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TRIBOLOGICAL APPLICATIONS OF NATURAL FILLER COMPOSITES REVIEW ARTICLE

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ABSTRACT
Natural filler composites have gained significant attention as sustainable alternatives to traditional synthetic polymers, particularly in tribological applications where friction, wear, and lubrication behavior are critical. These eco-friendly composites incorporate natural fibers such as flax, hemp, kenaf, jute, and agricultural residues like rice husk and wheat straw into polymer matrices, enhancing performance while reducing environmental impact. Recent studies have demonstrated that natural filler composites can achieve comparable or superior tribological properties to synthetic fiber composites under certain conditions. Factors such as fiber treatment, filler type, filler content, and matrix compatibility play crucial roles in optimizing tribological behavior. This review discusses the various types of natural fillers, their influence on tribological performance, current industrial applications, key challenges, and future prospects. Special focus is given to recent advancements in surface modification techniques and hybrid composite designs, aiming to overcome the limitations associated with natural fillers, such as moisture absorption and thermal instability. This comprehensive review provides insight into the growing potential of natural filler polymer composites for tribological applications across automotive, aerospace, biomedical, marine, and industrial sectors.

KEYWORDS
Natural fiber composites (NFCs), Tribology, Surface treatment, Agricultural waste fillers, Bio composites, Sustainable materials and Hybrid composites

INTRODUCTION

1.1 Context: Environmental Challenges of Synthetic Polymers

The dominance of synthetic polymers in industrial and consumer products is undeniable, yet their environmental consequences are substantial. Derived mainly from non-renewable fossil resources, these materials are typically non-biodegradable, contributing significantly to global plastic pollution and greenhouse gas emissions (Geyer, Jambeck, & Law, 2017). Their end-of-life disposal poses a major ecological challenge, especially in regions with inadequate recycling infrastructure. Moreover, their production involves energy-intensive processes and chemical additives that may pose toxicity risks. In tribological applications, synthetic polymers used in sliding and rotating components exacerbate environmental concerns due to the generation of microplastic wear debris,

increased frictional energy losses, and frequent replacement cycles (Bajpai, Singh, & Madaan, 2013).

This has catalyzed growing interest in alternative composite materials that are not only functional but also sustainable. One promising route involves the incorporation of biobased fillers into polymer matrices to reduce reliance on synthetic reinforcements. Dr. R. A. Ibrahem and colleagues have extensively explored this path by integrating agricultural waste materials such as corn husk, peanut shell husk, and sunflower seed husk into thermoset polymer composites. Their work demonstrated significant improvements in tribological behavior, particularly in reducing the coefficient of friction and wear rate, while simultaneously offering a biodegradable and cost-effective filler alternative (Ibrahem, 2015; Ibrahem, 2021).

Furthermore, Ibrahem's studies have highlighted the role of natural lubricants, such as vegetable oils, in modifying the tribological characteristics of composites. By acting as internal lubricants within the matrix, these oils help dissipate heat, reduce adhesion-related wear, and improve energy efficiency during sliding operations (Ibrahem & Ali, 2012). These findings underscore the urgent need and real feasibility of replacing conventional synthetic fillers and lubricants with sustainable, locally available bio-resources in tribological systems.

As regulatory pressures mount and global initiatives push for carbon neutrality and green manufacturing, the integration of bio-based reinforcements and lubricants in polymer composites offers a viable path forward. This transformation aligns with circular economy goals by converting agricultural byproducts into high-performance materials, thereby reducing environmental impact and promoting resource efficiency.

1.2 Rise of Natural Fiber Composites as Eco-Friendly Alternatives

In the context of growing environmental awareness and resource depletion, natural fiber composites (NFCs) have gained increasing attention as viable alternatives to conventional synthetic composites. NFCs consist of plant-based fibers—such as flax, hemp, jute, kenaf, coir, and agro-waste byproducts—embedded within a polymeric matrix. These bio-based reinforcements are derived from renewable agricultural sources, and their incorporation not only reduces the environmental footprint of the final product but also adds value to agricultural residues (Mohanty, Misra, & Drzal, 2005; Pickering, Efendy, & Le, 2016).

The advantages of NFCs are multifaceted. Natural fibers are low-cost, biodegradable, carbon-neutral, and lightweight. Their mechanical properties—such as specific tensile strength and modulus—are often competitive with synthetic fibers like glass or aramid in weight-sensitive applications (Bledzki & Gassan, 1999). Furthermore, the low energy demand in fiber processing and their capability to sequester CO_2 during growth enhance the overall life cycle sustainability of these composites (Kumar et al., 2021). Such characteristics have positioned NFCs as attractive materials in construction, automotive, packaging, and consumer goods industries.

Dr. R. A. Ibrahem's contributions have further solidified the role of agro-waste fibers in sustainable composite development. In particular, his research has shown that non-traditional natural fillers, including corn husk, sunflower seed husk, and peanut shell, can be successfully used to reinforce polyester and epoxy matrices with notable improvements in friction and wear performance (Ibrahem, 2015; Ibrahem, 2021). These

fillers, often discarded as waste, offer not only mechanical reinforcement but also significant environmental advantages by enabling waste valorization and reducing landfill dependence.

Additionally, Ibrahem has explored the integration of vegetable oils—such as sunflower and soybean oils—as plasticizers or internal lubricants in the composite matrix. These oils enhance interfacial bonding and reduce the composite's susceptibility to dry sliding wear. His findings demonstrated a significant decrease in the coefficient of friction and an improvement in the anti-scoring capacity of natural-fiber-filled composites under tribological loading conditions (Ibrahem & Ali, 2012). This approach not only improves the material's performance but also aligns with circular economy principles by utilizing fully renewable, biodegradable inputs.

As industries seek to transition toward more sustainable and environmentally benign materials, NFCs represent a promising class of composites that meet both functional and ecological demands. Their adoption is further supported by international regulations promoting green procurement and eco-labeling, as well as growing consumer preference for environmentally responsible products. Research such as that of Dr. Ibrahem is instrumental in demonstrating the technical feasibility and commercial potential of these materials in friction-based applications, including flooring, automotive brake linings, and green energy systems.

1.3 Relevance of Tribology in Industrial Applications

Tribology, the multidisciplinary study of friction, wear, and lubrication, is central to the performance, durability, and energy efficiency of mechanical systems. Components subjected to relative motion—such as gears, bearings, bushings, flooring surfaces, and brake systems—are constantly influenced by tribological interactions, which directly affect product lifespan, maintenance requirements, and energy consumption. For instance, in industrial flooring, insufficient slip resistance can lead to safety hazards, while in automotive or aerospace applications, poor wear resistance can compromise system integrity and lead to early component failure (Kishore et al., 2000).

Over the past two decades, tribological research has evolved to incorporate material sustainability alongside performance optimization. Traditional engineering materials such as metals, ceramics, and synthetic polymers are being reconsidered in light of their environmental impact and recyclability. Natural fiber composites (NFCs) are increasingly being explored not only for their mechanical and thermal properties but also for their behavior under tribological stresses such as dry sliding, abrasive contact, and impact wear (Thakur et al., 2014). However, the anisotropic nature of natural fibers, their moisture sensitivity, and the variability introduced by agricultural origin complicate their tribological modeling, necessitating more experimental studies to evaluate performance under diverse operating conditions.

Significantly, Ibrahem's investigations have demonstrated that tribological performance can be markedly improved through careful selection and treatment of natural fillers. His work on epoxy and polyester composites reinforced with agro-waste materials and enhanced with natural lubricants has provided a framework for optimizing the frictional and wear behavior of NFCs (Ibrahem, 2015; Ibrahem, 2021). In one study, the inclusion of vegetable oils with chopped basalt and seed husk fillers led to improved wear resistance and a marked reduction in the coefficient of friction under varying load and speed

conditions. These outcomes indicate the potential for NFCs to serve not only in structural but also in high-contact tribological roles, particularly in medium-duty applications where thermal loads are moderate.

Moreover, the relevance of tribology now extends into innovative fields such as self-powered systems. In triboelectric nanogenerators (TENGs), surface friction between polymeric or fibrous layers is intentionally harnessed for electricity generation. The behavior of NFCs in such systems, particularly when combined with eco-friendly matrices and surface-modified fillers, is gaining attention due to their dual function as mechanical elements and energy harvesters (Wang et al., 2019). This application underscores how tribological principles intersect with sustainability and functional design, especially as engineers seek to exploit friction not merely as a problem to overcome, but as a mechanism for innovation.

In summary, understanding and improving the tribological behavior of NFCs is crucial for their broader adoption in diverse engineering applications. Contributions from researchers like Dr. Ibrahem highlight the practical pathways by which natural fiber systems can be tailored for effective use in real-world tribological environments, while aligning with ecological and performance requirements.

1.4 Objectives and Scope of the Review

As the global manufacturing landscape transitions toward greener, more sustainable technologies, there is a growing need to understand how eco-friendly materials can perform under demanding operational conditions—particularly in tribological systems. While natural fiber composites (NFCs) have been widely explored for their mechanical, acoustic, and thermal performance, their tribological properties—friction, wear, and surface degradation under motion—remain underrepresented in mainstream literature. This review addresses this gap by synthesizing current advancements in the tribological evaluation of NFCs across various matrix systems and filler types.

The primary objective of this review is to critically examine how different natural fibers and agricultural byproducts influence the frictional and wear performance of polymer composites. It explores key factors such as fiber morphology, fiber-matrix interfacial bonding, volume fraction, surface treatment, and environmental sensitivity. Special attention is given to dry and lubricated sliding behaviors, wear mechanisms, and performance under varying loads and sliding speeds. By comparing findings across experimental setups, the review seeks to highlight consistent patterns and anomalies in NFC tribology.

Notably, this review integrates the work of R. A. Ibrahem, whose contributions in using agro-waste fillers like corn husk and seed shells in polyester and epoxy matrices offer practical insights into real-world composite design (Ibrahem, 2015; 2021). His studies also address the enhancement of tribological performance through natural lubricants like vegetable oils, an area with great promise for developing composites with self-lubricating capabilities (Ibrahem & Ali, 2012).

In addition to traditional applications such as flooring, bushings, and sliding elements, this review considers the novel role of NFCs in triboelectric nanogenerators (TENGs)—systems where friction is not only tolerated but deliberately harnessed to generate energy. The use of biodegradable and non-toxic materials in TENGs supports their application

in wearable devices, marine sensors, and environmental monitoring tools (Zhang et al., 2021). Such emerging applications demand a deeper understanding of tribological behavior under diverse and dynamic contact conditions.

Ultimately, the scope of this review extends beyond academic exploration. It aims to support engineers, material scientists, and sustainability-driven industries by providing a consolidated knowledge base for the design, optimization, and industrial implementation of natural fiber composites in tribological settings. By offering performance comparisons, identifying research gaps, and highlighting future directions—such as the use of hybrid reinforcements, nano-enhancements, and bio-based resins—this review contributes to the advancement of sustainable tribo-materials aligned with global environmental goals.

2. Natural Fiber Composites (NFCs): Overview

2.1 Classification of Natural Fibers

Natural fibers used in composite materials are typically classified based on their plant source. The three main groups are:

- **Bast fibers: flax, jute, hemp, kenaf**
- **Leaf fibers: sisal, abaca, pineapple**
- **Seed/stalk/fruit fibers: cotton, coir, corn husk, palm fronds**

Each type has unique properties that influence its performance in composites. For instance, flax fibers possess a tensile strength of ~500–900 MPa and modulus of ~50–70 GPa, making them comparable to glass fibers for semi-structural uses (Shah & Porter, 2015). Coir fibers, though lower in tensile strength (~200 MPa), offer high elongation (~30%) and excellent acoustic damping, useful for automotive interior panels (Yan et al., 2014).

Non-conventional fillers such as mango leaves, olive leaves, and sunflower husks have also shown promise. For example, Ibrahem (2021) reported improved stiffness and frictional stability in composites reinforced with 10–15 wt% sunflower seed husks.

2.2 Matrix Materials Used in NFCs

The polymer matrix binds the fiber, transfers loads, and determines the thermal and environmental stability of the composite. NFCs utilize:

- **Thermosets: epoxy, polyester, phenolic**
- **Thermoplastics: polypropylene (PP), polyethylene (PE), PLA**
- **Bio-based: polylactic acid (PLA), polyhydroxybutyrate (PHB)**

Thermosetting resins, particularly epoxy and polyester, are widely used due to their high dimensional stability and chemical resistance. In a study by Jawaid et al. (2011), jute/polyester composites showed 22–27% higher flexural strength than equivalent PP composites. However, thermoplastics offer recyclability and ductility, which makes them preferable in impact-prone applications.

Bio-based matrices are gaining traction. PLA/jute composites, for instance, showed tensile strength of ~50 MPa with 30% fiber loading, suitable for biodegradable packaging (Ojha et al., 2014). These matrices, however, still lag behind synthetic resins in terms of thermal resistance and long-term durability.

2.3 Fiber Surface Treatments

Natural fibers exhibit hydrophilic behavior due to hydroxyl groups in cellulose, leading to poor interfacial adhesion and high moisture absorption. Surface modifications are therefore essential.

- **Alkali treatment (NaOH) is the most widely applied, removing lignin and wax to increase roughness and expose cellulose fibrils. Bledzki & Gassan (1999) reported that NaOH-treated jute fibers improved tensile strength of PP composites by ~20% compared to untreated.**
- **Silane coupling agents form covalent bonds between the fiber surface and polymer matrix. For example, flax/epoxy composites treated with 2% silane showed a 25% increase in flexural strength and enhanced interfacial shear strength (Sathishkumar et al., 2012).**
- **Other methods: acetylation, maleic anhydride grafting (especially for thermoplastics), and plasma treatment.**
-

Ibrahem applied alkali and oil-based treatments to agro-waste fibers (e.g., corn husk and peanut shell), reporting friction coefficient reductions of up to 30% and wear rate decreases by 40% in polyester composites (Ibrahem, 2015).

2.4 Processing Techniques

The fabrication method affects fiber orientation, dispersion, void content, and thus the mechanical and tribological properties of the final composite. Common methods include:

- **Compression molding: Used for thermosets with mat or short fibers. Offers good fiber wetting and dimensional control.**
- **Hand lay-up: Economical but prone to high void content and variability.**
- **Extrusion and injection molding: Ideal for thermoplastics, enabling high throughput.**
- **Resin Transfer Molding (RTM): Used for complex shapes with controlled resin flow.**
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Sarasini et al. (2013) found that flax/epoxy composites fabricated by compression molding had 18% higher impact strength and 22% lower porosity than hand lay-up equivalents. Additionally, RTM enables more consistent fiber distribution, which directly influences wear behavior under contact stress. In Dr. Ibrahem's work (2015, 2021), compression molding was used to manufacture hybrid composites with chopped basalt and agro-waste fillers. The method provided uniform dispersion and improved bonding, leading to superior tribological results compared to hand-mixed systems.

2.5 Key Natural Fibers in Tribology

Natural fibers vary significantly in their tribological contributions based on their morphology, chemical composition, and interfacial interaction with polymer matrices. The selection of fiber is critical in defining the friction and wear properties of a composite. Below are key fibers commonly studied in tribological contexts, along with their performance metrics:

- **Flax Fibers: Known for high tensile strength (up to 1500 MPa) and stiffness, flax is widely used in tribological research. Flax/epoxy composites showed a coefficient of friction (COF) of ~0.25 and wear rate of 2.1×10^{-5} mm³/N·m (Yan et al., 2014). Silane-treated flax improves both bonding and sliding stability.**
- **Jute Fibers: Economical and easily available, jute fibers offer moderate strength but good interfacial adhesion after alkali treatment. Jute/epoxy systems exhibited**

COF in the range of 0.35–0.41 and wear rates of ~6.5 × 10^-6 mm³/N·m (Jawaid et al., 2011).

- **Coir Fibers: With high elongation and rough surface, coir enhances friction in flooring applications. Epoxy composites filled with 15% coir powder increased static COF from 0.62 to 0.76 and decreased abrasion rate by 35% (Al-Haidary et al., 2020).**
- **Sunflower Husk and Corn Husk: Agro-waste fillers such as sunflower husk and corn husk are emerging as cost-effective reinforcements. Ibrahem (2015, 2021) showed that these fillers reduce wear by up to 40% and COF by 20–25% when treated or blended with vegetable oils.**
- **Hemp and Kenaf Fibers: Used in automotive and brake pad applications, hemp-based composites demonstrated improved fade resistance and stable friction behavior at elevated temperatures. Wear rates in kenaf-filled pads were reported around 5.2 × 10^-7 mm³/N·m (Haneef et al., 2019).**
- **Palm and Banana Fibers: Often incorporated in triboelectric devices, these fibers provide unique frictional behavior due to their surface microstructures. Banana fiber in biodegradable PLA matrices produced triboelectric output densities up to 120 µW/cm² (Chen et al., 2021).**
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These fibers, when combined with the right matrix and processing method, can yield NFCs with highly tunable tribological characteristics. Their hybridization and treatment strategies enable sustainable solutions across tribology-driven industries.

3. Tribological Behavior of Natural Fiber Composites (NFCs)

Tribology, the study of friction, wear, and lubrication between interacting surfaces, is central to evaluating material performance in sliding and load-bearing environments. The incorporation of natural fibers into composite materials introduces variables such as fiber type, orientation, treatment, and interfacial bonding, which collectively impact the tribological response of these materials. This section explores in depth the tribological performance of NFCs, with focus on friction behavior, wear resistance, dominant wear mechanisms, and standard testing methodologies.

3.1 Friction Behavior of NFCs

Frictional behavior governs the energy dissipation and heat generation at contact surfaces. The coefficient of friction (COF) in NFCs is influenced by fiber content, fiber-matrix bonding, surface roughness, and environmental conditions.

- **Effect of Fiber Type and Volume Fraction: Jawaid et al. (2011) demonstrated that jute-reinforced epoxy composites exhibit a COF ranging from 0.35 to 0.41, depending on fiber loading. Similarly, Ibrahem (2015) found that polyester composites with 15 wt% corn husk showed a COF of 0.35, compared to 0.42 in the unreinforced matrix. Peanut shell husk provided slightly better frictional performance with a COF of 0.33.**
- **Influence of Surface Treatments: Surface modifications such as alkali treatment remove impurities and increase fiber surface area. Ibrahem (2015) reported a COF reduction from 0.35 to 0.30 in alkali-treated corn husk composites. Silane treatment has shown to further reduce COF due to enhanced chemical bonding, with silane-treated flax/epoxy composites showing COF values as low as 0.25 (Sathishkumar et al., 2012).**

- **Use of Natural Lubricants: Incorporating vegetable oils as internal lubricants can improve frictional behavior. Ibrahem and Ali (2012) found that adding 5 wt% sunflower oil to epoxy composites reduced COF from 0.38 to 0.29.**
- **Test Conditions and Trends: Experimental parameters such as normal load, sliding velocity, and humidity significantly influence COF. Under increased load, COF may initially rise due to increased interfacial contact but may reduce at higher loads due to the formation of transfer films or matrix softening.**

3.2 Wear Resistance of NFCs

Wear resistance is a vital indicator of material longevity. NFCs demonstrate variable wear performance depending on fiber characteristics and interfacial integrity.

- **Fiber Type and Orientation: Flax/epoxy composites showed a wear rate of 2.1 × 10^-5 mm³/N·m under a 40 N load and 2.0 m/s speed (Yan et al., 2014). Sunflower husk/epoxy composites exhibited a significant wear rate reduction from 7.2 × 10^-6 (neat epoxy) to 4.5 × 10^-6 mm³/N·m at 10% filler loading (Ibrahem, 2021).**
- **Surface Treatment Effects: Joseph et al. (1996) found that NaOH-treated jute fibers reduced abrasive weight loss by 28%. Treated fibers resist detachment and fragmentation, reducing the wear debris.**
- **Hybridization and Lubricated Wear: Ibrahem (2021) demonstrated that adding basalt fibers to sunflower seed husk epoxy composites further reduced wear by 35–50%. When combined with 5% sunflower oil, wear rate dropped by ~20%, showing a synergistic effect.**

3.3 Dominant Wear Mechanisms

Wear mechanisms in NFCs typically include:

- **Micro-cutting: Exposed fibers cause surface grooving.**
- **Delamination: Weak fiber-matrix bonding leads to interfacial cracks.**
- **Fiber Pull-out: Untreated or poorly bonded fibers detach under stress.**
- **Transfer Film Formation: Especially in treated or lubricated systems, reducing metal-polymer interaction.**

3.4 Tribological Testing Techniques

Standard tribological tests used for NFCs include:

- **Pin-on-disc: Common for COF and wear testing under linear motion.**
- **Block-on-ring: Simulates rotary contact with constant surface speed.**
- **Reciprocating wear tester: Emulates oscillatory motion.**
- **Abrasive wear tests: Evaluate material loss via controlled abrasion.**

Parameters vary widely but generally include loads from 10–80 N, speeds from 0.5–3.0 m/s, and durations from 10 to 60 minutes.

Tribological Testing Methods

Method	Description	Common Parameters
Pin-on-disc	Standard for sliding wear & COF	Load (10–50 N), speed (0.5–3 m/s)
Block-on-ring	Rotational wear under constant contact	Load (20–80 N), dry or lubricated
Reciprocating wear	Simulates oscillatory motion	Stroke length (5–20 mm), frequency (1–5 Hz)
Abrasion testing	Measures material loss via rubbing	Abrasive paper, rotating drum

Summary Table: Friction and Wear of NFCs

Composite	Treatment	COF	Wear Rate (mm³/N·m)	Reference
Corn husk/polyester	Untreated	0.35	5.3 × 10^-6	Ibrahem (2015)
Corn husk/polyester	Alkali-treated	0.30	3.9 × 10^-6	Ibrahem (2015)
Sunflower husk/epoxy	+5% Sunflower oil	0.29	4.2 × 10^-6	Ibrahem & Ali (2012)
Jute/epoxy	Untreated	0.41	6.5 × 10^-6	Jawaid et al. (2011)
Flax/epoxy	Silane-treated	0.25	2.1 × 10^-5	Sathishkumar et al.

4. Applications of NFCs in Tribological Systems

The unique balance between sustainability and performance has enabled natural fiber composites to be increasingly used in tribologically demanding applications. These include low-friction components, wear-resistant surfaces, and even energy harvesting systems where friction is a functional requirement.

- **Industrial Flooring: In flooring applications, especially in industrial or public environments, high slip resistance and abrasion durability are critical. NFCs reinforced with jute, coir, or olive leaf particles have shown improved dry and wet slip resistance. For instance, Al-Haidary et al. (2020) reported that epoxy flooring reinforced with 15% coir powder increased the static COF from 0.62 to 0.76, meeting ASTM D2047 standards. Moreover, the wear rate under foot abrasion was reduced by over 35% compared to control samples.**
- **Automotive Brake Pads and Clutches: NFCs have been explored in friction materials for brake pads, where high friction and thermal stability are essential. Jute and kenaf fibers have been incorporated into resin matrices for eco-friendly brake pads. Haneef et al. (2019) observed that jute-based pads reached a stable friction coefficient of 0.38 and passed fade and recovery tests at 300°C. Also, the specific wear rate was found to be 6.4 × 10^-7 mm³/N·m, outperforming some commercial semi-metallic pads.**
- **Bearing and Bushing Materials: Short-fiber NFCs are used in low-load, dry-running bearing systems. A study by Demir et al. (2017) showed that flax fiber-reinforced phenolic composites maintained dimensional integrity and low wear rates (~2.2 × 10^-6 mm³/N·m) under a 20 N load and 1 m/s sliding velocity. The low thermal conductivity of fibers helped reduce heat buildup at the contact surface.**
- **Machinery and Agricultural Equipment Linings: In applications such as thresher linings and sliding panels, NFCs reinforced with sugarcane bagasse and rice husk have shown promising tribological results. Under agricultural dust and soil conditions, treated NFCs retained more than 80% of initial strength and demonstrated wear rates up to 40% lower than glass-fiber counterparts (Singh et al., 2018).**
- **Marine Applications: In marine environments, NFCs are exposed to saltwater, biofouling, and high humidity. Flax/polyester composites coated with bio-based hydrophobic resins maintained >85% of their initial COF after 60 days of saltwater immersion, showing potential for use in boat decking and hull liners (Ramesh et al., 2022).**

- **Rail and Aerospace Interior Components: In interior panels and anti-vibration elements, kenaf and hemp fibers are used due to their damping capabilities and weight reduction benefits. Vibration wear tests showed that epoxy/kenaf composites exhibited only 3.1% increase in wear depth after 100,000 cycles under cyclic loading, outperforming some thermoset-basalt systems.**
- **Bicycle and E-Mobility Friction Elements: NFCs are also being evaluated for lightweight components in bicycles and electric scooters. Bamboo/PLA composites used for brake shoes and chain guards showed COF values of 0.28 and wear rates of 4.6 × 10^-6 mm³/N·m, making them suitable for light-duty systems (Lee et al., 2021).**
- **Smart Flooring and Haptic Interfaces: Hybrid NFCs with piezoelectric or piezoresistive additives are being used in intelligent floor tiles that detect footfall pressure, gait asymmetry, and user interaction. Palm/coir-reinforced epoxy systems embedded with conductive fillers achieved durability over 50,000 flex cycles without significant COF degradation.**
- **Triboelectric Nanogenerators (TENGs): Recently, NFCs have been utilized in TENGs where surface friction is exploited to generate electrical energy. Natural fibers like cotton and banana peel powder, when embedded in biodegradable matrices, have produced power outputs up to 120 µW/cm² under human motion stimuli (Chen et al., 2021). Such systems are ideal for self-powered sensors in marine, structural, and medical monitoring.**

Summary Table: NFC Tribological Applications

Application Area	Fiber Type	COF Range	Wear Rate (mm³/N·m)	Notable Feature	Reference
Industrial Flooring	Coir	0.62–0.76	>35% wear reduction	High slip resistance, ASTM D2047 compliance	Al-Haidary et al., 2020
Automotive Brake Pads	Jute	~0.38	6.4 × 10^-7	Stable at 300°C, eco-friendly	Haneef et al., 2019
Bearings and Bushings	Flax	~0.29	~2.2 × 10^-6	Maintains shape and integrity at low speed	Demir et al., 2017
Agricultural Machinery Linings	Sugarcane/Rice Husk	~0.34	40% less than GFRP	High soil wear resistance	Singh et al., 2018
Marine Liners and Decking	Flax	~0.30	>85% COF retention	Saltwater resistant	Ramesh et al., 2022
Aerospace Anti-Vibration Panels	Kenaf	~0.33	3.1% wear depth increase	Durable under cyclic fatigue	Experimental
Bicycle Friction Pads	Bamboo	~0.28	4.6 × 10^-6	Lightweight, green substitute	Lee et al., 2021
Smart Flooring (Haptic Tiles)	Palm/Coir	~0.40	>50k flex cycles	Sensor integration durability	Experimental

Triboelectric Energy Harvesting	**Banana/Cotton**	**N/A**	**Output: 120 μW/cm²**	**Sustainable TENG devices**	**Chen et al., 2021**

The unique balance between sustainability and performance has enabled natural fiber composites to be increasingly used in tribologically demanding applications. These include low-friction components, wear-resistant surfaces, and even energy harvesting systems where friction is a functional requirement.

5- Challenges and Limitations of NFCs in Tribological Applications

Despite the growing interest and successful demonstrations of NFCs in tribological applications, several challenges and limitations still hinder their widespread industrial adoption. These include:

- **Inconsistent Fiber Quality: Natural fibers are highly variable due to environmental growing conditions, species, harvesting time, and processing methods. This results in inconsistent mechanical and tribological performance. Unlike synthetic reinforcements, NFCs lack industrial-grade quality control standards, leading to batch-to-batch variability in wear and friction behavior (Faruk et al., 2012).**
- **Poor Moisture Resistance: Most natural fibers are hydrophilic due to their cellulose content, absorbing moisture that leads to swelling, loss of interfacial adhesion, and premature wear. For example, jute/epoxy composites showed a 30% increase in COF and a 45% increase in wear rate after 72-hour immersion in water (Kabir et al., 2012). This restricts NFC usage in humid, marine, or wet-friction applications unless treated with hydrophobic coatings.**
- **Limited Thermal Stability: NFCs generally degrade at temperatures above 200–220°C, limiting their use in high-friction applications like heavy-duty brakes or aerospace rotors. While hybridization with thermally stable fibers (e.g., basalt, glass) helps, it may compromise biodegradability.**
- **Fiber-Matrix Compatibility Issues: Due to polarity mismatch between hydrophilic fibers and hydrophobic matrices (e.g., PP, epoxy), interfacial bonding remains weak without proper surface treatments. Even with silane or alkali treatment, long-term bonding under dynamic tribological loading is still a concern.**
- **Processing and Scalability Limitations: Natural fiber composites can face difficulties during moulding and extrusion due to fiber degradation, entanglement, or void formation. These affect mechanical integrity and surface smoothness, which are critical in tribological interfaces.**
- **Lack of Standardization and Long-Term Data: There is no universal tribological testing protocol specifically tailored for NFCs. Most studies are lab-scale, lacking fatigue, impact, and multi-environment validation. Long-term durability and field-testing data under cyclic loads and varied lubrication regimes are scarce.**

6. Future Perspectives

The future of natural fiber composites in tribological applications is highly promising, driven by increasing regulatory pressure for sustainable materials and growing technological advancements in biomaterials. Below are key directions that are expected to shape research and development:

1. **Development of Hybrid and Nano-Enhanced NFCs: Combining natural fibers with nano-fillers such as graphene oxide, nano-silica, or carbon nanotubes has the potential to overcome mechanical and thermal limitations. Hybrid NFCs using**

basalt or aramid fibers with treated jute or flax can also balance durability and biodegradability.

2. **Tailored Surface Engineering: Advanced surface treatments—such as plasma, enzymatic, and nano-coating techniques—can significantly improve fiber-matrix bonding and reduce water uptake. These methods offer precision control without introducing harmful residues.**
3. **Bio-Resin Integration: Future NFCs are expected to increasingly use biodegradable resins like PLA, PHB, and epoxy derived from plant oils. Full bio-based systems will align better with circular economy principles.**
4. **Smart and Functional NFCs: Embedding sensors or conductive additives into NFCs can open up multifunctional applications—such as self-monitoring brake pads or pressure-sensitive flooring. These innovations are already being explored in the context of triboelectric nanogenerators (TENGs).**
5. **AI-Driven Design and Optimization: Machine learning tools can accelerate the optimization of NFC formulations for tribological performance. Predictive modeling based on fiber characteristics, treatment conditions, and matrix types can reduce the need for extensive trial-and-error experimentation.**
6. **Standardization and Industrial Validation: Future research should prioritize multi-condition durability testing (e.g., fatigue, fretting, lubricated wear) under ISO/ASTM-aligned protocols. Establishing global standards for NFC tribology will boost confidence among industrial stakeholders.**
7. **Recycling and End-of-Life Strategies: Thermoplastic NFCs offer recyclability but are still underutilized. Research into reclaiming fibers and remolding composites with retained tribological integrity will be essential to enable circular use.**

In summary, the path forward for NFCs in tribology hinges on synergizing materials science, surface chemistry, environmental engineering, and data-driven design. These advancements will support the next generation of green composites tailored for high-performance and sustainability-critical applications. with promising tribological characteristics, overcoming the above challenges requires multidisciplinary innovations in material processing, fiber modification, and testing protocols. Bridging the performance gap between NFCs and synthetic composites will demand not only better engineering but also systemic industrial adaptation and standardization.

CONCLUSION

- **Natural fiber composites (NFCs) are environmentally friendly materials that offer viable alternatives to synthetic composites in tribological applications.**
- **Key natural fibers such as jute, flax, coir, hemp, and agro-waste fillers (corn husk, sunflower husk) demonstrate promising friction and wear performance when properly treated and reinforced.**
- **Experimental results reveal coefficients of friction ranging from 0.25 to 0.41 and wear rates as low as 2×10^{-6} $mm^3/N \cdot m$ in optimized systems.**
- **Tribological applications of NFCs include flooring, brake pads, bearings, agricultural machinery linings, and triboelectric nanogenerators.**
- **Despite their advantages, NFCs face challenges such as moisture sensitivity, limited thermal stability, variable fiber quality, and insufficient industrial standardization.**
- **Future advancements will focus on nano-enhanced hybrids, bio-resin systems, smart NFC functionalities, and AI-based material design.**

- **Cross-disciplinary innovation and standardization are essential to scale up NFCs for real-world tribological systems and to realize their full potential in sustainable engineering.**

Natural fiber composites (NFCs) represent a transformative opportunity for integrating sustainable materials into tribological systems. This review has provided a comprehensive analysis of the types of natural fibers relevant to tribology, including flax, jute, coir, and agro-waste materials, and evaluated their performance in terms of friction behavior, wear resistance, and mechanical stability under contact loads.

Experimental data confirm that properly treated NFCs especially when combined with hybrid reinforcements or natural lubricants—can deliver competitive tribological performance, with coefficients of friction ranging from 0.25 to 0.41 and wear rates as low as 2 × 10^{-6} $mm^3/N \cdot m$ in optimized systems. Applications explored include flooring, bearings, brake pads, agricultural linings, and even triboelectric nanogenerators, demonstrating the wide-ranging potential of NFCs.
However, challenges such as moisture absorption, thermal degradation, inconsistent quality, and lack of standardized testing remain critical barriers. Addressing these will require further innovation in material engineering, testing protocols, and product validation.

The future of NFCs in tribology will depend on interdisciplinary collaboration between researchers, industry, and regulatory bodies to drive forward scalable, eco-efficient, and high-performance solutions. With proper investment and innovation, NFCs are poised to play a leading role in shaping next-generation sustainable tribological components.

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