. Mkaddem, Fiber type effect on tribological behavior when cutting natural fiber reinforced plastics, *Wear*, 2015, **332–333**, 1–14.
130 A. Shalwan and B. F. Yousif, In state of art: Mechanical and tribological behaviour of polymeric composites based on natural fibres, *Mater. Des.*, 2013, **48**, 14–24.
131 S. Behera, R. K. Gautam, S. Mohan and A. Chattopadhyay, Hemp fiber surface modification: Its effect on mechanical and tribological properties of hemp fiber reinforced epoxy composites, *Polym. Compos.*, 2021, **42**(10), 4905–4918.
132 S. SMR, S. Siengchin, J. Parameswaranpillai, M. Jawaid, C. I. Pruncu and A. Khan, A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization, *Carbohydr. Polym.*, 2019, **207**, 108–121.
133 P. Lyu, Y. Zhang, X. Wang and C. Hurren, Degumming methods for bast fibers—A mini review, *Ind. Crops Prod.*, 2021, **174**, 114158.
134 P. Tahir, A. B. Ahmed, S. O. A. SaifulAzry and Z. Ahmed, Retting process of some bast plant fibers and its effect on fibre quality: a review, *BioResources*, 2011, **6**(4), 5260–5281.
135 M. R. Karim, *et al.*, Design, development, and performance evaluation of a power-operated jute fiber extraction machine, *AgriEngineering*, 2021, **3**(2), 403–422.
136 V. S. Sreenivasan, S. Somasundaram, D. Ravindran, V. Manikandan and R. Narayanasamy, Microstructural, physico-chemical and mechanical characterisation of Sansevieria cylindrica fibres – An exploratory investigation, *Mater. Des.*, 2011, **32**, 453–461.
137 M. A. Nasreen, M. M. Ali, S. Akhter, D. M. A. R. Tahmina and M. M. Uddin, Mechanization of fibre extraction: an eco-friendly alternative method of jute retting, *J. Sci. Technol. Environ. Inform.*, 2021, **11**(01), 749–755.
138 V. S. Sreenivasan, S. Somasundaram, D. Ravindran, V. Manikandan and R. Narayanasamy, Microstructural, physico-chemical and mechanical characterisation of Sansevieria cylindrica fibres – An exploratory investigation, *Mater. Des.*, 2011, **32**(1), 453–461.
139 A. Ali, *et al.*, Hydrophobic treatment of natural fibers and their composites—A review, *J. Ind. Text.*, 2018, **47**(8), 2153–2183.
140 N. Karthi, *et al.*, A review of natural fiber composites: Extraction methods, chemical treatments and applications, *Mater. Today: Proc.*, 2021, **45**, 8017–8023.
141 C. H. Lee, A. Khalina, S. H. Lee and M. Liu, A comprehensive review on bast fibre retting process for optimal performance in fibre-reinforced polymer composites, *Adv. Mater. Sci. Eng.*, 2020, **2020**, 1–27.
142 S. Banik, *et al.*, Ribbon retting of jute—a prospective and eco-friendly method for improvement of fibre quality, *Ind. Crops Prod.*, 2003, **17**(3), 183–190.
143 J. Summerscales, A review of bast fibres and their composites: Part 4 ∼ organisms and enzyme processes, *Composites, Part A*, 2021, **140**, 106149.
144 D. E. Akin, B. Condon, M. Sohn, J. A. Foulk, R. B. Dodd and L. L. Rigsby, Optimization for enzyme-retting of flax with pectate lyase, *Ind. Crops Prod.*, 2007, **25**(2), 136–146.
145 S. Réquilé, *et al.*, Retting and degumming of natural fibers by pectinolytic enzymes produced from Bacillus tequilensis

SV11 UV37 using solid state fermentation, *Ind. Crops Prod.*, 2021, **164**, 113337.

146 M. M. H. Parvez, S. M. N. Rupom, M. M. Adil, T. Tasnim, M. S. Rabbi and I. Ahmed, Investigation of mechanical properties of rattan and bamboo fiber reinforced vinyl ester composite material for automotive application, *Results Mater.*, 2023, **19**, 100437.

147 A. K. Ghorai and A. K. Chakraborty, Sustainable in-situ jute retting technology in low volume water using native microbial culture to improve fibre quality and retting waste management, *Int. J. Curr. Microbiol. Appl. Sci.*, 2020, **9**(11), 1080–1099.

148 M. C. Subash and P. Muthiah, Eco-friendly degumming of natural fibers for textile applications: A comprehensive review, *Cleaner Eng. Technol.*, 2021, **5**, 100304.

149 S. Kalia, K. Thakur, A. Celli, M. A. Kiechel and C. L. Schauer, Surface modification of plant fibers using environment friendly methods for their application in polymer composites, textile industry and antimicrobial activities: A review, *J. Environ. Chem. Eng.*, 2013, **1**(3), 97–112.

150 A. V. Kiruthika, A review of leaf fiber reinforced polymer composites, *J. Eng. Appl. Sci.*, 2024, **71**, 24.

151 P. Jagadeesh, M. Puttegowda, S. Mavinkere Rangappa and S. Siengchin, A review on extraction, chemical treatment, characterization of natural fibers and its composites for potential applications, *Polym. Compos.*, 2021, **42**(12), 6239–6264.

152 H. Tibolla, F. M. Pelissari and F. C. Menegalli, Cellulose nanofibers produced from banana peel by chemical and enzymatic treatment, *LWT Food Sci. Technol.*, 2014, **59**, 1311–1318.

153 A. Hasan, M. S. Rabbi and M. M. Billah, Making the lignocellulosic fibers chemically compatible for composite: A comprehensive review, *Cleaner Mater.*, 2022, **4**, 100078.

154 P. G. Baskaran, M. Kathiresan and P. Pandiarajan, Effect of alkali-treatment on structural, thermal, tensile properties of Dichrostachys cinerea bark fiber and its composites, *J. Nat. Fibers*, 2022, **19**(2), 433–449.

155 A. Bezazi, H. Boumediri, G. Garcia Del Pino, B. Bezzazi, F. Scarpa, P. N. Reis and A. Dufresne, Alkali treatment effect on physicochemical and tensile properties of date palm rachis fibers, *J. Nat. Fibers*, 2022, **19**(10), 3770–3787.

156 M. Boumaaza, A. Belaadi and M. Bourchak, The effect of alkaline treatment on mechanical performance of natural fibers-reinforced plaster: Optimization using RSM, *J. Nat. Fibers*, 2021, **18**(12), 2220–2240.

157 C. Tenazoa, H. Savastano, S. Charca, M. Quintana and E. Flores, The effect of alkali treatment on chemical and physical properties of Ichu and Cabuya fibers, *J. Nat. Fibers*, 2021, **18**(7), 923–936.

158 G. Bar and K. Chaudhary, Characterization of textile grade novel Bauhinia vahlii fiber, *J. Nat. Fibers*, 2023, **20**(1), 2143464.

159 S. Sun, S. Pillay and H. Ning, Mechanical behaviors of composites made of natural fibers through environmentally friendly treatment, *J. Thermoplast. Compos. Mater.*, 2024, **37**(12), 3715–3734.

160 M. Mohammed, A. J. A. M. Jawad, A. M. Mohammed, J. K. Oleiwi, T. Adam, A. F. Osman, O. S. Dahham, B. O. Betar, S. C. Gopinath and M. Jaafar, Challenges and advancement in water absorption of natural fiber-reinforced polymer composites, *Polym. Test.*, 2023, **124**, 108083.

161 A. Kudva, M. Gt and D. Pai, Influence of chemical treatment on the physical and mechanical properties of bamboo fibers as potential reinforcement for polymer composites, *J. Nat. Fibers*, 2024, **21**(1), 2332698.

162 M. Abisha, R. K. Priya, K. P. Arunachalam, S. Avudaiappan, E. I. Saavedra Flores and P. F. Parra, Biodegradable green composites: Effects of potassium permanganate (KMnO4) treatment on thermal, mechanical, and morphological behavior of Butea parviflora (BP) fibers, *Polymers*, 2023, **15**(9), 2197.

163 N. K. Kulandaiyappan, V. Raja, C. A. Saleel, M. Alwetaishi, B. S. Arputharaj, A. M. H. Deif and H. A. AL-Bonsrulah, Manufacturing and experimental characterization of new-developed natural fiber reinforced polymer nanocomposite, *J. Mater. Res. Technol.*, 2023, **26**, 6084–6095.

164 P. Acharya, D. Pai and G. T. Mahesha, Effect of chemical treatments on physical and mechanical characteristics of Helicteres isora natural fiber, *Mater. Today: Proc.*, 2023.

165 K. J. Caren, N. D. Kenneth and M. M. David, Strength properties of surface-modified Giant Cavendish (Musa Acuminata) banana fibers, *J. Nat. Fibers*, 2022, **19**(16), 12746–12759.

166 M. Knežević, A. Kramar, T. Hajnrih, M. Korica, T. Nikolić, A. Žekić and M. Kostić, Influence of potassium permanganate oxidation on structure and properties of cotton, *J. Nat. Fibers*, 2022, **19**(2), 403–415.

167 J. Z. Milanovic, M. Milosevic, I. Jankovic-Castvan and M. M. Kostic, Capillary rise and sorption ability of hemp fibers oxidized by non-selective oxidative agents: Hydrogen peroxide and potassium permanganate, *J. Nat. Fibers*, 2022, **19**(12), 4567–4582.

168 B. K. Palai and S. K. Sarangi, Characterization of chemical treated Eichhornia crassipes fibers and its composites, *J. Nat. Fibers*, 2022, **19**(15), 10883–10896.

169 N. Premalatha, S. S. Saravanakumar, M. R. Sanjay, S. Siengchin and A. Khan, Structural and thermal properties of chemically modified Luffa cylindrica fibers, *J. Nat. Fibers*, 2021, **18**(7), 1037–1043.

170 S. Shenoy Heckadka, S. Y. Nayak, T. Joe, N. J. Zachariah, S. Gupta, N. V. Kumar and M. Matuszewska, Comparative evaluation of chemical treatment on the physical and mechanical properties of areca frond, banana, and flax fibers, *J. Nat. Fibers*, 2022, **19**(4), 1531–1543.

171 D. Matykiewicz, M. Barczewski, O. Mysiukiewicz and K. Skórczewska, Comparison of various chemical treatments efficiency in relation to the properties of flax, hemp fibers and cotton trichomes, *J. Nat. Fibers*, 2021, **18**(5), 735–751.

172 S. Pradhan, V. Prakash and S. K. Acharya, Influence of chemical modification on structural, morphological, thermal, and weathering behavior of Eulaliopsis binata fiber and its composites, *J. Nat. Fibers*, 2022, **19**(15), 11870–11884.

173 T. Ramkumar, K. Hariharan, M. Selvakumar and M. Jayaraj, Effect of various surface modifications on characterization of new natural cellulosic fiber from coconut tree secondary flower leaf stalk fiber (CSF), *J. Nat. Fibers*, 2022, **19**(16), 13362–13375.

174 S. Sahu, S. B. Sahu, S. Nayak, J. Mohapatra, S. K. Khuntia, C. Malla, *et al.*, Characterization of natural fiber extracted from Bauhinia vahlii bast subjected to different surface treatments: A potential reinforcement in polymer composite, *J. Nat. Fibers*, 2023, **20**(1), 2162185.

175 D. Verma, K. L. Goh and V. Vimal, Interfacial studies of natural fiber-reinforced particulate thermoplastic composites and their mechanical properties, *J. Nat. Fibers*, 2022, **19**(6), 2299–2326.

176 K. J. Sheeba, R. K. Priya, K. P. Arunachalam, S. Avudaiappan, E. S. Flores and P. Kozlov, Enhancing structural, thermal, and mechanical properties of Acacia pennata natural fibers through benzoyl chloride treatment for construction applications, *Case Stud. Constr. Mater.*, 2023, **19**, e02443.

177 S. Thamarai Selvi, R. Sunitha, L. Ammayappan and C. Prakash, Impact of chemical treatment on surface modification of Agave americana fibres for composite application–A futuristic approach, *J. Nat. Fibers*, 2023, **20**(1), 2142726.

178 M. A. S. Siddiqui, M. S. Rabbi, R. U. Ahmed, F. Alam, M. A. M. Hossain, S. Ahsan and N. M. Miah, Bioinspired composite structures: A comprehensive review of natural materials, fabrication methods, and engineering applications, *Compos., Part C: Open Access*, 2025, **17**, 100578.

179 M. Del Angel-Monroy, V. Escobar-Barrios, M. G. Peña-Juarez, L. E. Lugo-Uribe, J. Navarrete-Damian, E. Perez and J. A. Gonzalez-Calderon, Effect of coconut fibers chemically modified with alkoxysilanes on the crystallization, thermal, and dynamic mechanical properties of poly (lactic acid) composites, *Polym. Bull.*, 2024, **81**(1), 843–870.

180 D. Matykiewicz, B. Dudziec, K. Skórczewska and K. Sałasińska, The effect of silanes treatments on thermal and mechanical properties of nettle fibre/bio epoxy composites, *J. Nat. Fibers*, 2024, **21**(1), 2332913.

181 M. Fei, W. Liu, L. Shao, Y. Cao, B. J. Bliss, B. Zhao and J. Zhang, Hemp fiber reinforced dual dynamic network vitrimer biocomposites with direct incorporation of amino silane, *Chem. Eng. J.*, 2024, **480**, 148091.

182 P. T. Arasu, P. S. Seenidurai, A. Murugan and S. Elangovan, Functional modification of Borassus flabellifer shealth fibers using isocyanate, *Lett. Appl. NanoBioScience*, 2021, **10**(1), 1889–1895.

183 M. Yang, J. Su, Y. Zheng, C. Fang, W. Lei and L. Li, Effect of different silane coupling agents on properties of waste corrugated paper fiber/polylactic acid composites, *Polymers*, 2023, **15**(17), 3525.

184 E. Gorgun, A. Ali and M. S. Islam, Biocomposites of poly (lactic acid) and microcrystalline cellulose: Influence of the coupling agent on thermomechanical and absorption characteristics, *ACS Omega*, 2024, **9**(10), 11523–11533.

185 A. Dhanola, A comprehensive overview on tribo-mechanical characteristics of hybrid plant fiber-based biocomposites, *Emergent Mater.*, 2023, **6**, 1707–1726.

186 Y. Liu and Y. Ma, The improvement of the tribological behaviour of chemically treated abaca fibre-reinforced polymer composites, *Materials*, 2024, **17**(1), 229.

187 M. Ramesh, L. Rajeshkumar and V. Bhuvaneswari, Leaf fibres as reinforcements in green composites: a review on processing, properties and applications, *Emergent Mater.*, 2022, **5**, 833–857.

188 A. A. Musa and A. P. Onwualu, Potential of lignocellulosic fiber reinforced polymer composites for automobile parts production: Current knowledge, research needs, and future direction, *Heliyon*, 2024, **10**(7), e24683.

189 R. Punyamurthy, D. Sampathkumar, B. Bennehalli, R. Patel and S. C. Venkateshappa, Abaca fiber reinforced epoxy composites: Evaluation of impact strength, *Int. J. Basic Appl. Sci.*, 2014, **18**(2), 305–317.

190 M. Milosevic, D. Dzunic, P. Valasek, S. Mitrovic and A. Ruggiero, Effect of fiber orientation on the tribological performance of abaca-reinforced epoxy composite under dry contact conditions, *J. Compos. Sci.*, 2022, **6**(7), 204.

191 Y. Liu, Y. Ma, J. Yu, J. Zhuang, S. Wu and J. Tong, Development and characterization of alkali treated abaca fiber reinforced friction composites, *Compos. Interfaces*, 2018, **25**(4), 123–141.

192 R. A. Kurien, D. P. Selvaraj and C. P. Koshy, Worn surface morphological characterization of NaOH-treated chopped abaca fiber reinforced epoxy composites, *J. Bio- Tribo-Corros.*, 2021, **7**, 31.

193 N. Kumar, S. Singh, A. Singh and T. Han, Mechanical, water absorption, and tribological behavior of polymer composites: Role of pineapple leaf fiber orientation, *Lubricants*, 2025, **13**(4), 161.

194 R. Venkatesh, A. D. Das, R. M. Kamatchi, G. Kaliyaperumal, M. Ajin and R. Shanmugam, Synthesis and functional behavior of sisal fiber-incorporated epoxy hybrid nanocomposite enriched by nano-SiC, *J. Inst. Eng. (India): Ser. D*, 2024, 1–5.

195 S. Behera, R. K. Gautam and S. Mohan, The effect of eco-friendly chemical treatment on sisal fiber and its epoxy composites: Thermal, mechanical, tribological, and morphological properties, *Cellulose*, 2022, **29**(12), 9055–9072.

196 H. O. Maurya, K. Jha and Y. K. Tyagi, Tribological behavior of short sisal fiber reinforced epoxy composite, *Polym. Polym. Compos.*, 2017, **25**(3), 215–219.

197 M. Hareesha, D. Saravanabavan, B. Yogesha, L. Girisha and T. H. Raju, Fabrication, microstructure study, and wear characteristics of coconut shell powder filled natural sisal

and jute fiber reinforced epoxy composites, *J. Inst. Eng. (India): Ser. D*, 2025, **106**(1), 459–469.

198 H. O. Maurya, K. Jha and Y. K. Tyagi, Tribological behavior of short sisal fiber reinforced epoxy composite, *Polym. Polym. Compos.*, 2017, **25**(3), 215–219.

199 N. Chand and U. K. Dwivedi, Influence of fiber orientation on high stress wear behavior of sisal fiber-reinforced epoxy composites, *Polym. Compos.*, 2007, **28**(5), 437–441.

200 R. Venkatesh, S. Ballal, A. M. Krishnan, S. Prabagaran, S. Mohankumar and E. Ramaraj, Effect of fiber layer formation on mechanical and wear properties of natural fiber filled epoxy hybrid composites, *Heliyon*, 2023, **9**, e15934.

201 T. F. Santos, J. P. da Costa, L. V. G. da Silva, B. O. Reis and D. M. de Barros, Towards sustainable and ecofriendly polymer composite materials from bast fibers: a systematic review, *Eng. Res. Express*, 2024, **6**(1), 012501.

202 S. Sahu, B. P. J. Sahu, S. Nayak, M. K. Roul and S. K. Khuntia, Effect of chemical treatment and fiber loading on various properties of Bauhinia vahlii bast fibers/acrylonitrile butadiene styrene composites for automotive body parts, *Polym. Compos.*, 2022, **43**(8), 5174–5187.

203 T. C. Mokhena, A. Mtibe, T. H. Mokhothu, M. J. Mochane and M. J. John, A review on bast-fibre-reinforced hybrid composites and their applications, *Polymers*, 2023, **15**(16), 3414.

204 G. Teli, V. K. Mahakur, R. Paul and S. Bhowmik, Investigation of dry sliding tribological behaviour of epoxy composites filled with hemp particulates using artificial neural networks, *Arabian J. Sci. Eng.*, 2023, **48**, 3989–4001.

205 N. Kumar, T. Singh, J. S. Grewal, A. Patnaik and G. Fekete, Experimental investigation on the physical, mechanical and tribological properties of hemp fiber-based non-asbestos organic brake friction composites, *Mater. Res. Express*, 2019, **6**(8), 085710.

206 P. H. K. Patil, P. Shetty, V. Jeevan Dias, T. I. V. Resham, M. Shetty and N. H. Padmaraj, Influence of process parameters on tribological behavior of hemp powder reinforced epoxy composites, *Cogent Eng.*, 2024, **11**(1), 2322075.

207 M. Bartoli, D. Duraccio, M. G. Faga, E. Piatti, D. Torsello, G. Ghigo and G. Malucelli, Mechanical, electrical, thermal, and tribological behavior of epoxy resin composites reinforced with waste hemp-derived carbon fibers, *J. Mater. Sci.*, 2022, **57**, 14861–14876.

208 M. Morino, T. Kajiyama and Y. Nishitani, Influence of epoxy resin treatment on the mechanical and tribological properties of hemp-fiber-reinforced plant-derived polyamide 1010 biomass composites, *Molecules*, 2021, **26**, 1228.

209 V. Mishra and S. Biswas, Three-body abrasive wear behavior of short jute fiber reinforced epoxy composites, *Polym. Compos.*, 2016, **37**, 270–278.

210 F. Z. Alshammari, K. H. Saleh, B. F. Yousif, A. Alajmi, A. Shalwan and J. G. Alotaibi, The influence of fibre orientation on tribological performance of jute fibre reinforced epoxy composites considering different mat orientations, *Tribol. Ind.*, 2018, **40**(3), 335–348.

211 K. Singh, M. L. Rinawa, N. Ahamad, V. Chaudhary, P. P. Das, S. Gupta and P. Gupta, Optimization of tribological performance of natural fibers/epoxy composites using ANOVA & TOPSIS approach, *Mater. Today: Proc.*, 2021, **44**, 2617–2622.

212 B. S. Rana, G. Bhushan and P. Chandna, A comparative analysis of dry sliding wear characterization of textile wastes (cotton/jute fabrics) reinforced nano fly ash filled epoxy based hybrid composites, *Aircr. Eng. Aerosp. Technol.*, 2023, **95**(8), 1286–1294.

213 M. Bhargav and V. Suresh Babu, Experimental investigation of fiber orientation effect on mechanical and erosive wear performance of TiO2 filled woven jute fiber-based epoxy composites, *Mater. Today: Proc.*, 2021, **44**, 2617–2622.

214 A. K. Jha, S. Mantry, A. Satapathy and A. Patnaik, Erosive wear performance analysis of jute-epoxy-SiC hybrid composites, *J. Compos. Mater.*, 2010, **44**(13), 1623–1636.

215 A. Paturkara, A. Mache, A. Deshpande and A. Kulkarni, Experimental investigation of dry sliding wear behavior of jute/epoxy and jute/glass/epoxy hybrids using Taguchi approach, *Mater. Today: Proc.*, 2018, **5**, 23974–23983.

216 M. Hareesha, D. Saravanabavan, B. Yogesha, L. Girisha and T. H. Raju, Fabrication, microstructure study and wear characteristics of coconut shell powder filled natural sisal and jute fiber reinforced epoxy composites, *J. Inst. Eng. (India): Ser. D*, 2025, **40**(3), 335–348.

217 B. Suresha, S. L. Guggare and N. V. Raghavendra, Effect of TiO2 filler loading on physico-mechanical properties and abrasion of jute fabric reinforced epoxy composites, *Mater. Sci. Appl.*, 2016, **7**, 510–526.

218 B. F. Yousif and C. W. Chin, Potential of kenaf fibres as reinforcement for tribological applications, *Wear*, 2009, **267**(9), 1550–1557.

219 N. Sapiai, A. Jumahat, M. Jawaid and C. Santulli, Abrasive wear behavior of CNT-filled unidirectional Kenaf–epoxy composites, *Processes*, 2021, **9**(1), 128.

220 T. Venkategowda, L. H. Manjunatha and P. R. Anilkumar, Adhesive and abrasive wear behavior of Kenaf long fiber reinforced epoxy composites, *Mater. Today: Proc.*, 2021, **45**, 150–155.

221 B. F. Yousif and C. W. Chin, Epoxy composite based on kenaf fibres for tribological applications under wet contact conditions, *Surf. Rev. Lett.*, 2012, **19**(5), 1250050.

222 S. Kasolang, M. A. Ahmad, F. A. Ghazali and A. M. Azmi, Preliminary study of dry sliding wear in Kenaf Epoxy and Carbon Epoxy composites, *Appl. Mech. Mater.*, 2011, **52–54**, 464–469.

223 F. M. Khan, A. H. Shah, S. Wang, S. Mehmood, J. Wang, W. Liu and X. Xu, A comprehensive review on epoxy biocomposites based on natural fibers and bio-fillers: Challenges, recent developments and applications, *Adv. Fiber Mater.*, 2022, **4**, 683–704.

224 H. H. Parikh, Tribology of plant-based natural fiber reinforced polymer matrix composites—a short review, *J. Nat. Fibers*, 2023, **20**(1), 2172639.
225 S. Dhanalakshmi, R. Punyamurthy, B. Bennehalli and S. C. Venkateshappa, Physical characterization of natural lignocellulosic single areca fiber, *Cienc. Tecnol. Mater.*, 2015, **27**(3), 121–135.
226 M. A. Akhter, D. Mondal, A. K. Debnath and M. S. Rabbi, Evaluation of mechanical and thermal performance of jute and coconut fiber-reinforced epoxy composites with rice husk ash for wall insulation applications, *Heliyon*, 2025, **11**(17), e42211.
227 A. J. Sankarathil, R. Rosari, V. S. Joseph, S. Jannet and A. A. Mathew, Chopped Areca Nut Fibers as Filler in Epoxy Matrix: Mechanical and Tribological Studies, *Trends Sci.*, 2023, **20**(12), 7155.
228 R. B. Ashok, C. V. Srinivasa and B. Basavaraju, Study on morphology and mechanical behavior of areca leaf sheath reinforced epoxy composites, *Adv. Compos. Hybrid Mater.*, 2020, **3**, 552–564.
229 P. S. Suresh, K. Dilip Kumar, S. N. Gautham, S. Preetham, C. V. Srinivasa and B. Basavaraju, Tribological properties of areca sheath fiber composites, *Mater. Today: Proc.*, 2021, **45**(Part 2), 2419–2424.
230 P. K. Choudhary, B. P. Nanda and A. Satapathy, Development, characterization, and parametric analysis of dry sliding wear behavior of epoxy-short betel nut fiber composite using response surface method and neural computation, *Polym. Polym. Compos.*, 2022, **30**, 1–11.
231 S. J. Irudaya Raja and S. Sivaganesan, Experimental investigation on wear properties with micro-structure behavior of arecanut reinforced polymer composite material, *Mater. Today: Proc.*, 2021, **39**, 682–689.
232 V. G. Geethamma, K. T. Mathew, R. Lakshminarayanan and S. Thomas, Composite of short coir fibres and natural rubber: effect of chemical modification, loading and orientation of fibre, *Polymer*, 1998, **39**(6–7), 1483–1491.
233 L. Yan, B. Kasal and L. Huang, A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering, *Composites, Part B*, 2016, **92**, 94–132.
234 L. Yan, N. Chouw and K. Jayaraman, Flax fibre and its composites – a review, *Composites, Part B*, 2014, **56**, 296–317.
235 G. Das and S. Biswas, Erosion wear behavior of coir fiber-reinforced epoxy composites filled with Al2O3 filler, *J. Ind. Text.*, 2017, **47**(4), 472–488.
236 R. Paul, D. Zindani and S. Bhowmik, Investigation on physicomechanical, tribological, and optimality condition for coir filler-reinforced polymeric composites, *Arabian J. Sci. Eng.*, 2023, **48**, 3615–3630.
237 P. Valášek, R. D'Amato, M. Müller and A. Ruggiero, Mechanical properties and abrasive wear of white/brown coir epoxy composites, *Composites, Part B*, 2018, **5611**, 1–9.
238 A. Shalwan, S. Mallampati and B. F. Yousif, Abrasive wear performance of coir fiber-reinforced polymer composite, *Tribol. Ind.*, 2023, **45**(3), 532–541.
239 A. I. Imran, J. P. Siregar, M. R. Mat Rejab, T. Cionita, A. E. Hadi, J. Jaafar, D. F. Fitriyana and R. Dewi, Opportunities and challenges in the sustainable integration of natural fibers and particles in friction materials for eco-friendly brake pads, *Mech. Eng. Soc. Ind.*, 2024, **4**(3), 337–367.
240 U. Nirmal, J. Hashim and K. O. Low, Adhesive wear and frictional performance of bamboo fibers reinforced epoxy composite, *Tribol. Int.*, 2012, **47**, 122–133.
241 B. A. Oliver, Q. Dong, M. Ramezani, M. A. Selles and S. Sanchez-Caballero, Tribological performance of bamboo fabric reinforced epoxy composites, *Macromol. Mater. Eng.*, 2023, **308**, 2300077.
242 H. Hu, M. Zhang, W. Liu, C. Wang, C. Xiang and C. Kong, Mechanical and erosive wear performances of natural bamboo fibers/SiO2/epoxy ternary composites, *Polym. Test.*, 2023, **124**, 108058.
243 S. Biswas and A. Satapathy, A comparative study on erosion characteristics of red mud filled bamboo–epoxy and glass–epoxy composites, *Mater. Des.*, 2009, **31**(5), 1752–1767.
244 D. Wang, T. Bai, W. Cheng, C. Xu, G. Wang, H. Cheng and G. Han, Surface modification of bamboo fibers to enhance the interfacial adhesion of epoxy resin-based composites prepared by resin transfer molding, *Polymers*, 2019, **11**(12), 2107.
245 S. Biswas and A. Satapathy, An assessment of erosion wear response of SiC filled epoxy composites reinforced with glass and bamboo fibers, *Int. Polym. Process.*, 2010, **XXV**, 205–222.
246 N. Kumari and K. Kumar, Estimation of tribological properties of orthotic calipers fabricated using bamboo reinforced epoxy composite, *Mater. Today: Proc.*, 2021, **46**, 243–245.
247 P. J. Chavali and G. B. Taru, Effect of fiber orientation on mechanical and tribological properties of banana-reinforced composites, *J. Fail. Anal. Prev.*, 2020, **21**(1), 1–8.
248 U. S. Gupta, S. Tiwari and U. Sharma, Enhancing the abrasive wear performance of banana fiber reinforced epoxy composites through low-pressure nitrogen treatment of banana fiber, *J. Inst. Eng. (India): Ser. D*, 2025, **106**(1), 459–469.
249 T. P. Mohan and K. Kanny, Tribological properties of nanoclay infused banana fiber reinforced epoxy composites, *J. Tribol.*, 2019, **141**(5), 052003.
250 B. F. Yousif and A. Shalwan, Influence of date palm fibre and graphite filler on mechanical and wear characteristics of epoxy composites, *Mater. Des.*, 2014, **59**, 264–273.
251 N. A. M. Tahir, M. F. B. Abdollah, R. Hasan and H. Amiruddin, The effect of sliding distance at different temperatures on the tribological properties of a palm kernel activated carbon–epoxy composite, *Tribol. Int.*, 2016, **94**, 352–359.
252 M. Bakry, M. O. Mousa and W. Y. Ali, Friction and wear of friction composites reinforced by natural fibres, *Mater. Sci. Eng., A*, 2013, **44**(1), 21–28.

253 D. N. F. Mahmud, M. F. B. Abdollah, N. A. B. Masripan, N. Tamaldin and H. Amiruddin, Influence of contact pressure and sliding speed dependence on the tribological characteristics of an activated carbon-epoxy composite derived from palm kernel under dry sliding conditions, *Friction*, 2019, **9**(2), 250–272.

254 S. Majhi, S. P. Samantarai and S. K. Acharya, Tribological behavior of modified rice husk filled epoxy composite, *Int. J. Sci. Eng. Res.*, 2012, **3**(6), 1–5.

255 S. P. Samantrai, G. Raghavendra and S. K. Acharya, Effect of carbonization temperature and fibre content on the abrasive wear of rice husk char reinforced epoxy composite, *Proc. Inst. Mech. Eng., Part J*, 2013, **228**(4), 463–469.

256 V. S. Aigbodion, Explicit simultaneous enhancement of adhesion strength and wear resistance of functional value-added epoxy-functionalized rice husk ash nanoparticle composite coating, *Int. J. Adv. Manuf. Technol.*, 2020, **109**, 2205–2214.

257 A. P. Irawan, D. F. Fitriyana, J. P. Siregar, T. Cionita, P. T. Anggarina, D. W. Utama, *et al.*, Influence of varying concentrations of epoxy, rice husk, Al2O3, and Fe2O3 on the properties of brake friction materials prepared using hand layup method, *Polymers*, 2023, **15**(12), 2597.

258 P. Deepak, H. Sivaramana, R. Vimal and R. V. Kumar, Study of wear properties of jute/banana fibers reinforced molybdenum disulphide modified epoxy composites, *Mater. Today Proc.*, 2017, **4**, 2910–2919.

259 K. S. Krupesh, R. Suresh, B. M. Rudresh and K. Ajaykumar, Effect of abrasive grit grade on the abrasion wear behaviour of long banana-jute fibers reinforced hybrid epoxy composites, *Mater. Res. Express*, 2023, **10**(12), 125102.

260 A. Suresh, L. Jayakumar and A. Devaraju, Investigation of mechanical and wear characteristics of banana/jute fiber composite, *Mater. Today: Proc.*, 2020, **28**, 2145–2150.

261 S. K. Acharya, T. Bera, V. Prakash and S. Pradhan, Effect of stacking sequence on the tribological behaviour of jute-glass hybrid epoxy composite, *Mater. Today: Proc.*, 2019, **28**, 1200–1206.

262 M. D. Kumar, C. Senthamaraikannan, S. Jayasrinivasan and S. Aushwin, Study on static and dynamic behavior of jute/sisal fiber reinforced epoxy composites, *Mater. Today: Proc.*, 2021, **46**(19), 9425–9428.

263 S. Ragunath, C. Velmurugan and T. Kannan, Optimization of tribological behavior of nano clay particle with sisal/jute/glass/epoxy polymer hybrid composites using RSM, *Polym. Adv. Technol.*, 2017, **28**, 1813–1822.

264 H. Manjulaiah, S. Dhanraj, Y. Basavegowda, L. N. Lamani, M. Puttegowda, S. M. Rangappa and S. Siengchin, A novel study on the development of sisal-jute fiber epoxy filler-based composites for brake pad application, *Biomass Convers. Biorefin.*, 2023, **14**, 23411–23423.

265 M. Jawaid and H. P. S. Abdul Khalil, Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review, *Carbohydr. Polym.*, 2011, **86**(1), 1–18.

266 M. Ardanuy, J. Claramunt and R. D. Toledo Filho, Cellulosic Fiber Reinforced Cement-Based Composites: A Review of Recent Research, *Constr. Build. Mater.*, 2015, **79**, 115–128.

267 M. Ardanuy, J. Claramunt, R. Arévalo, F. Parés, E. Aracri and T. Vidal, Nanofibrillated cellulose (NFC) as a potential reinforcement for high performance cement mortar composites, *BioResources*, 2012, **7**(3), 3883–3894.

268 L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid and M. S. Islam, A review on natural fiber reinforced polymer composite and its applications, *Int. J. Polym. Sci.*, 2015, **2015**, 243947.

269 S. Mahanta, S. Samanta and M. Chandrasekaran, Processing and investigation of tribological properties of basalt epoxy composites, *Mater. Today: Proc.*, 2017, **4**(8), 8185–8191.

270 M. V. De Poures, K. Sudhir Chakravarthy, M. D. Jabihulla Shariff, Y. Srinivasa Reddy, V. Siva Prasad, K. Sreenivasa Rao, *et al.*, Excellence of Nano SiC on mechanical behaviour of low density polyethylene hybrid nanocomposite, *J. Inst. Eng. (India): Ser. D*, 2024, 1–6.

271 T. Sen and H. N. J. Reddy, A review of natural fibers for structural upgradation and sustainable development, *Int. J. Innovat. Technol. Manag.*, 2011, **2**(3), 192–198.

272 M. Idicula, S. K. Malhotra, K. Joseph and S. Thomas, Dynamic mechanical analysis of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites, *Compos. Sci. Technol.*, 2005, **65**(7–8), 1077–1087.

273 M. Ramesh, C. Deepa, L. R. Kumar, M. Sanjay and S. Siengchin, Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: A critical review, *J. Ind. Text.*, 2020, **51**(4_suppl), 5518S–5542S.

274 M. Ramesh, L. Rajesh Kumar, A. Khan and A. M. Asiri, Self-healing polymer composites and its chemistry. in *Self-Healing Composite Materials*, ed. Khan A., Jawaid M., Raveendran S. N. and Asiri A. M. A., Woodhead Publishing, 2020, pp. 415–427.

275 M. H. N. Hussin, A. Hambali, M. Yaakob, Z. Marjom, T. Taufik and H. Y. Saifuddin, A review of current development in natural fiber composites in automotive applications, *Appl. Mech. Mater.*, 2014, **564**, 3–7.

276 I. Tawakkal, M. Cran and S. Bigger, Effect of kenaf fibre loading and thymol concentration on the mechanical and thermal properties of PLA/kenaf/thymol composites, *Ind. Crops Prod.*, 2014, **61**, 74–83.

277 P. Ribeiro, L. Neuba, P. P. Mendonça da Silveira, F. Luz, A. Figueiredo, S. Monteiro and M. Moreira, Mechanical, thermal, and ballistic performance of epoxy composites reinforced with Cannabis sativa hemp fabric, *J. Mater. Res. Technol.*, 2021, **12**, 221–233.

278 J. M. Khare, S. Dahiya, B. Gangil, L. Ranakoti, S. Sharma, M. R. M. Huzaifah, *et al.*, Comparative analysis of erosive wear behaviour of epoxy, polyester and vinyl esters based thermosetting polymer composites for human prosthetic applications using Taguchi design, *Polymers*, 2021, **13**(20), 3607.

279 P. S. Suresh, K. Dilip Kumar, S. Dhanalakshmi, C. V. Srinivasa and B. Basavaraju, Effect of fiber fraction on the physical and mechanical properties of short areca sheath fiber reinforced polymer composite, *Mater. Today: Proc.*, 2021, **44**(Part 2), 4972–4975.

280 C. Xu, Y. Gu, Z. Yang, M. Li, Y. Li and Z. Zhang, Mechanical properties of surface-treated ramie fiber fabric/epoxy resin composite fabricated by vacuum-assisted resin infusion molding with hot compaction, *J. Compos. Mater.*, 2015, **50**(9), 1189–1198.

281 S. Sankar Lal, S. Kannan and S. K. Sahoo, Influence of flax fiber orientation on mechanical, thermo-mechanical and interfacial adhesion properties of epoxidized methyl ricinoleate modified epoxy composite: A sustainable green composite for cleaner production, *Mater. Today Commun.*, 2022, **33**, 104648.

282 K. R. Sumesh, V. Kavimani, G. Rajeshkumar, S. Indran and G. Saikrishnan, Effect of banana, pineapple and coir fly ash filled with hybrid fiber epoxy based composites for mechanical and morphological study, *J. Mater. Cycles Waste Manag.*, 2021, **23**, 1277–1288.

283 V. Mittal, R. Saini and S. Sinha, Natural fiber-mediated epoxy composites – A review, *Composites, Part B*, 2016, **99**, 425–435.

284 A. R. Banagara, S. C. Venkateshappa, S. S. Kamath and B. Bennehalli, Tensile and flexural properties of areca sheath fibers, *Mater. Today: Proc.*, 2018, **5**(13), 28080–28088.

285 P. Manimaran, P. Senthamaraikannan, M. R. Sanjay, M. K. Marichelvam and M. Jawaid, Study on characterization of Furcraea foetida new natural fiber as composite reinforcement for lightweight applications, *Carbohydr. Polym.*, 2018, **181**, 650–658.

286 D. Klosterman, C. Browning, I. Hakim and K. Lach, Investigation of various techniques for controlled void formation in fiberglass/epoxy composites, *J. Compos. Mater.*, 2020, **55**, 489–506.

287 M. J. Suriani, R. A. Ilyas, M. Y. M. Zuhri, A. Khalina, M. T. H. Sultan, S. M. Sapuan, *et al.*, Critical review of natural fiber reinforced hybrid composites: Processing, properties, applications and cost, *Polymers*, 2021, **13**(20), 3514.

288 G. Rajeshkumar, V. Hariharan, S. Indran, M. R. Sanjay, S. Siengchin, J. P. Maran, *et al.*, Influence of sodium hydroxide (NaOH) treatment on mechanical properties and morphological behaviour of Phoenix sp. fiber/epoxy composites, *J. Polym. Environ.*, 2020, **29**, 765–774.

289 R. A. A. Rusdi, N. A. Halim, N. M. Nurazzi, Z. H. Z. Abidin, N. Abdullah, F. C. Ros, *et al.*, The effect of layering structures on mechanical and thermal properties of hybrid bacterial cellulose/Kevlar reinforced epoxy composites, *Heliyon*, 2022, **8**(6), e09442.

290 G. K. Chowdari, D. V. V. Krishna Prasad and S. B. R. Devireddy, Physical and thermal behaviour of areca and coconut shell powder reinforced epoxy composites, *Mater. Today Proc.*, 2020, **26**(2), 1402–1405.

291 M. Jawaid, S. A. Awad, M. Asim, H. Fouad, O. Y. Alothman and C. Santulli, A comparative evaluation of chemical, mechanical, and thermal properties of oil palm fiber/pineapple fiber reinforced phenolic hybrid composites, *Polym. Compos.*, 2021, **42**(12), 6383–6393.

292 H. Arumugam, B. Krishnasamy, G. Perumal, A. A. Dilip, M. I. Abdul Aleem and A. Muthukaruppan, Bio-composites of rice husk and saw dust reinforced bio-benzoxazine/epoxy hybridized matrices: Thermal, mechanical, electrical resistance and acoustic absorption properties, *Constr. Build. Mater.*, 2021, **312**, 125381.

293 A. Nigrawal, A. Kumar Sharma and F. Z. Haque, Influence of surface modification technique on the properties of jute – Sisal fibre filled epoxy composites, *Mater. Today: Proc.*, 2022, **65**, 2578–2580.