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Sustainable Alternatives to Asbestos in Brake Pads: Hybridization of Natural Fibres from Agro-Waste for Enhanced Mechanical and Tribological Performance: A Review

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Abstract
The global transition away from asbestos-based brake pads has driven extensive research into sustainable, high-performance alternatives. Asbestos, formerly valued for its exceptional thermal stability ansd durability, has been phased out due to its severe health risks, necessitating the development of non-toxic friction materials. This review explores alternative materials for brake pad manufacturing, with a particular focus on natural green fibres as filler materials, including coconut shells, rice husks, palm kernel shells, banana peels, and other plant-based fibres. These materials offer key advantages, such as biodegradability, cost-effectiveness, and environmental sustainability, while maintaining essential mechanical and thermal properties. Furthermore, the hybridization of these natural fibres to develop a superior, asbestos-free composite material for brake pad production has been investigated. The review examines recent advancements in material formulation and evaluates the potential for next-generation, eco-friendly brake pads. By integrating renewable resources, the automotive industry can enhance safety, reduce environmental impact, and align with international sustainability standards.

Keywords: *Ecofriendly, sustainable, biodegradable, hybridization, environmental sustainability.*

1.0 Introduction

Brake pads are essential components of automotive braking systems, converting kinetic energy into thermal energy through friction to decelerate or stop a vehicle. This process involves pressing brake pads against a rotating disc, generating heat that dissipates into the environment. Key performance parameters include abrasion resistance, friction coefficient (typically 0.3–0.5), hardness, tensile and compressive strength, thermal conductivity, and stopping time, all of which influence braking efficiency and durability. (bala *et al.* 2021; *Edokpia et al. 2014)*, As vehicle speeds increase, there is a growing demand for materials with higher friction coefficients, superior thermal conductivity, and minimal wear rates while remaining lightweight, corrosion-resistant, and cost-effective.

Modern brake pads consist of steel backing plates combined with various friction materials, including: Non-metallic materials e.g cellulose, aramid, sintered glass) – gentle on rotors but with shorter lifespans. Semi-metallic materials (synthetics combined with metals) – offering a balance between durability and performance but increasing rotor wear. Fully metallic materials (used in racing) – highly durable but cause significant rotor wear. Ceramic materials (comprising clay, porcelain, and copper flakes) – durable but with limited heat dissipation. (Tarini and santosh 2023; Vijay *et al.* 2024; Mulani *et al.* 2022; Aranke *et al.* 2019; Shahrukh *et al.* 2020; Darius *et al.* 2005; Tomasek *et al.* 2020).

The mid-20th century transition from drum to disc brakes improved heat dissipation and reduced wear rates. Initially, asbestos was widely used for its durability and thermal resistance, but its severe health risks led to global bans, driving research into safer, eco-friendly alternatives. (lawal *et al.* 2019; Abutu *et al.* 2014; Yashwhanth; *et al.* 2021; Ikpambese; *et al. 2016).* Agricultural waste materials, such as coconut shells, rice husks, bagasse, palm kernel shells, banana peels, cow bones, snail shells, and periwinkle shells, have shown promise as fillers and reinforcements, offering cost-effectiveness, reduced environmental impact, and comparable performance to asbestos-based pads. (Elahame *et al.* 2014; Idris *et al.* 2015.) The shift towards sustainable brake pads has promoted the use of agro-waste fibres, such as cellulose from bamboo, sugarcane bagasse, and rice husks, which provide renewable, cost-effective raw materials. However, their properties vary based on growth conditions, necessitating precise characterisation for optimal use. Recent studies highlight the importance of formulation and compositional control, as additives and reinforcements significantly impact the final properties of friction materials. Agricultural waste-derived materials, such as palm kernel shells, have demonstrated superior reinforcement potential, advancing eco-friendly braking solutions.

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The transition from asbestos-based to agro-waste-reinforced brake pads represents a significant step towards sustainable industrial practices. By leveraging renewable resources, researchers aim to develop high-performance, cost-effective brake pads that mitigate health risks and support environmental conservation, aligning with global sustainability objectives.

Table1: Physical and mechanical properties of natural fibres

Types of fibre	**Density gm-3**	**Tensile strength (MPa)**	**Young's modulus (GPa)**	**Elongation at break (%)**	**References**
Banana	0.65-1.36	51.6-55.2	3.00-3.78	1.21-3.55	Alwani *et al.,* 2015; Sumaila *et al.,* 2013; Sakthivel and Ramesh 2013
Oil palm	0.7-1.55	227.5-78.4	2.7-3.2	2.13-5.00	Abdul *et al.*, 2008
Bagasse	0.31-1.25	257.3-290.	5 15-18	6.20-8.2	Hemmasi *et al.* 2011; Driemeier *et al.* 2012
Corn stalks	0.21-0.38.33	40.34-80.4	10-4.50	1.90-2.30	Rodriguez *et al.,* 2010
Bamboo	0.6–1.1	360.5–590.3	22.2–54.2	4.0–7.0	Rathod and Kolhatkar, 2014
Kenaf	0.15-0.55	295-955	23.1-27.1	1.56-1.78	Munawar *et al.,* 2007; Paridah and Khalina, 2009
Flax	1.27-1.55	500-900	50-70	2.70-3.6	Bongarde and Shinde, 2014; Soiela *et al.,* 2005
Abaca	1.42-1.65	879-980	38-45	9-11	Vijayalakshmi *et al.,* 2014
Kapok	0.68-1.47	80.3-111.5	4.56-5.12	1.20-1.75	Mwaikambo and Nsell 2001; Chaiarrekij *et al.,* 2011
Sisal	1.45-1.5	300-500	10-30 4.	10-4.3	Vijayalakshmi *et al.,* 2014; Alves *et al.,* 2009; Bongarde and Shinde2014
Rice straw	0.86-0.87	435-450	24.67-26.33	2.11-2.25	Bouasker *et al.,* 2014; Reddy and Yang 2006
Coconut (coir)	0.67-1.15	173.5-175.0	4.0-6.0	27.21-32.32	Alwani *et al.,* 2015; Sakthivel and Ramesh, 2013
Jute	1.3-1.45	300-700	20-50	1.69-1.83	Vijayalakshmi *et al.,* 2014, Alves *et al.* 2009; Ongarde and Shinde, 2014
Pineapple	1.25-1.60	166-175	5.51-6.76	2.78-3.34	Alwani *et al.,* 2015

Table 1 provides a summary of the mechanical and physical properties of selected natural fibres. These properties are significantly influenced by various factors, including cultivation requirements, environmental conditions, climatic factors, chemical composition, extraction methods, and fibre-to-matrix ratios (Cristaldi *et al.*, 2010; Huang *et al.*, 2012). Natural fibre production can be carried out using different methods, resulting in reinforcing elements with varying mechanical properties. The mechanical properties of natural fibres depend on numerous parameters, such as whether fibre bundles or individual fibres are being tested. Table 3 clearly illustrates the mechanical properties of different types of fibres derived from various sources. However, the substantial variation in these properties has become a key concern for researchers and practitioners. The physical and mechanical properties of biomass fibres are intrinsically linked to their structure. Biomass fibres, predominantly natural organic materials, display considerable variability in their properties, raising critical questions regarding the accurate characterisation of their physical and mechanical attributes. Among physical properties, density is the most significant, while the mechanical properties of individual fibres are typically assessed using modulus and tensile strength measurements. It is essential to highlight the advancement of biomass fibres as biomaterials and their application in the manufacture of polymer composites (Biagiotti *et al.*, 2024; Puglia *et al.*, 2005). Table 1 compares the physical and mechanical properties of selected biomass fibres, providing valuable insights for their use in engineering and materials science.

Table 2: The chemical properties of natural fibres

% Composition of selected natural fibres					
Type of biomass	**Cellulose**	**Extractive**	**Hemicellulose**	**Hemicellulose**	**Reference**
Sisal	43.85-56.63	2	7.21-9.20	21.12-4.53	Khalil *et al.* 2012
Oil palm	44.20-49.60	4	18.30-33.54	17.30- 6.51	Jawaid and Khalil 2011; Khalil *et al.* 2007
Bamboo	73	3	12	10	Jawaid and Khalil, 2011
Coconut (coir) -	36.62- 43.21		0.15-0.25	41.23-5.33	Satyanarayana 2009
Rice straw	28.42-48.33	17	23.22-28.45	12.65-6.72	Reddy and Yang, 2005; Zhao *et al.* 2012
Flax	69.22-71.65	6	18.31-18.69	3.05-2.56	Khalil *et al.* 2012; Leão *et al.* 2006
Kenaf	37.50-63.00	6.4	15.10-21.40	18.00-24.30	Leão *et al.* 2006; Khalil *et al.* 2010; Thiruchitrambalam *et al.* 2012
Sugarcane (Bagasse)	55.60-57.40	10	23.90-24.50	24.35-26.30	Khalil *et al.* 2012; Wahlang *et al.* 2012; Hemmasi *et al.* 2011
Banana	60.25-65.21		48.20-59.2	5.55-10.35	Guimarães *et al.* 2009; Preethi *et al.* 2013
Pineapple	70.55-82.31		18.73-21.90	5.35-12.33	Pardo *et al.* 2014
Bamboo	73	3	12	10	Jawaid and Khalil, 2011

As noted by Kumar *et al.* 2009, agricultural biomass primarily consists of cellulose, hemicellulose, and lignin, with smaller quantities of pectin, protein, and ash. Cellulose is a semi-crystalline polysaccharide composed of D-anhydroglucose units linked by glycosidic bonds. It contributes significantly to the strength, stiffness, and structural stability of the fibre, maintaining the plant's structure and serving as a key determinant of its mechanical properties. Hemicellulose, on the other hand, is a branched, fully amorphous polymer. Lignin is a complex hydrocarbon polymer containing both aliphatic and aromatic components. It is closely associated with hemicellulose in the cells of agricultural plants and plays a crucial role in providing natural resistance to decay in agro-biomass materials (Majhi *et al.*, 2010). The chemical composition of natural fibre is highly variable, as reflected in Table 2. The polymer content depends significantly on the plant species. Additionally, the composition, structure, and properties of biomass are influenced by various factors, including the age of the plant, soil conditions, and environmental factors such as humidity, stress, and temperature (Jawaid and Khalil, 2011). The polymer chemistry of these fibres directly affects their characteristics, functionalities, and overall properties (Gorshkova *et al.*, 2012). Understanding these chemical properties is essential for optimising the use of natural fibres in engineering applications.

2.0 Research Trend on natural fiber as alternatives of asbestos material in brake pad production

2.1 Rice Husk Dust:

Bahari *et al.* (2012) investigated the use of rice husk dust (RHD) as a filler in brake pads, assessing its hardness and impact resistance. The study incorporated RHD in different mesh sizes (80 and 100) at varying compositions (10% and 30%) using phenol formaldehyde as a binder. Findings showed that finer RHD particles improved performance, with lower filler content increasing the friction coefficient and reducing wear rates. The study concluded that higher RHD content enhances brake pad hardness and impact resistance, making it aviable alternative filler.

2.2 Palm Kernel Fibres, Palm Kernel Shell, and Palm Slag

Palm kernel shell (PKS) is a by-product of palm oil processing, with studies confirming its effectiveness as an asbestos substitute in brake pads. Ikpambese *et al.* (2016) developed asbestos-free brake pads using palm kernel fibres, showing good mechanical and tribological properties. Pujari and Srikiran (2018) proposed eco-friendly formulations incorporating PKS and other natural materials, improving friction performance and wear resistance. Yashwhanth *et al.* (2020) and Bretotean *et al.* (2020) further validated the viability of organic-based brake pads. Achebe *et al.* (2018) found that increasing PKF content (up to 40%) enhanced hardness (178 MPa), compressive strength (96.2 MPa), and wear resistance while reducing water and oil absorption, confirming its potential as a reinforcement material. Similarly, Fono-Tamo (2014) and

Ibhadode & Dagwa (2008) demonstrated that PKS-based brake pads met NIS 323 standards, though they exhibited increased wear at speeds above 80 km/h.

Elakhame *et al.* (2014) analysed PKS of varying particle sizes (100 µm to 1 mm) and found that finer particles improved hardness, density, and mechanical properties. Microstructural analysis showed uniform resin distribution, enhancing pad durability. Fono-Tamo & Koya (2013) further confirmed PKS-based brake pads met required automotive standards, with a friction coefficient of 0.43. Ghazali *et al.* (2011, 2012) explored palm slag as a filler, finding it exhibited superior hardness, compressive strength, and wear resistance. Palm slag composites demonstrated excellent thermal stability (50–1000°C), making them cost-effective alternatives in brake pad formulations.

2.3 Orange Peel Dust

Charles and Devaprasad (2016) developed asbestos-free brake pads reinforced with orange peel dust using the hand lay-up method. Mechanical and tribological tests showed comparable properties to commercial asbestos-based pads, highlighting orange peel dust as a viable eco-friendly friction material.

2.4 Cow Bone and Hoof-Based Composite

Dele & Adewole (2016) found that finer cow bone particles improved composite strength, while coarser ones enhanced toughness. Adegbola *et al.* (2017) demonstrated that cow bone-reinforced brake pads exhibited superior mechanical properties, rivaling commercial pads. Bala *et al.* (2021) produced brake pads using pulverised cow hooves, proving their potential as sustainable alternatives in brake pad manufacturing.

2.5 Pineapple Leaf Fibre (PALF)

Felix & Prasanth (2015) developed PALF-reinforced brake pads using epoxy resin. Increasing PALF content reduced compressive strength, hardness, and wear resistance while increasing water absorption. Although PALF is a promising filler, its impact on performance requires optimisation.

2.6 Banana Peels

Bashir *et al.* (2015) found that increasing banana peel powder content enhanced hardness and resin binding at high temperatures. A 40 wt% phenolic resin and 60 wt% banana peel mix yielded the best frictional properties (friction coefficient: 0.78, fade coefficient: 0.39). Idris *et al.* (2013) confirmed that banana peels improved strength and durability, with optimal results at 25–30 wt% banana peel content. Yigrem *et al.* (2022) demonstrated that banana peel composites exhibited superior mechanical properties, making them a promising eco-friendly asbestos alternative.

2.7 Cashew Nut Shell

Cashew nut shell dust, processed into fine particles, enhances brake pad stability, impact absorption, and heat resistance. Blau *et al.* (2021) highlighted its wear-reducing properties. Lawal *et al.* (2019) developed cashew nut shell-based brake pads using a locally sourced gum binder instead of conventional resins, further promoting sustainable brake pad production.

2.8 Bagasse

Aigbodion *et al.* (2010) developed asbestos-free brake pads using bagasse, a sugarcane industry byproduct. Finer bagasse particles improved tribological properties, outperforming commercial asbestos-based pads, demonstrating its potential as a sustainable alternative.

2.9 Lemon Peel Powder

Ramanathan *et al.* (2017) developed asbestos-free brake pads using lemon peel powder as a filler with epoxy resin. A composition of 40% resin, 10% lemon peel powder, and other additives exhibited superior wear resistance, hardness, and stability, proving lemon peel powder as a viable asbestos alternative.

2.10 Coconut Fibres / Coconut Shell

Kholil *et al.* (2020) found that a composite with 20% coconut fibre, 20% wood powder, and 10% cow bone achieved comparable performance to commercial pads. Rudramurthy *et al.* (2014) showed that coconut shell powder increased compressive strength, wear resistance, and bonding in phenol-formaldehyde and epoxy resin composites. Bahari *et al.* (2012) demonstrated that brake pads with 100-mesh coconut husk (10%) exhibited the highest friction coefficient, while a 30% composition improved thermal stability. Maleque *et al.* (2012) found that coconut fibre-reinforced composites with 5–10% fibre content improved density, compressive strength, and porosity. Ossia *et al.* (2020) studied coconut shell-based brake pads, finding that smaller particle sizes enhanced hardness and bonding. A 90 µm grain size formulation showed superior mechanical properties, suggesting further refinement could optimize performance.

2.11 Cocoa Bean Shell (CBS)

Olabisi *et al.* (2016) developed asbestos-free brake pads using cocoa bean shell (CBS) as a filler with epoxy resin. Increasing CBS content improved friction but reduced wear rate and tensile strength. CBS proved to be a viable, sustainable alternative for friction linings.

2.12 Maize Husks

Ademoh and Olabisi (2015) and Sotah and Adeleke (2017) developed asbestos-free brake pads using maize husks. Higher maize husk content improved friction and absorption but reduced hardness and strength. The 100 µm sieve grade provided the best results, demonstrating that maize husks are a suitable alternative to asbestos.

2.13 Eggshell-Based Brake Pads

Edokpia *et al.* (2014) explored eggshell-based brake pads with Gum Arabic as a binder. Increasing Gum Arabic content (15–18%) enhanced bonding and thermal resistance, outperforming asbestos-based pads, confirming eggshells as an eco-friendly alternative.

2.14 Periwinkle Shell

Yakubu *et al.* (2016), Aku *et al.* (2012), and Yawas *et al.* (2016) investigated periwinkle shell-based brake pads, showing that smaller particle sizes (125 µm) improved strength, density, and friction while reducing wear. The material withstood higher temperatures than asbestos, making it a strong alternative.

2.15 Snail Shells

Ossia and Big-Alabo (2021) and Abutu *et al.* (2018) developed asbestos-free brake pads from snail shells. Mechanical properties were superior to conventional pads, with process parameters like pressure and curing time significantly affecting performance.

2.2 Hybrid Materials

Hybrid composites combine different materials to enhance strength, durability, and tribological properties in brake pads.Singh and Patnaik (2014) found that a 25:5 lapinus-to-aramid ratio optimizes wear resistance. Singh *et al.* (2023) explored Grewia optiva fibre, demonstrating improved braking performance. Casamassa *et al.* (2021) assessed potassium titanates (KTO/KMTO), finding platelet KMTO superior in wear resistance. Nishimura *et al.* (2023) used fluorescence microscopy to detect ultra-fine asbestos fibres, enhancing asbestos contamination analysis. Du *et al.* (2023) studied aluminium-metal matrix composites with 19 wt.% SiC, confirming a correlation between wear rate and friction. Abhulimen and Orumwense (2017) found that snail shell and rubber-seed husk hybrids influence mechanical properties. Onyeneke *et al.* (2014) developed a periwinkle–coconut shell brake pad with comparable performance to asbestos pads. Atmika *et al.* (2019) created a basalt, shell, and alumina composite with superior wear resistance. Adeyemi (2016) and Eziwhuo *et al.* (2023) investigated mixed agro-waste and organic materials (CBS, MH, PKS, coconut fibres, oyster shells), demonstrating improved friction, wear rate, and sustainability. Rao *et al.* (2015) compared agro-waste-based brake pads with asbestos-based pads, showing similar density, wear rate, and compressive strength.

3.0 Conclusion

This review examines the potential of natural fibres as sustainable alternatives to asbestos in brake pad production, as well as the hybridization of multiple natural fibres to enhance performance. The findings indicate that both natural and hybrid fibre composites exhibit mechanical and tribological properties comparable to, or exceeding, those of asbestos-based brake pads, without the associated health and environmental risks. Although extensive laboratory research is underway, these innovations are yet to be widely adopted in commercial applications.

The mechanical and physical properties of composite brake pads are significantly influenced by filler content. Studies suggest that a reduction in filler content enhances thermal conductivity, hardness, compressive strength, and tensile strength, whereas an increase in filler content raises density, water absorption, and oil absorption. Research by Adetunji *et al.* (2022), Achebe *et al.* (2018), and Ibhadode & Dagwa (2008) further highlights that higher vehicle speeds result in increased contact pressure between the brake pad and rotor, leading to greater wear. Additionally, palm kernel fibre (PKF) brake pads exhibit a higher wear rate, while palm kernel shell (PKS) brake pads demonstrate a lower coefficient of friction.

The integration of natural fibres into friction formulations enhances wear resistance, with finer particle sizes improving overall brake pad performance. Studies by Yashwhanth *et al.* (2020), Charles & Devaprasad (2016), Elakhame *et al.* (2014), and Bala *et al.* (2021) confirm that smaller particle sizes positively influence wear rate and friction coefficient, aligning with industry standards. Physical and chemical treatments can mitigate the poor wettability and high moisture absorption often associated with natural fibres.

Agricultural waste materials offer a promising, cost-effective alternative for brake pad production. Their mechanical properties, combined with sustainable sourcing, present an opportunity to convert waste into high-value engineering applications in form filler in brake pad production.

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References

Abhulimen, E., & Orumwense, F. (2017). Characterization and development of asbestos-free brake pad using snail shell and rubber seed husk. *African Journal of Engineering Research*, 5, 24–34.

Abutu, J., Lawal, S. A., Ndalima, M. B., Lafia-Araga, R. A., Adedipe, O., & Choudhury, I. A. (2018). Effects of process parameters on the properties of brake pads developed from seashell as reinforcement material using grey relational analysis. *Engineering Science and Technology, an International Journal.* https://doi.org/10.1016/j.jestch.2018.05.014

Achebe, C., Chukwuneke, J., Anene, F., & Ewulonu, C. (2018). A retrofit for asbestos-based brake pad employing palm kernel fiber as the base filler material. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 1464420718796050.

Adegbola, J. O., Adedayo, S. M., & Ohijeagbon, I. O. (2017). Development of cow bone resin composites as a friction material for automobile braking systems. *Journal of Production Engineering*, 20(1), 69–74.

Ademoh, N. A., & Olabisi, A. I. (2015). Development and evaluation of maize husks (asbestos-free) based brake pad. Development, 5.

Aigbodion, V. S., Akadike, U., Hassan, S. B., Asuke, F., & Agunsoye, J. O. (2010). Development of asbestos-free brake pad using bagasse. *Tribology in Industry*, 32, 100855.

Aigbodion, V. S., Idris, U. D., Abubakar, I. J., & Nwoye, C. I. (2015). Eco-friendly asbestos-free brake pad: Using banana peels. *Journal of King Saud University - Engineering Sciences,* 27, 185–192. https://doi.org/10.1016/j.jksues.2013.06.006

Aku, S., Yawas, D., Madakson, P., & Amaren, S. (2012). Characterization of periwinkle shell as asbestos-free brake pad material. *The Pacific Journal of Science and Technology*, 13, 57–63.

Alves, C., Freitas, M., Silva, A., Luz, S., & Alves, D. (2009). Sustainable design procedure: The role of composite materials to combine mechanical and environmental features for agricultural machines. Materials & Design, 30, 4060–4068.

Alwani, M. S., Khalil, H. A., Islam, N., Sulaiman, O., Zaidon, A., & Dungani, R. (2015). Microstructural study, tensile properties, and scanning electron microscopy fractography failure analysis of various agricultural residue fibers. *Journal of Natural Fibers*, 12, 154–168.

Amaren, S. G., Yawas, D. S., & Aku, S. Y. (2013). Effect of periwinkle shell particle size on the wear behavior of asbestos-free brake pad. Results in Physics, 3, 109–114. https://doi.org/10.1016/j.rinp.2013.06.004

Aranke, O., Algenaid, W., Awe, S., & Joshi, S. (2019). Coatings for automotive gray cast iron brake discs: A review. Coatings, 9(9), 552. doi: 10.3390/coatings9090552

Atmika, I. K. A., Subagia, I. D. G. A., Surata, I. W., & Sutantra, I. N. (2019). Development of environmentally friendly brake lining material. E3S Web of Conference, 120. https://doi.org/10.1051/e3sconf/2019103052003005

Bahari, S. A., Isa, K. H., Kassim, M. A., Mohamed, Z., & Othman, E. A. (2012). Investigation on hardness and impact resistance of automotive brake pad composed with rice The Eurasia Proceedings of Science, Technology, Engineering & Mathematics husk dust. *AIP Conference Proceedings*, 155-161.

Bala, K. C., Lawal, S. S., Ademoh, N. A., Abdulrahman, A. S., & Adedipe, O. (2021). Effects of Nigerian plant gum binder in the optimized multi-response performance of cashew nut shells-based composites for automobile brake pads. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics, 12, 17–27.*

Biagiotti, J., Fiori, S., Torre, L., López-Manchado, M., & Kenny, J. M. (2004). Mechanical properties of polypropylene matrix composites reinforced with natural fibers: *A statistical approach. Polymer Composites,* 25, 26-36.

Bongarde, U., & Shinde, V. (2014). Review on natural fiber reinforcement polymer composites. *International Journal of Engineering Science and Innovative Technology*, 3, 431–436.

Bouasker, M., Belayachi, N., Hoxha, D., & Al-Mukhtar, M. (2014). Physical characterization of natural straw fibers as aggregates for construction materials applications. Materials, 7, 3034–3048.

Casamassa, E., Gautier, G., Sin, A., Kukutschova, J., & Faga, M. G. (2021). Granular and platelet titanate as promising brake pad ingredients. Open Ceramics, 6, 100128. https://doi.org/10.1016/j.oceram.2021.100128

Chaiarrekij, S., Apirakchaiskul, A., Suvarnakich, K., & Kiatkamjornwong, S. (2011). Characteristics of Kapok fiber as a potential pulp source for papermaking. BioResources, 7, 0475–0488.

Charles, J. S., & Devaprasad, M. E. (2016). Development of brake pad using orange peel reinforcement polymer composite. *Global Journal of Advanced Engineering Technologies and Sciences*, 3(5), 29–41.

Cicala, G., Cristaldi, G., Recca, G., & Latteri, A. (2010). Composites based on natural fibre fabrics. In Woven Fabric Engineering. InTech.

Driemeier, C., Santos, W. D., & Buckeridge, M. S. (2012). Cellulose crystals in fibrovascular bundles of sugarcane culms: Orientation, size, distortion, and variability. Cellulose, 19, 1507–1515.

Du, A., Lattanzi, L., Jarfors, A. E. W., Zheng, J., Wang, K., & Yu, G. (2023). Role of matrix alloy, reinforcement size, and fraction in the sliding wear behavior of Al-SiCp MMCs against brake pad material. Wear, 530–531, 204969. https://doi.org/10.1016/j.wear.2023.204969

Edokpia, R. O., Aigbodion, V. S., Obiorah, O. B., & Atuanya, C. U. (2014). Evaluation of the properties of eco-friendly brake pad using egg shell particles–gum arabic. *Results in Physics.* https://doi.org/10.1016/j.rinp.06.003

Elakhame, Z., Alhassan, O., & Samuel, A. (2014). Development and production of brake pads from palm kernel shell composites. *International Journal of Scientific & Engineering Research*, 5, 735–744.

Fono-Tamo, R., & Koya, O. (2013). Evaluation of mechanical characteristics of friction lining from agricultural waste. International Journal of Advancements in Research & Technology, 2, 1-5.

Fono-Tamo, R., & Sephyrin, R. (2014). Agro-waste-based friction material for automotive application.

Ghazali, C. M. R., Kamarudin, H., Jamaludin, S. B., & Abdullah, M. (2011). Comparative study on thermal, compressive, and wear properties of palm slag brake pad composite with other fillers. Advanced Materials Research, 1636-1641.

Ghazali, C. M. R., Kamarudin, H., Jamaludin, S. B., Abdullah, M., & Rafiza, A. (2012). Mechanical properties and wear behavior of brake pads produced from palm slag. Advanced Materials Research, 26-30.

Gorshkova, T., Brutch, N., Chabbert, B., Deyholos, M., Hayashi, T., Lev-Yadun, S., *et al.* (2012). Plant fiber formation: State of the art, recent and expected progress, and open questions. Critical Reviews in Plant Sciences, 31, 201-228.

Hemmasi, A., Samariha, A., Tabei, A., Nemati, M., & Khakifirooz, A. (2011). Study of morphological and chemical composition of fibers from Iranian sugarcane bagasse. *American-Eurasian Journal of Agriculture & Environmental Science,* 11, 478–481.

Ibhadode, A. O. A., & Dagwa, I. M. (2008). Development of asbestos-free friction lining material from palm kernel shell. J. Braz. Soc. Mech. Sci. Eng., 1, 1-2.

Idris, U. D., Aigbodion, V. S., Abubakar, I. J., & Nwoye, C. I. (2015). Eco-friendly asbestos-free brake pad using banana peels. Journal of King Saud University - Engineering Sciences, 27(2), 185–192. https://doi.org/10.1016/j.jksues.2013.06.006

Ikpambese, K. K., Gundu, D. T., & Tuleun, L. T. (2016). Evaluation of palm kernel fibers (PKFs) for production of asbestos-free automotive brake pads. *Journal of King Saud University - Engineering Sciences,* 28(2), 110–118. https://doi.org/10.1016/j.jksues.2014.02.001

Ilanko, A. K., & Vijayaraghavan, S. (2016). Wear behavior of asbestos-free eco-friendly composites for automobile brake materials. Friction, 4, 144–152.

Jawaid, M., & Khalil, H. A. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: *A review. Carbohydrate Polymers,* 86, 1-18.

Khalil, H. A., Alwani, M. S., Ridzuan, R., Kamarudin, H., & Khairul, A. (2008). Chemical composition, morphological characteristics, and cell wall structure of Malaysian oil palm fibers. *Polymer-Plastics Technology and Engineering*, 47, 273–280.

Khalil, H. A., Bhat, A., & Yusra, A. I. (2012). Green composites from sustainable cellulose nanofibrils: A review. Carbohydrate Polymers, 87, 963-979.

Khalil, H. A., Hanida, S., Kang, C., & Fuaad, N. N. (2007). Agro-hybrid composite: The effects on mechanical and physical properties of oil palm fiber (EFB)/glass hybrid reinforced polyester composites. Journal of Reinforced Plastics and Composites, 26, 203-218.

Kholil, A., Dwiyati, S. T., Siregar, P., & Riyadi, S. (2020). Development of brake pad from composites of coconut fiber, wood powder, and cow bone for electric motorcycles. *International Journal of Science & Technology Research*, 9(2).

Kumar, P., Barrett, D. M., Delwiche, M. J., & Stroeve, P. (2009). Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. Industrial & Engineering Chemistry Research, 48, 3713-3729.

Kumar, S., Patel, V. K., & Mer, K. K. S. (2018). Influence of woven bast-leaf hybrid fiber on the physicomechanical and sliding wear performance of epoxy-based polymer composites. *Materials Research Express,* 5, 105705.

Kumar, S., Patel, V. K., Mer, K. K. S., Gangil, B., Singh, T., & Fekete, G. (2019). Himalayan natural fiber-reinforced epoxy composites: Effect of Grewia optiva/Bauhinia Vahlii fibers on physicomechanical and dry sliding wear behavior. Journal of Natural Fibers. https://doi.org/10.1080/15440478.2019.1612814

Lawal, S. S., Ademoh, N. A., & Bala, K. C. (2019). Reviews in automobile brake pads production and prospects of agro-based composites of cashew nut shells and Nigerian gum Arabic binder. *Covenant Journal of Engineering Technology,* 3(2), 2682-5317.

Leão, A., Sartor, S. M., & Caraschi, J. C. (2006). Natural fibers-based composites–Technical and social issues. Molecular Crystals and Liquid Crystals, 448, 161/[763]-177/[779].

Majhi, S. K., Nayak, S. K., Mohanty, S., & Unnikrishnan, L. (2010). Mechanical and fracture behavior of banana fiber reinforced polylactic acid biocomposites. *International Journal of Plastics Technology*, 14, 57-75.

Maleque, M., Atiqah, A., Talib, R., & Zahurin, H. (2012). New natural fibre reinforced aluminium composite for automotive brake pad. International Journal of Mechanical and Materials Engineering, 7, 166-170.

Mulani, S. M., Kumar, A., Shaikh, H. N. E. A., Saurabh, A., Singh, P. K., & Verma, P. C. (2022). A review on recent development and challenges in automotive brake pad-disc system. Materials Today: Proceedings. doi: 10.1016/j.matpr.2022.01.410

Munawar, S. S., Umemura, K., & Kawai, S. (2007). Characterization of the morphological, physical, and mechanical properties of seven nonwood plant fiber bundles. Journal of Wood Science, 53, 108–113.

Mwaikambo, L., & Ansell, M. (2001). The determination of porosity and cellulose content of plant fibers by density methods. Journal of Materials Science Letters, 20, 2095–2096..

Nishimura, T., Ishida, T., Funabashi, H., Hirota, R., Ikeda, T., & Kuroda, A. (2023). Detection of fine asbestos fibers using fluorescently labeled asbestos-binding proteins in talc. Journal of Hazardous Materials Advances, 12, 100332. https://doi.org/10.1016/j.hazadv.2023.100332

Olabisi, A. I., Adam, A. N., & Okechukwu, O. M. (2016). Development and assessment of composite brake pad using pulverized cocoa beans shells filler. International Journal of Materials Science and Applications, 5, 66-78.

Oladele, I. O., & Adewole, T. A. (2013). Influence of cow bone particle size distribution on the mechanical properties of cow bone-reinforced polyester composites. Biotechnology Research International, 5. https://doi.org/10.1155/2013/725396

Patel, V. K., Chauhan, S., & Katiyar, J. (2018). Physico-mechanical and wear properties of novel sustainable sour weed fiber reinforced polyester composites. Materials Research Express, 5, 045310.

Paridah, M., & Khalina, A. (2009). Effects of soda retting on the tensile strength of kenaf (Hibiscus cannabinus L.) bast fibres. Project Report Kenaf EPU, 21.

Pinca-Bretotean, C., Josan, A., & Putan, V. (2020). Testing of brake pads made of non-asbestos organic friction composite on a specialized station. Materials Today: Proceedings, 22, 4183–4188. https://doi.org/10.1016/j.matpr.2020.12.039

Ramanathan, K., Saravanakumar, P., Ramkumar, S., Kumar, P. P., & Surender, S. R. (2017). Development of asbestos-free brake pads using lemon peel powder. International Journal of Innovative Research in Science, Engineering and Technology, 6, 7.

Rathod, A., & Kolhatkar, A. (2014). Analysis of physical characteristics of bamboo fabrics. International Journal of Research in Engineering and Technology, 3, 21–25.

Reddy, N., & Yang, Y. (2006). Properties of high-quality long natural cellulose fibers from rice straw. Journal of Agricultural and Food Chemistry, 54, 8077–8081.

Reddy, N., & Yang, Y. (2005). Biofibers from agricultural byproducts for industrial applications. Trends in Biotechnology, 23, 22–27.

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Rodriguez, M., Rodriguez, A., Bayer, J., Vilaseca, F., Girones, J., & Mutje, P. (2010). Determination of corn stalk fibers' strength through modeling of the mechanical properties of its composites. BioResources, 5, 2535–2546.

Saleem, A., Medina, L., & Skrifvars, M. (2020). Mechanical performance of hybrid bast and basalt fibers reinforced polymer composites. Journal of Polymer Research, 27(61). https://doi.org/10.1007/s10965-020-2028-6

Sakthivel, M., & Ramesh, S. (2013). Mechanical properties of natural fiber (banana, coir, sisal) polymer composites. Science Park, 1, 1–6.

Satyanarayana, K. G., Arizaga, G. G., & Wypych, F. (2009). Biodegradable composites based on lignocellulosic fibers—An overview. Progress in Polymer Science, 34, 982–1021.

Shahrukh, S., Mubarak, S., Borse, P. N., & Student, P. G. (2020). Improvement in performance characteristics of brake disc by design & analysis. Retrieved from http://ijesc.org/

Singh, T., da Silva Gehlen, G., Ferreira, N. F., Yesukai de Barros, L., Lasch, G., Poletto, J. C., Ali, S., & Neis, P. D. (2023). Automotive brake friction composite materials using natural Grewia optiva fibers. Journal of Materials Research and Technology, 26, 6966–6983. https://doi.org/10.1016/j.jmrt.2023.09.072

Singh, T., & Patnaik, A. (2015). Performance assessment of lapinus-aramid based brake pad hybrid phenolic composites in friction braking. Archives of Civil and Mechanical Engineering, 15(1), 151–161. https://doi.org/10.1016/j.acme.2014.01.009

Sri Karthikeyan, S., Balakrishnan, E., Meganathan, S., Balachander, M., & Ponshanmugakumar, A. (2019). Elemental analysis of brake pad using natural fibres. Materials Today: Communications, 16, 1067–1074.

Stadler, Z., Krnel, K., & Kosmač, T. (2008). Friction and wear of sintered metallic brake linings on a C/C-SiC composite brake disc. Wear, 265, 278–285. https://doi.org/10.1016/j.wear.2007.10.015

Soiela, M., Ilves, A., Viikna, A., & Erberg, E. (2005). Properties of flax fiber-reinforced polyethylene films. Cheminė Technologija, 36, 38–45.

Sumaila, M., Amber, I., & Bawa, M. (2013). Effect of fiber length on the physical and mechanical properties of randomly oriented, nonwoven short banana (Musa balbisiana) fiber/epoxy composite. Cellulose, 62, 64.

Swamidoss, V. F., & Prasanth. (2015). Fabrication and characterization of brake pad using pineapple leaf fiber (PALF). International Journal of Research in Computer Applications and Robotics, 3, 5.

Thiruchitrambalam, M., Alavudeen, A., & Venkateshwaran, N. (2012). Review on kenaf fiber composites. *Review of Advanced Materials Science*, 32, 106–111.

Tomášek, V., Kratošová, G., Yun, R., Fan, Y., & Lu, Y. (2009). Effects of alumina in nonmetallic brake friction materials on friction performance. *Journal of Materials Science*, 44(1), 266–273. doi: 10.1007/s10853-008-3041-z

Venkateshwaran, N., & Elayaperumal, A. (2010). Banana fiber-reinforced polymer composites—a review. *Journal of Reinforced Plastics and Composites*, 29, 2387–2396.

Vijayalakshmi, K., Neeraja, C. Y., Kavitha, A., & Hayavadana, J. (2014). Abaca fibre. Transactions on Engineering and Sciences, 2, 16–19.

Wahlang, B., Nath, K., Ravindra, U., Chandu, R., & Vijayalaxmi, K. (2012). Processing and utilization of sugarcane bagasse for functional food formulations. *Proceedings of the International Conference and Exhibition on Food Processing and Technology*, 106–112.

Yan-hui, H., Ben-hua, F., Yan, Y., & Rong-jun, Z. (2012). Plant age effect on mechanical properties of moso bamboo (Phyllostachys heterocycla var. pubescens) single fibers. Wood and Fiber Science, 44, 196-201.

Yashwhanth, S., Mohan, M. M., Anandhan, R., & Selvaraj, S. K. (2021). Present knowledge and perspective on the role of natural fibers in the brake pad material. *Materials Today: Proceedings*, 21, 7329–7337. https://doi.org/10.1016/j.matpr.2020.12.995

Yigrem, M., Fatoba, O., & Tensay, S. (2022). Tribological and mechanical properties of banana peel hybrid composite for brake-pad application. *Materials Today: Proceedings*, 62, 2829–2838. https://doi.org/10.1016/j.matpr.2022.02.381

Yawas, D., Aku, S., & Amaren, S. (2016). Morphology and properties of periwinkle shell asbestos-free brake pad. Journal of King Saud University - *Engineering Sciences*, 28(2), 103–109. https://doi.org/10.1016/j.jksues.2015.01.006

Zhao, X., Zhang, L., & Liu, D. (2012). Biomass recalcitrance. Part I: The chemical compositions and physical structures affecting the enzymatic hydrolysis of lignocellulose. Biofuels, Bioproducts and Biorefining, 6, 465–482.