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Exploring polymer matrix composites reinforced with agro-waste wheat straw fibers from a tribological perspective in sustainable materials

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KEYWORDS

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ABSTRACT

Burning agro-waste materials creates pollution, but repurposing them into inexpensive, biodegradable, and lightweight products reduces pollution and conserves the environment by reducing reliance on woody products. In this study, tribological testing was conducted per ASTM G99 standards using a Pin-on-Disc Tribometer on commercial brake friction materials and wheat straw composites, both treated and untreated. The contact pressure ranged from 1 MPa to 3 MPa in steps of 0.5 MPa, with a fixed rubbing velocity of 2.1 m/s for 20 minutes. Results showed a significant reduction in specific wear rate (SWR) by 17% to 56% and a marginal increase in the coefficient of friction (COF) in cashew nutshell liquid (CNSL)-treated composites compared to untreated ones. The 1:3 MFR treated composite exhibited 2% to 41% less SWR than the 1:5 MFR treated composite. Additionally, the variation in COF and SWR for brake pad material ranged from 0% to 7% and 0% to 18% with respect to contact pressure. COF and SWR results suggest that treated natural fibers could be partially or fully utilized in various products like brake friction materials, particle boards, and wooden flooring to minimize negative environmental impact. Additionally, worn surface morphology was analyzed under scanning electron microscopy.

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ABBREVIATIONS

CNSL	Cashew Nutshell Liquid
COF	Coefficient of friction.
MFR	Matrix to Filler ratio
NFCs	Natural fiber composites
POD	Pin-on-Disc
RH	Rice husk
SEM	Scanning electron microscope
SWR	specific wear rate
WS	Wheat straw

1.0 INTRODUCTION

Composite materials are favored for their properties such as lightweight, fire resistance, thermal stability, corrosion resistance, and high strength-to-weight ratio. The need to develop alternative materials, high cost of synthetic fibers, environmental pollution, recyclability requirements, and biodegradability requirements have motivated researchers to explore natural material composites as alternatives (Holbery & Houston, 2006)(Balan et al., 2020)(Pradhan et al., 2020)(Omrani et al., 2016) (Shalwan & Yousif, 2013) . Moreover, there is a strong insistence on improving and promoting rural economies, minimizing the world's dependence on petroleum products, finding alternatives to woody products, reducing deforestation, and addressing the environmental impact of burning agro-residue. These factors are pushing researchers to consider natural fiber-reinforced materials made from agro-waste such as wheat straw (WS), rice husk (RH), coconut husks, sugarcane bagasse, pineapple leaves, banana leaves, and corn stover(Michael A. Fuqua & Ulven, 2012)(Panthapulakkal & Sain, 2015) (Girase et al., 2025). Additionally, sugarcane is the most widely grown crop in the world (FAO, 2022) , but the water consumption requirements of rice and sugarcane are higher than other major crops (NABARD & ICRIER, 2018)(Luo et al., 2022). The fourth largest grown crop in the world, and the most widely grown crop in Asia, is wheat, which has a global share of 43.7%. According to the United States Department of Agriculture (USDA) Foreign Agriculture Service data, the gross wheat production in the world equals 787.4 million metric tons in the year 2023-24 (United States Department of Agriculture, 2024). Moreover, WS and RH are abundantly available agro-waste materials that are rich in silica. This silica is important for abrasive properties in tribological applications(Michael A. Fuqua & Ulven, 2012) (Panthapulakkal & Sain, 2015).

There are pros and cons to natural fibers. The advantages of natural fibers include biodegradability, recyclability, and minimal harm to the surrounding ecosystem, lower cost, and easy availability. However, they have certain disadvantages, such as high moisture absorption and, consequently, a high swelling rate, less dimensional stability, poor resistance to fire and chemicals, and poor mechanical properties. These drawbacks can be significantly reduced by certain treatments on natural fibers (Verma & Goh, 2021). To improve the physical and mechanical properties of natural fibers, various surface treatments are available. Some treatments aim to remove non-cellulosic constituents to create a clean surface, while others focus on increasing the surface area by splitting larger fibers into smaller ones. These treatments are classified into physical treatments, physico-chemical treatments, and chemical treatments. Physical treatments alter the structure and surface properties of lignocellulosic fibers to enhance fiber-matrix adhesion. Examples include calendaring, electric discharge, fiber stretching, rolling, laser, solvent extraction, γ-ray, and thermo-treatments. Physico-chemical treatments, which combine physical and chemical methods, produce fine, clean fibers with high cellulose content, closely resembling pure cellulose fiber and significantly improving mechanical properties (Michael A. Fuqua & Ulven, 2012).Chemical treatments improve the interfacial matrix bond between natural fibers and binders by removing waxes and sugar components (hemicellulose, lignin) from the fiber surface, making it rougher and more compatible with binders. Common chemical treatments include alkaline, silane, acetylation, permanganate, benzoylation, peroxide, isocyanate, and Cashew Nutshell Liquid (CNSL) treatments (Bisht et al., 2020) (Goriparthi et al., 2012) (Li et al., 2007) (Petchwattana et al., 2012) (Radzi et al., 2020) . The most effective treatments are chemical treatments.

The factors responsible for the mechanical and tribological properties of natural fiber composites (NFCs) are fiber volume, physical characteristics of fibers, fiber orientation, and type of treatments (Shalwan & Yousif, 2013) (Parikh, 2023) . One of the main challenges of NFCs is that natural fibers are hydrophilic in nature, while the matrix is hydrophobic. The remedy for this problem is chemical treatments. Chemical treatments reduce moisture affinity to a great extent, making the fiber surface rough and improving bonding with the matrix (Seisa et al., 2022). Due to better interfacial bonding of the fiber with the matrix, efficient stress transfer can occur from fiber to matrix, thereby improving mechanical properties (Girase et al., 2025). Moreover, the presence of wax, hemicellulose, lignin, and pectin affects the mechanical and tribological properties of the composites. A higher cellulose amount boosts the tensile properties of natural fibers, whereas an increase in non-cellulosic content like wax, hemicellulose, lignin, and pectin diminishes these properties. Additionally, reducing the diameter of natural fibers can improve their mechanical performance. Optimum chemical treatments must remove impurities completely without removing the cellulose content in the fibers. Complete replacement of synthetic fibers is not possible, but partial replacement of synthetic fibers with natural fibers will reduce environmental burden. Some researchers, such as Boegler O et al., have explained the potential of natural fibers and suggested that Ramie fiber-based composites can be used for aircraft wing boxes without compromising structural integrity(Arockiam et al., 2018) (Boegler et al., 2014). Currently, NFCs are utilized in vehicles by manufacturers like BMW, Ford, Mercedes-Benz, Toyota, and Audi for components such as engine insulation, seat backs, door panels, and internal engine covers (Omrani et al., 2016) (Nirmal et al., 2015) .

Many studies have been conducted on NFCs, showing improved results with various treatments. Compared to synthetic fibers, natural fibers like jute, coconut fiber, sisal, coir, flax, kenaf, rice husk, and wheat straw have shown promising results in various studies on natural fiber-reinforced polymer composites. NaOH is often used in alkaline treatments because it can create wide openings in lattice planes (Li et al., 2007) . R. Sahai et al. experimented with four treatments for a wheat straw polystyrene composite: 2% maleic anhydride, 1% silane, 20% NaOH, and a combination of 20% NaOH and 1% silane. They found that the treatment with 20% NaOH and 1% silane resulted in the best mechanical properties, including impact strength, tensile strength, tensile modulus, and water absorption (Sahai & Pardeshi, 2021). According to Nidhi et al., a 10 wt. % CNSL-modified resin exhibited the best wear and friction properties. They tested composites with phenolic resin modified with 10, 12.5, and 15 wt. % CNSL and found that 10 wt. % CNSL was optimal for severe conditions. Beyond this point, the coefficient of friction, fading, and recovery performance decreased (Nidhi et al., 2006). Rashid et al. observed a substantial enhancement in wear resistance in treated sugar palm fiber composites. They compared alkali-treated samples with 0.5% NaOH, seawater-treated samples, and untreated samples. The seawater-treated and alkali-treated samples showed volume reductions of 20.2% and 37.9%, respectively, compared to the untreated samples, with corresponding reductions in the coefficient of friction (COF) of 10% and 13% (Rashid et al., 2017). M. Naidu et al. investigated hemp fiber composites using a Pin-on-Disc (POD) Tribometer, prepared composites with 2%, 4%, and 6% NaOH-treated hemp fiber. They found that sliding velocity (2.02%), composition (42.12%), and load (54.5%) affected the specific wear rate (SWR), with the 6% NaOH-treated hemp fiber composite performing the best (Naidu et al., 2023). Ghloam et al. developed WS composites that were untreated and treated with CNSL, using various ratios of phenolic resin to WS fiber (1:1, 1:2, 1:3, 1:4, 1:5). The tensile strength, flexural strength, and impact energy of the 1:3 CNSL-treated composite were substantially enhanced compared to others, reaching 15.5 MPa, 30.21 MPa, and 2.93 J, respectively (Ghloam et al., 2023).

This research primarily concentrates on the tribological analysis of various natural fiber composites, fiber treatments, wear and friction mechanisms, and comparisons with commercial brake pad materials, aiming to develop eco-friendly materials. Using a POD device, 1:3 and 1:5 MFR wheat straw composites, both treated with CNSL and untreated, along with commercial brake pad material, were tested against on a grey cast iron disc at 1 to 3 Mpa pressure in steps of 0.5 Mpa. The study measured the coefficient of friction and specific wear rate, and scanning electron microscopy (SEM) was used to examine the surface morphology of the worn surfaces.

2.0 MATERIALS AND METHODS

WS composites were prepared through the following process: To prepare the treated composites, 3mm WS fibers were wetted in CNSL resin amounting to 10% by weight of Novolak phenolic resin for 24 hours. Both treated and untreated composites were then processed using a two-roll mill for ten minutes at temperatures between 90°C to 110°C. This involved thoroughly mixing 3mm WS fibers, both treated and untreated separately, with phenolic resin, calcium oxide, stearic acid, Hardener 269E, and hexamethylenetetramine (HMTA). For both treated and untreated composites, the MFR (Novolak phenolic resin to WS fiber by weight percentage) was set at 1:3 and 1:5. The mixtures were then kept at 60°C in a hot air oven for four hours to dry. The mixtures were filled into a mould and put under a hot compression moulding machine at 1800 psi pressure and heated to 200°C for 20 minutes to form 8 mm diameter pins of untreated and treated composites with MFR of 1:3 and 1:5. The pins were then allowed to dry at room temperature for an hour (Ghloam et al., 2023) (Girase et al., 2025). The thermosetting phenolic resin causes the composite to convert to a thermoset (Nusyirwan et al., 2023). Commercial four-wheeler disc brake pads from a renowned manufacturer were procured and used to create 8 mm diameter pins for testing as brake pad friction material. A gray cast iron disc, with a hardness of 180 BHN and a surface roughness (Ra) of 1.5 microns, and dimensions of 180 mm in diameter and 8 mm in thickness, was fabricated to rub against the pins on a POD tribometer. Pins of untreated, CNSL-treated composites with MFR of 1:3 and 1:5, and commercial disc brake pad material were tested as per ASTM G99 standards on a DUCOM make POD Tribometer (Yusubov, 2021) (Ramkumar & Petchiappan, 2023) (Patil & Ahuja, 2014).

3.0 RESULTS AND DISCUSSION

Table 1 shows the parameters used and results obtained from the experimentation. All tests were conducted at a constant rubbing velocity of 2.1 m/s for a duration of 20 minutes. Brake pad pressure for conventional braking ranges from 1 Mpa to 3 Mpa (Federici et al., 2018) (K. Bode et.al, 2014). For wear, the load or contact pressure is a more significant factor than rubbing velocity and sliding distance (Rashid et al., 2017; Naidu et al., 2023) . Therefore, the normal force was applied on the pin varied from 5 kg to 15 kg in steps of 2.5 kg, resulting in contact pressures ranging from 1 Mpa to 3 Mpa in steps of 0.5 Mpa. Load cell was used for measuring frictional force (LS., 2021), and the coefficient of friction (COF) was obtained. The wear amount was measured using the weight loss method. The results are depicted graphically in Figures 1 and 2, aligning with the work of M. Naidu et al. and Rashid et al.

Table 1: Results of untreated, treated composite and commercial brake pad material.

Composition	**Pressure (Mpa)**	**Density (gm/cm^3)**	**Coefficient of friction (COF)**	**Wear (gm)**	**Specific wear rate (SWR) (mm^3/Nm)**
1:3 MFR Untreated wheat straw composite	1	0.915	0.43	0.008	6.275×10^{-05}
	1.5		0.4	0.01	5.229×10^{-05}
	2		0.39	0.012	4.706×10^{-05}
	2.5		0.35	0.019	4.768×10^{-05}
	3		0.29	0.025	5.228×10^{-05}
1:3 MFR Treated wheat straw composite	1	1.034	0.45	0.006	4.706×10^{-05}
	1.5		0.44	0.007	3.660×10^{-05}
	2		0.42	0.01	3.922×10^{-05}
	2.5		0.38	0.015	3.764×10^{-05}
	3		0.33	0.018	3.764×10^{-05}
1:5 MFR Untreated wheat straw composite	1	0.6845	0.44	0.008	9.482×10^{-05}
	1.5		0.43	0.011	8.692×10^{-05}
	2		0.42	0.016	9.482×10^{-05}
	2.5		0.38	0.025	9.479×10^{-05}
	3		0.36	0.032	10.111×10^{-05}
1:5 MFR Treated wheat straw composite	1	0.8476	0.45	0.005	4.786×10^{-05}
	1.5		0.43	0.006	3.829×10^{-05}
	2		0.4	0.009	4.307×10^{-05}
	2.5		0.39	0.018	5.512×10^{-05}
	3		0.37	0.025	6.379×10^{-05}
Commercial brake pad material	1	2.61	0.313	0.0019	5.906×10^{-06}
	1.5		0.31	0.0025	5.181×10^{-06}
	2		0.305	0.0033	5.129×10^{-06}
	2.5		0.3	0.0041	5.098×10^{-06}
	3		0.293	0.0047	4.870×10^{-06}

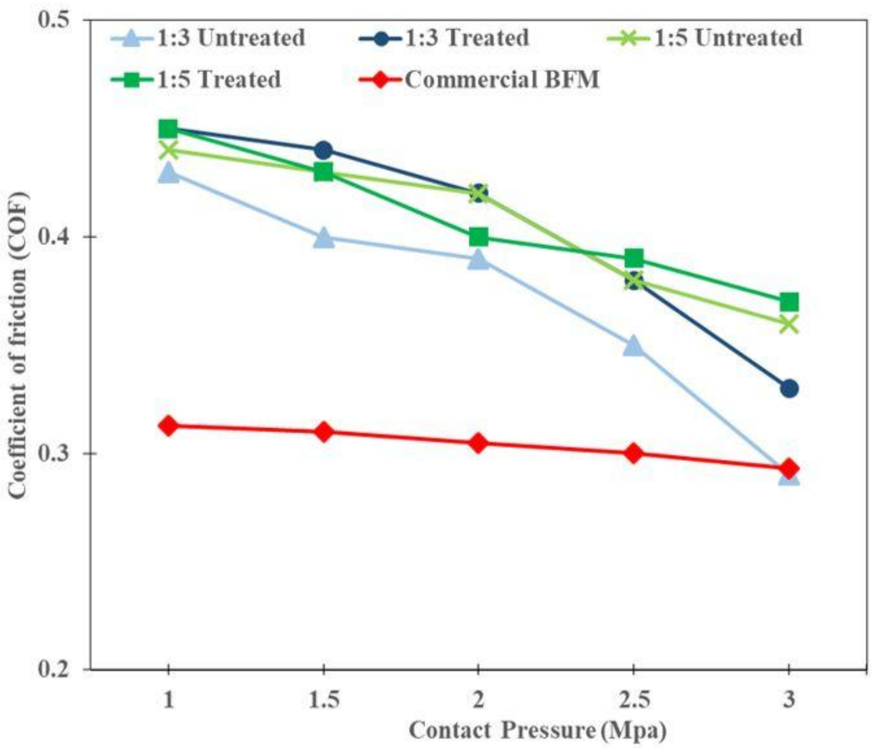


Figure 1: Variation of coefficient of friction (COF) with respect to contact pressure.

As shown in Figure 1, a reduction in the COF with an increase in load or contact pressure was observed. This is due to the behavior of polymeric composites. Amonton's law is not applicable to polymeric composites. In the case of polymeric composites, as the harshness of operating parameters such as load or pressure, temperature, and speed increases, there is a decrease in the COF (Kalel et al., 2021). The COF is determined by the ratio of the frictional force (Fr) to the normal force (F_N), expressed as COF = Fr/F_N. The increase in normal force increases the frictional force, but if this increase in frictional force is less than the proportional increase in normal force, the COF will decrease. This smaller increase in frictional force is due to an increase in the real area of contact and the frictional heat generated in the contact zone. The increase in the real area of contact is due to the elastic and plastic deformation of contacting asperities because of the increase in load. The frictional heat causes thermal softening of polymers, which can lead to a reduction in surface hardness and an increase in the real area of contact (Chand et.al, 2017). These factors are responsible for the reduction in the COF at higher contact pressure. Gehlen et al. also studied environmentally friendly brake friction materials and found that an increase in pressure in the contact zone increases the real area of contact, thereby reducing the COF (Gehlen et al., 2023). Furthermore, the COF increased by 5% to 14% in the 1:3 MFR treated composite compared to the untreated 1:3 MFR composite, and 0% to 3% in the 1:5 MFR treated composite compared to its untreated composite. This rise in COF could be due to the characteristics of CNSL, as the side chains of CNSL molecules may cause slight resistance and better bonding between matrix and fiber due to CNSL treatment.

Mechanisms including fiber pullouts, voids, matrix cracks, delamination, plastic deformation, and fiber-matrix debonding cause wear in polymer matrix composites. Higher stresses during sliding motion cause a thick coating to form, which eventually fractures and flakes off the surface, increasing wear. Equation (1) defines the specific wear rate (SWR).

$$SWR = \frac{(\Delta m)}{\rho \cdot F_N \cdot S} \tag{1}$$

where, Δm - mass loss (grams), ρ – Density (gm/mm^3), F_N – Normal load on pin (Newton) and S – Sliding distance (meters)., SWR - Specific wear rate (mm^3/Nm)

From equation (1), it is observed that for the same material and a constant sliding distance, if the load increases, the wear loss will also increase. However, if this increase in wear loss is not proportional to the increase in load, the SWR decreases. This decrease in the SWR value implies that the material has improved wear resistance at higher contact pressure. Conversely, an increase in SWR with an increase in load implies that the material has poor wear resistance at higher contact pressure (Rashid et al., 2017; Naidu et al., 2023).

As shown in Figure 2, both treated composites have a lower SWR than the untreated one. For the 1:3 MFR treated composite, the SWR was observed to be 17% to 28% less than that of the 1:3 MFR untreated composite, and for the 1:5 MFR treated composite, the SWR was observed to be 37% to 56% less than that of the 1:5 MFR untreated composite. Moreover, the 1:3 MFR treated composite had 2% to 41% less SWR than the 1:5 MFR treated composite, and this decrease in SWR was more pronounced at higher contact pressure. Additionally, it was observed that there was a reduction in SWR for the 1:3 MFR treated composite and commercial brake friction material at higher contact pressure, while the SWR for the 1:3 untreated and both 1:5 MFR untreated and treated composites increased at higher contact pressure. This implies improved wear resistance for the 1:3 MFR treated composite and brake friction material, and poor wear resistance for the 1:3 untreated and both 1:5 MFR untreated and treated composites at higher contact pressure. In other words, better bonding exists between fibers and the matrix in the 1:3 MFR treated composite and the ingredients of the brake friction material (Rashid et al., 2017) (Naidu et al., 2023).

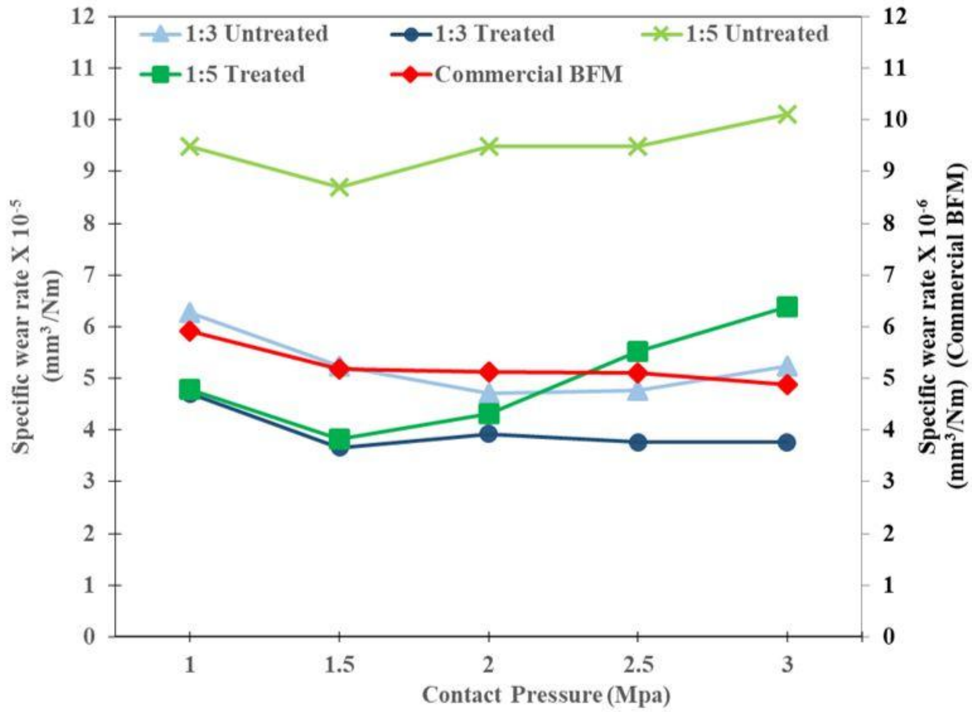
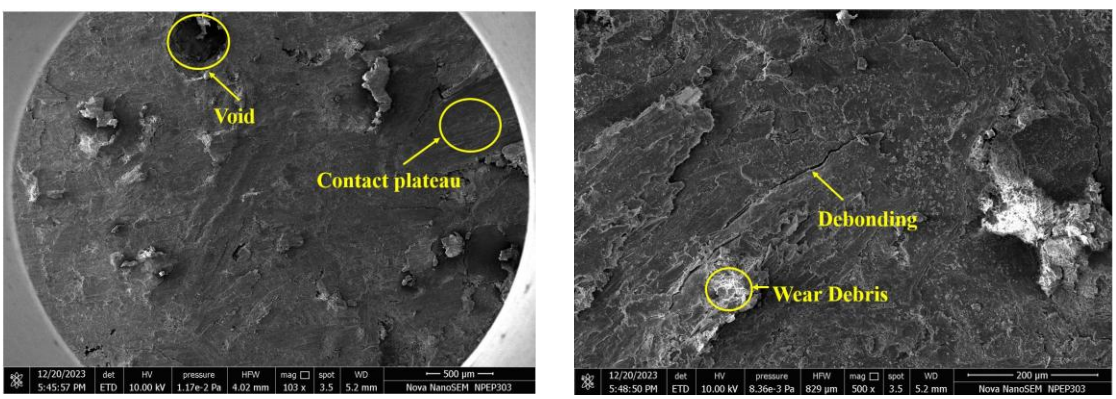


Figure 2: Variation of Specific wear rate (SWR) with respect to contact pressure.

Compared to wheat straw composites, a commercial brake pad material's specific wear rate (SWR) was almost ten times lower. Moreover, the COF and SWR variation of the brake pad material ranged from 0% to 7% and 0% to 18%, respectively, with respect to contact pressure. This is mainly because commercial friction materials contain friction modifiers like graphite and wear-resistant reinforcing fibers like metallic fibers, along with filler and other chemical components that preserve the COF and lessen wear. However, unlike conventional brake pad materials, the natural fiber composite employed in this study solely contained phenolic resin and treated natural fibers and no other ingredients were added to reduce wear. But not all friction material ingredients are good for the environment. Naidu et al. prepared a brake friction material with improved SWR by combining conventional friction material constituents such phenolic resin, graphite, vermiculite, alumina, and barium sulphate with hemp fiber that had been treated with NaOH (Naidu et al., 2023).Thus, treated natural fibers can be used in part to generate green friction materials along with fillers and other eco-friendly ingredients. Not only can friction materials benefit from natural fibers, but many other applications, such as particle boards and wooden flooring, can also use these fibers with the right treatments. They have the potential to replace synthetic fibers. Many natural fibers remain untapped.

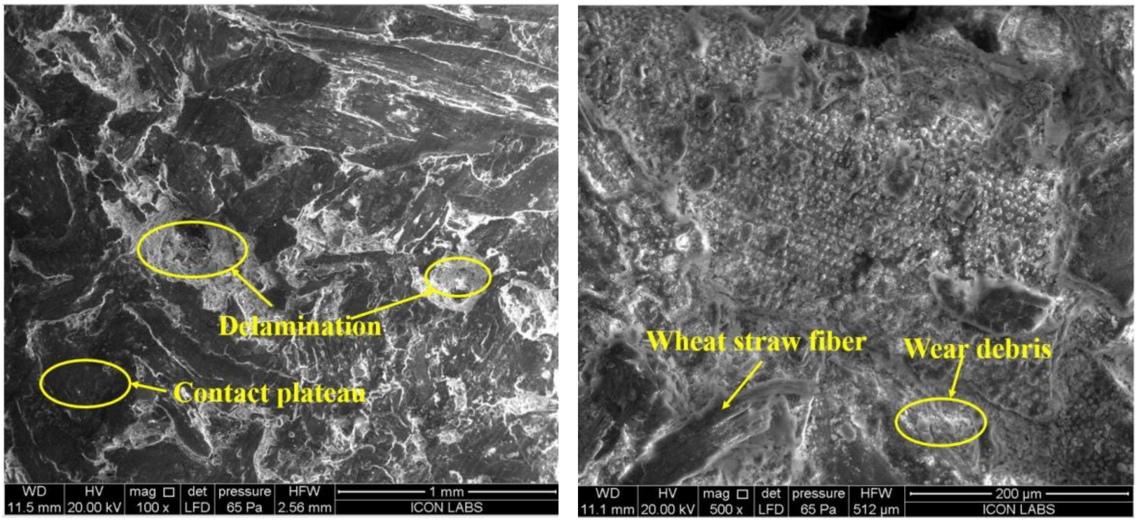
3.1 Worn Surface Morphology

The worn surface morphology at various magnifications of 1:3 MFR untreated WS, 1:3 MFR treated WS, 1:5 MFR untreated WS, 1:5 MFR treated WS, and commercial brake pad material under a 3 Mpa pressure is displayed in Figures from 3 to 7. In the 1:3 MFR untreated material, debonding from the matrix and void formation were observed as wear mechanisms. For the 1:5 MFR untreated composite, delamination and secondary plateau development were the primary wear mechanisms, likely due to poor bonding between the fiber and matrix. The fiber treatment in the treated composite roughened the fiber surface, improving the bonding between the fibers and matrix. This increased bonding in the treated composite enhanced stress transfer from fiber to matrix. In the 1:3 MFR treated composite, delamination was observed as the wear mechanism, while in the 1:5 MFR treated composite, the main wear mechanisms identified were debonding. The commercial brake pad material exhibited relatively little wear because wear mechanisms such as delamination, fiber pull-out, void generation, and crack formation were infrequent. Based on the worn surface morphology, it can be inferred that treated fibers can be partially utilized to create environmentally friendly friction materials.



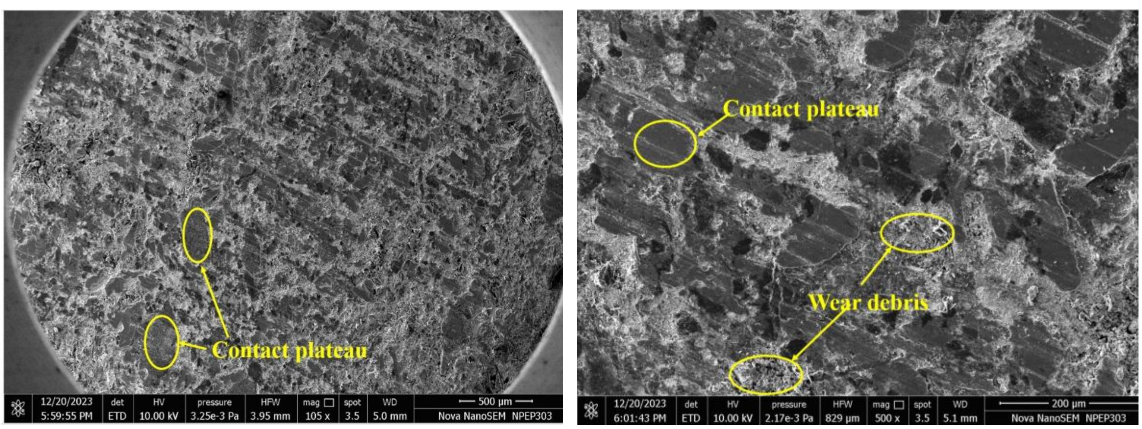
3(a) 3(b)

Figure 3: Worn surface morphology of 1:3 untreated wheat straw composite at 3 MPa pressure.



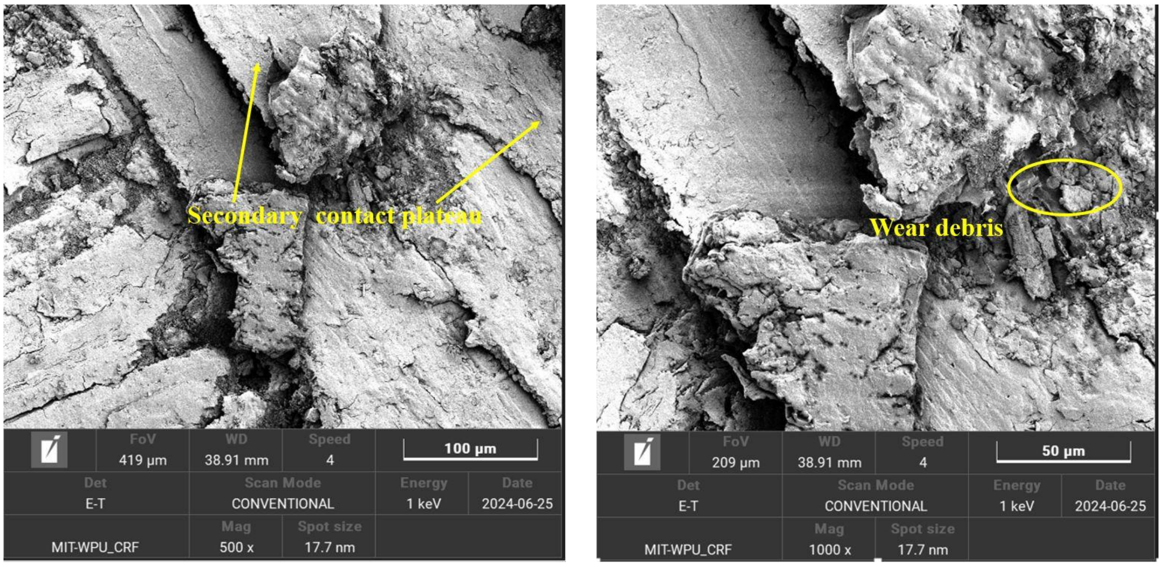
4(a) 4(b)

Figure 4: Worn surface morphology of 1:3 treated wheat straw composite at 3 MPa pressure.



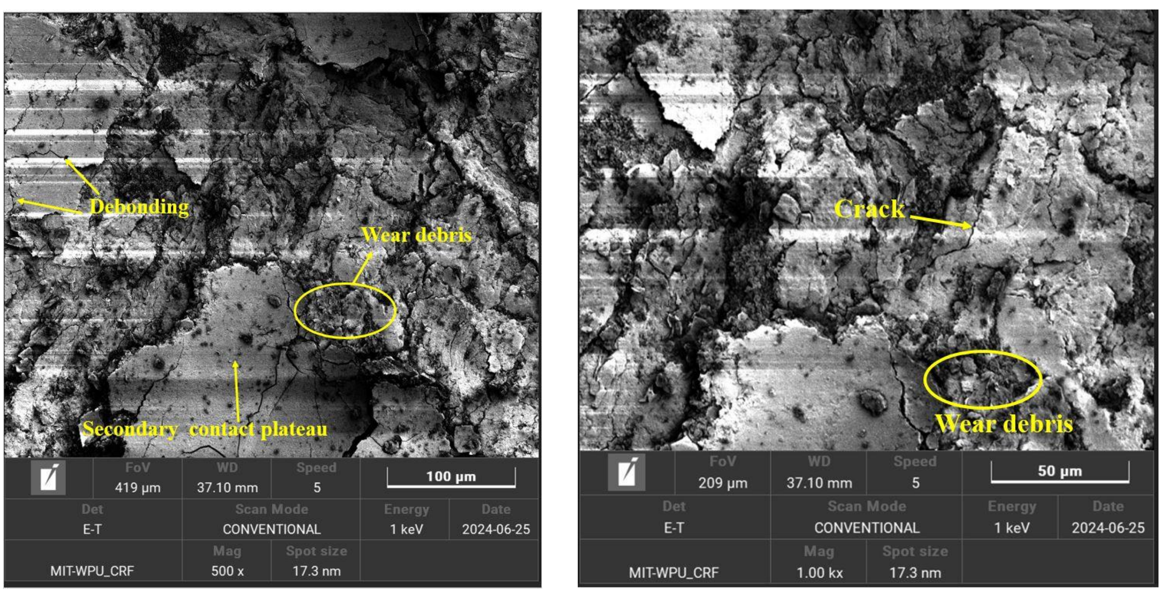
5(a) 5(b)

Figure 5: Worn surface morphology of commercial brake pad at 3 MPa pressure.



6(a) 6(b)

Figure 6: Worn surface morphology of 1:5 untreated wheat straw composite at 3 MPa pressure.



7(a) 7(b)

Figure 7: Worn surface morphology of 1:5 treated wheat straw composite at 3 MPa pressure.

CONCLUSIONS

This article explores the benefits and various treatments applied to natural fibers, highlighting the tribological importance of some natural fiber composites. It also provides a brief explanation of specific wear rate, wear mechanisms, friction, and recent advancements in the tribology of natural fiber composites. Additionally, the article presents experimental results on the tribology of commercial brake pad material and 1:3 and 1:5 MFR wheat straw composites, both CNSL-treated and untreated. The results revealed that the specific wear rate (SWR) of treated composites was significantly less than that of untreated composites. Moreover, the SWR of the 1:3 MFR treated composite was significantly less than that of the 1:5 MFR treated composite at higher contact pressure. These findings suggest that treated natural fiber composites could replace synthetic fibers in applications such as particle boards, wooden floors, brake friction materials, and various automotive components in an optimum MFR. Furthermore, many natural fibers and treatments remain underexplored, indicating that significant environmentally friendly advancements are possible in the tribology of natural fiber composites.

REFERENCES

Arockiam, N. J., Jawaid, M., & Saba, N. (2018). Sustainable bio composites for aircraft components. In Sustainable Composites for Aerospace Applications. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-102131-6.00006-2

Balan, G. S., Kumar, V. S., Rajaram, S., & Ravichandran, M. (2020). Investigation on water absorption and wear characteristics of waste plastics and seashell powder reinforced polymer composite. Jurnal Tribologi, 27(November), 57–70.

Bisht, N., Gope, P. C., & Rani, N. (2020). Rice husk as a fibre in composites: A review. Journal of the Mechanical Behavior of Materials, 29(1), 147–162. https://doi.org/10.1515/jmbm-2020-0015

Boegler, O., Kling, U., Empl, A., & Isikveren, A. T. (2014). Potential of Sustainable Materials in Wing Structural Design. Deutscher Luft- Und Raumfahrtkongress, 327(April 2015), 1–6.

Chand et.al. (2017). Tribology of natural fiber polymer composites. In Woodhead Publishing Limited (Vol. 4, Issue 1). Woodhead Publishing Limited and CRC Press LLC.

FAO, 2022. (2022). Food and Agriculture Organization of the United Nations. FAOSTAT/ Crops and Livestock Products. https://www.fao.org/faostat/en/#data/QCL/visualize

Federici, M., Gialanella, S., Leonardi, M., Perricone, G., & Straffelini, G. (2018). A preliminary investigation on the use of the pin-on-disc test to simulate off-brake friction and wear characteristics of friction materials. Wear, 410–411(July), 202–209. https://doi.org/10.1016/j.wear.2018.07.011

Gehlen, G. S., Nogueira, A. P. G., Carlevaris, D., Barros, L. Y., Poletto, J. C., Lasch, G., Straffelini, G., Ferreira, N. F., & Neis, P. D. (2023). Tribological assessment of rice husk ash in eco-friendly brake friction materials. Wear, 516–517. https://doi.org/10.1016/j.wear.2022.204613

Girase, S., Kothavale, B. S., Kulkarni, M., Gholam, N., Subramanian, R., & Siva, I. (2025). Tribological assessment of rice paddy straw filled green modified phenol formaldehyde composites. Engineering Research Express. https://doi.org/10.1088/2631-8695/adb12b

Ghloam, N., Katkar, S., Mahanwar, P. A., Amberkar, T., Hajare, B., Radhakrishnan, S., & Kulkarni, M. B. (2023). Effect of cashew Nutshell liquid on mechanical, thermal and morphological properties of paddy straw filled phenolic composites. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-023-04560-8

Goriparthi, B. K., Suman, K. N. S., & Mohan Rao, N. (2012). Effect of fiber surface treatments on mechanical and abrasive wear performance of polylactide/jute composites. Composites Part A: Applied Science and Manufacturing, 43(10), 1800–1808. https://doi.org/https://doi.org/10.1016/j.compositesa.2012.05.007

Holbery, J., & Houston, D. (2006). Natural-Fiber-Reinforced Polymer Composites in Automotive Applications.

K. Bode et.al. (2014). Low μ at low pressure– potential for reducing residual drag? Proceedings of Eurobrake, Lille, France. https://go.fisita.com/store/papers/EuroBrake2014/EB2014-DF-017

Kalel, N., Bhatt, B., Darpe, A., & Bijwe, J. (2021). Copper-free brake-pads: A break-through by selection of the right kind of stainless steel particles. Wear, 464–465, 203537. https://doi.org/10.1016/j.wear.2020.203537

Li, X., Tabil, L. G., & Panigrahi, S. (2007). Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review. J Polym Environ, 15(1), 25–33.

LS., B. (2021). Theoretical and experimental determination of the force generated by the pressure of the friction pad in the brake disc of railway vehicles. Indian Journal of Engineering, 18(50), 446–452.

Luo, W., Chen, M., Kang, Y., Li, W., Li, D., Cui, Y., Khan, S., & Luo, Y. (2022). Analysis of crop water requirements and irrigation demands for rice: Implications for increasing effective rainfall. Agricultural Water Management, 260, 107285. https://doi.org/https://doi.org/10.1016/j.agwat.2021.107285

Michael A. Fuqua, S. H., & Ulven, C. A. (2012). Natural Fiber Reinforced Composites. Polymer Reviews, 52(3), 259–320. https://doi.org/10.1080/15583724.2012.705409

Nabard & Icrier (2018). Water Productivity Mapping Of Major Indian Crops. 4(1), 9–15. https://www.nabard.org/auth/writereaddata/tender/1806181128Water Productivity Mapping of Major Indian Crops, Web Version (Low Resolution PDF).pdf

Naidu, M., Bhosale, A., Munde, Y., Salunkhe, S., & Hussein, H. M. A. (2023). Wear and Friction Analysis of Brake Pad Material Using Natural Hemp Fibers. Polymers, 15(1). https://doi.org/10.3390/polym15010188

Nidhi, Bijwe, J., & Mazumdar, N. (2006). Influence of amount and modification of resin on fade and recovery behavior of non-asbestos organic ({NAO}) friction materials. Tribol. Lett., 23(3), 215–222.

Nirmal, U., Hashim, J., & Megat Ahmad, M. M. H. (2015). A review on tribological performance of natural fibre polymeric composites. Tribology International, 83, 77–104. https://doi.org/10.1016/j.triboint.2014.11.003

Nusyirwan, N., Abiem, P., Hairul, A., Hendery, D., Eka, S., Eka, S., & Nanda, I. P. (2023). Methods for increasing fracture toughness of thermosetting polyester polymers with vinyl ester mixtures as raw materials for automotive components. Indian Journal of Engineering, 20(53), 1–10. https://doi.org/10.54905/disssi/v20i53/e20ije1648

Omrani, E., Menezes, P. L., & Rohatgi, P. K. (2016). State of the art on tribological behavior of polymer matrix composites reinforced with natural fibers in the green materials world. In Engineering Science and Technology, an International Journal (Vol. 19, Issue 2, pp. 717–736). Elsevier B.V. https://doi.org/10.1016/j.jestch.2015.10.007

Panthapulakkal, S., & Sain, M. (2015). The use of wheat straw fibres as reinforcements in composites. In Biofiber Reinforcements in Composite Materials (pp. 423–453). Elsevier Inc.

https://doi.org/10.1533/9781782421276.4.423
Parikh, H. H. (2023). Tribology of Plant-Based Natural Fiber Reinforced Polymer Matrix Composites–a Short Review. Journal of Natural Fibers, 20(1). https://doi.org/10.1080/15440478.2023.2172639
Patil, S. M., & Ahuja, B. B. (2014). Tribological Behaviour of PTFE Under Variable Loading Dry Sliding Condition. Journal of The Institution of Engineers (India): Series C, 95(2), 179–185. https://doi.org/10.1007/s40032-014-0106-4
Petchwattana, N., Covavisaruch, S., & Chanakul, S. (2012). Mechanical properties, thermal degradation and natural weathering of high density polyethylene/rice hull composites compatibilized with maleic anhydride grafted polyethylene. Journal of Polymer Research, 19(7). https://doi.org/10.1007/s10965-012-9921-6
Pradhan, S., Prakash, V., & Acharya, S. K. (2020). Modelling and parametric analysis of erosion wear response of eulaliopsis binata fiber polymer composites using response surface methodology. Jurnal Tribologi, 27(September), 19–41.
Radzi, N. A. M., Sofian, A. H., & Jamari, S. S. (2020). Structural studies of surface modified oil palm empty fruit bunch with alkaline pre-treatment as a potential filler for the green composite. Jurnal Tribologi, 26 (June), 75–83.
Ramkumar, P., & Petchiappan, R. (2023). Effect of ceramic reinforcement particle on mechanical and tribological properties of sintered copper-based brake composite friction materials using pin-on-disc tribometer. Jurnal Tribologi, 39(November), 117–133.
Rashid, B., Leman, Z., Jawaid, M., Ghazali, M. J., Ishak, M. R., & Abdelgnei, M. A. (2017). Dry sliding wear behavior of untreated and treated sugar palm fiber filled phenolic composites using factorial technique. Wear, 380–381, 26–35. https://doi.org/https://doi.org/10.1016/j.wear.2017.03.011
Sahai, R. S. N., & Pardeshi, R. A. (2021). Comparative study of effect of different coupling agent on mechanical properties and water absorption on wheat straw-reinforced polystyrene composites. Journal of Thermoplastic Composite Materials, 34(4), 433–450. https://doi.org/10.1177/0892705719843975
Seisa, K., Chinnasamy, V., & Ude, A. U. (2022). Surface Treatments of Natural Fibres in Fibre Reinforced Composites: A Review. Fibres and Textiles in Eastern Europe, 30(2), 82–89. https://doi.org/10.2478/ftee-2022-0011
Shalwan, A., & Yousif, B. F. (2013). In state of art: Mechanical and tribological behaviour of polymeric composites based on natural fibres. Materials and Design, 48, 14–24. https://doi.org/10.1016/j.matdes.2012.07.014
United States Department of Agriculture. (2024). Grain : World Markets and Trade. April 2024. https://fas.usda.gov/data/grain-world-markets-and-trade
Verma, D., & Goh, K. L. (2021). Effect of mercerization/alkali surface treatment of natural fibres and their utilization in polymer composites: Mechanical and morphological studies. Journal of Composites Science, 5(7). https://doi.org/10.3390/jcs5070175
Yusubov, F. (2021). Optimum design of brake friction composites. Jurnal Tribologi, 30(August), 133–148.