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| RESEARCH ARTICLE

Bio-Based Brake Pads: A Review of Natural Fillers and Their Performance Characteristics

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| ABSTRACT

The health and environmental hazards linked to asbestos-containing brake pads have precipitated a global initiative aimed at the development of sustainable alternatives derived from bio-based materials. This review article meticulously investigates the performance attributes of bio-based brake pads that incorporate natural fillers as viable substitutes for asbestos. The research emphasizes various agricultural byproducts, such as coconut shell powder, palm kernel shell, hemp fiber, sugarcane bagasse ash, and banana peel ash, assessing their mechanical, thermal, and tribological properties. The methodology encompasses an extensive analysis of the extant literature, elucidating the composition, processing methods, and performance indicators of these fillers within brake pad composites. Composites made from palm kernel shell demonstrated a compressive strength of up to 96.2 MPa, while materials based on coconut shell showcased exceptional hardness (up to 186.2 BHN) and wear resistance, with sugarcane bagasse ash and banana peel ash contributing to enhanced thermal stability attributable to their silica content. The conclusion accentuates the feasibility of these environmentally-friendly materials, which not only fulfill performance criteria but also alleviate the environmental and health concerns associated with asbestos. Recommendations entail the further optimization of filler compositions and surface treatments to enhance uniformity and adhesion within composite matrices, thereby facilitating sustainable applications in the automotive sector.

| KEYWORDS

Bio-based brake pads, natural fillers, palm kernel shell, coconut shell powder, banana peel ash, sugarcane bagasse ash, groundnut shell, tribological properties, thermal stability, eco-friendly composites, sustainable materials.

| ARTICLE INFORMATION

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1. Introduction

Over the past twenty years, the development of brake pad materials has experienced substantial transformations due to health concerns associated with asbestos-containing brake pads, prompting a concerted effort to create high-performance non-asbestos brake pad materials derived from agricultural byproducts (Ibhadode & Dagwa, 2008; Mahale et al., 2017; Polajnar et al., 2017; Shinde & Mistry, 2017) and composite materials (Agunsoye et al., 2018; Gbadeyan & Kanny, 2018; Ige et al., 2021). Given the omnipresence of automobile brake pads, it is imperative that the materials utilized in their fabrication be meticulously chosen to mitigate their adverse effects on both human health and the ecological environment (Ige et al., 2021). On a global scale, materials researchers and formulation engineers are engaged in the advancement of multi-phase friction composite materials, which consist of various combinations of fillers, fibers, binders, and friction modifiers that fulfill stringent quality standards, as the technology surrounding automotive braking systems continues to evolve (Ige et al., 2021; K. N. Kumar & Suman, 2017). The principal function of a binder is to cohesively bind the diverse components of the brake pad and to inhibit the degradation of its constituent parts (Bijwe & Kumar, 2007; Ingo et al., 2004). Fundamentally, fillers are incorporated to diminish the overall cost of the material while simultaneously enhancing the properties of the brake pad (Ige et al., 2021; Ikpambese et al., 2016).

Natural fibres have emerged as intriguing possibilities in the search for eco-friendly brake pad materials (Naidu et al., 2023). These fibres, which are made from renewable resources such as plants and agricultural leftovers, have various advantages: they are biodegradable, plentiful, and generally inexpensive. According to Naidu et al. (2023) and Andrew & Dhakal (2022), "the use of natural fiber composites is growing for many reasons, including their potential to replace synthetic fiber-reinforced plastics at a lower cost with improved sustainability". Recent research has examined several natural fibres, including coconut shell, rice husk, and palm kernel fibres, to determine their potential as fillers or reinforcements in brake pad composites. Krishnan et al. (2019) carried out a study on the tribological properties of palm kernel fiber for brake pad applications. Ammar et al. (2023) reviewed the influence of natural fiber content on the frictional material of brake pads. Maleque et al. (2012) worked on a new natural fiber-reinforced aluminum composite for automotive brake pads. Kumaran et al. (2019) investigated Caryota urens fibers on physical, chemical, mechanical, and tribological properties for brake pad applications. Also, Unal and Akkuş (2022) did an analytical and experimental investigation of composite pads created by using coke dust against the fading problem in railway vehicles. Similarly, Obika et al. (2020) researched the effect of cane wood and palm kernel fiber filler on the compressive strength and density of automobile brake pads. Anyanwu et al. (2019) worked on the effect of Kenaf Core Fibre (Hibiscus cannabinus) as one of the dispersing phases in brake pad composite production. P. M. Kumar (2017) developed and studied the tribological properties of biocomposites for brake pad application. Bashir et al. (2019) worked on the influence of lignocellulosic banana fiber on the thermal stability of brake pad material. Onyenanu et al. (2024) investigated the development of asbestos-free brake pads using bush mango shells (Irvingia gabonensis) and palm fruit fibre (PFF) as sustainable fillers. Eziwhuo et al. (2023) worked on the characterization of biodegradable brake pads from waste coconut fruit fiber and oyster shells as reinforcement materials. From these studies, it was found that natural fibres can improve the performance of brake pads in terms of heat stability, wear resistance, and frictional qualities.

Thus, this study offers a critical analysis of recent studies related to various facets of bio-based brake pad composites, encompassing the selection of sustainable reinforcement materials, mechanical and thermal characterisation, resistance to environmental degradation, and applications in automotive and industrial sectors (Chinedu et al., 2018).

2. Overview of Natural Filler Materials

Natural fillers, mostly sourced from renewable agricultural resources, have attracted considerable interest as sustainable substitutes for synthetic materials in composite manufacturing, especially in the production of automobile components like brake pads. Typically, these fillers come from plant-based sources such as fibres, husks, shells, seedpods, and agricultural waste. Their availability in vast quantities, biodegradability, affordability, and relatively low density make them appealing because these characteristics not only save material costs but also lessen the environmental impact of producing composites. Several natural filler categories have been investigated in brake pad formulations, each with distinct physical, thermal, and tribological properties.

2.1 Pentaclethra macrophylla (African oil bean seed pod)

Pentaclethra macrophylla, also known as African oil bean seed pod, is a lignocellulosic substance high in cellulose, hemicellulose, and lignin (Nsude & Orie, 2023) as shown in Fig. 1. It has a high tensile strength, superior thermal insulation, and excellent energy absorption properties (DIRISU et al., 2020). Its low density and biodegradability make it a sustainable filler (Nsude & Orie, 2023). Studies have demonstrated that it improves wear resistance and friction stability in composite brake pads. Iloabachie et al. (2023) examined the optimization of the hardness test for Powdered Pentaclethra macrophylla Pod /Bio-Epoxy Resin Based Brake Pad Composite Using Central Composite Design. Following their research, it was shown that powdered Pentaclethra macrophylla pods can be employed as a suitable asbestos alternative to improve the hardness of asbestos-free brake pads for automotive applications.

Fig. 1: Coconut shell powder (Etsy, 2024)

2.2 Coconut shell powder

Coconut shell powder is a dense, carbon-rich filler with a high lignin concentration (Singh et al., 2024) shown in Fig. 2. It is well-known for enhancing the hardness, wear resistance, and thermal stability of brake pads (Eziwhuo et al., 2024). The tiny particle structure allows for greater dispersion in resin matrices. Furthermore, its thermal degradation profile facilitates high-temperature performance in friction applications (SHETE & JADHAV, 2024). The study made by Shuaibu et al. (2023) shows that using Coconut Shell particles compares brilliantly with that of commercial Brake pads, hence it can be used as a good replacement for asbestos-based Brake pads. (Apasi et al., 2019) also designed and produced a brake pad using coconut shell as a base material. Based on the research, the typical homogenous bonded experimental brake pad/lining has a swell growth of 0.625% and a Brinell hardness value (BHN) of approximately 32.3. This shows that the overall performance of the coconut shell in brake pad formulation is comparable with asbestos-based linings and is recommended for use in automobile brake pads/linings (Apasi et al., 2019).

Table 1: Chemical Composition of Coconut Shell Powder

Component	Content (%)
Lignin	29.4%
Pentosans	27.7%
Cellulose	26.6%
Moisture	8.0%
Solvent Extractives	4.2%
Uronic Anhydrides	3.5%
Ash	0.6%

Source: (Ganthia et al., 2022)

2.3 Palm kernel shell

Palm kernel shell is a strong agricultural waste with high abrasion resistance and thermal resilience (Chinedu et al., 2018; Chinedu, 2019), shown in Fig. 3. It increases the mechanical integrity and compressive strength of brake pad composites (Adetunji et al., 2022; Okyere & Amedorme, 2023). Because of its high carbon content, it also improves frictional characteristics and heat conductivity. The study made by Popoola et al. (2021) showed that a combination of cow bone, seashell, and palm kernel shell is the best substitute to replace the commercially manufactured asbestos brake pad. Similarly, Achebe et al. (2019) worked on "A retrofit for asbestos-based brake pad employing palm kernel fiber as the base filler material". Their research showed that palm kernel fiber content has hardness, compressive strength, abrasion resistance, specific gravity, water absorption, and oil absorption of 178 MPa, 96.2 MPa, 1.67 mg/m, 1.8 g/cm3, 1.86%, and 0.89%, respectively. Their findings showed that palm kernel fiber is a possible and effective retrofit for asbestos as a filler material in automotive brake pad manufacture (Achebe et al., 2019).

Fig. 2: Coconut shell powder (Briskonimpex, 2025)

Fig. 3: Palm kernel shell (Folanature, 2021)

Table 2. Bulk physical and chemical characteristics of palm kernel shell.

Property	Parameter	Value (Ar)	Value (db)
Physical	Moisture content (%)	6.11	-
	Ash content (%)	8.68	
	*Bulk density ($kg·m^{-3}$)	740	9.24
	*Porosity (%)	28	650
Chemical	C (%)	46.75	49.79
	H (%)	5.92	5.58
	O (%)	37.97	34.66
	N (%)	0.68	0.72
	S (%)	<0.08	<0.08
	Cl (ppm)	84	89
Structural carbohydrates	Hemicellulose (%)	26.16	
	Cellulose (%)	6.92	
	Lignin (%)	53.85	

Source: (Okoroigwe et al., 2014)

2.4 Groundnut shell

Groundnuts are known biologically as *Arachis hypogaea* (Mohan Kumar et al., 2023). The powdered forms of groundnut shells (Fig. 4a) are used as reinforcements. In order to isolate the powder, the soil that adheres to the surface of the groundnut shells is eliminated through a thorough rinsing with distilled water (Mohan Kumar et al., 2023). Subsequently, the shells undergo treatment with an alkali solution possessing a concentration of 4% for a duration of approximately two hours (Mohan Kumar et al., 2023). Following this, the groundnut shells are subjected to another round of washing with distilled water and are then allowed to air-dry under sunlight (Okonji et al., 2019). The dried shells are subsequently processed into a fine powder (Fig. 4 b) and are subsequently sieved using various mesh sizes (0.5, 1, 2, and 3 mm) (Mohan Kumar et al., 2023; Raju & Kumarappa, 2011). Groundnut shells have moderate strength and strong heat resistance since they are high in lignin and cellulose (Ekpenyong et al., 2023). When ground into powder and used in composites, they lower wear rates and boost stiffness (Soni et al., 2023). Surface treatment is frequently required to enhance resin matrix adherence.

Fig. 4a: Groundnut shell (Mohan Kumar et al., 2023)

Fig. 4b: Groundnut shell powder after pretreatment (Raju & Kumarappa, 2011)

2.5 Tamarind seed (Tamarindus indica)

The Tamarindus indica is also known as the tamarind plant. The plant is widely grown in India, and its seed is used to make a hybrid composite. Initially, the tamarind seed (Fig. 5a) is extracted manually from the fruit and washed, and treated with an alkali solution to remove the stickiness. Later, the brownish layer of seed is removed and ground to a fine powder using commercially available flour grinders. To obtain enhanced mechanical behavior, such as impact resistance, shock resistance, vibration resistance, and water resistance, thixotropic high-viscosity epoxy resin can be used with a variety of hardeners to create natural fiber-reinforced composites. The research on the tamarind seed shell by Naik et al.has revealed that the enhanced characteristics, the tensile strength, and Young's modulus of composites are 27.69 MPa and 362.39 MPa for 10% and 20% composition of tamarind seed shell in a polymer matrix, respectively. The chemical composition of the tamarind shell comprises of greater weight percent of cellulose, which makes it a potential candidate for its use in composites, particularly for enhanced flexural and tensile strengths. These are graphically represented in Fig. 5 b.

Fig. 5a: Tamarind seed with brown shell (Raju & Kumarappa, 2011)

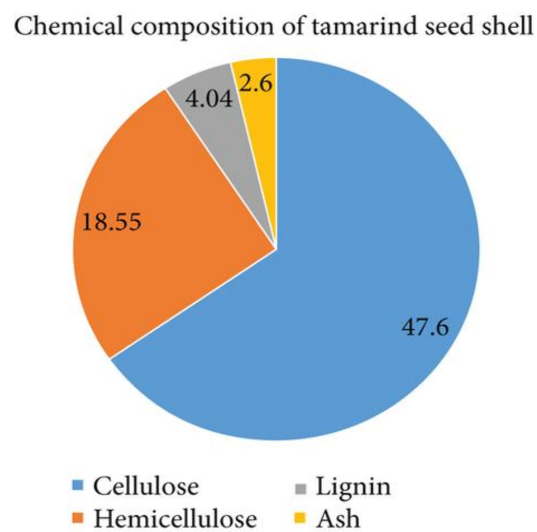

Fig. 5 b: Chemical composition of the tamarind seed shell (Raju & Kumarappa, 2011)

2.6 Palm fruit fiber

Palm fruit fibre is a lightweight natural fibre derived from oil palm processing. It has low density, high tensile strength, and thermal stability (Daramola et al., 2021; Shinoj et al., 2010). It is commonly used in conjunction with other fillers to increase pad performance and minimise noise. Its biodegradable nature is consistent with eco-friendly design concepts (Siregar et al., 2024; Erhimona et al., 2023). Mobi et al. (2021) worked on the optimization of the mechanical properties of palm fruit fiber automobile brake pads. Similarly, Onyenanu et al. (2024) investigated the development of asbestos-free brake pads using bush mango shells (Irvingia gabonensis) and palm fruit fibre (PFF) as sustainable fillers. The optimal brake pad composition, containing 30% BMS/PFF with a 300 μm particle size, exhibited competitive mechanical and wear properties: wear rate (2.97-3.96 mg/m), compressive strength (74.66-148 MPa), and hardness (94-104 HRB). Thermal stability was maintained between 200°C and 550°C. Their research deduced that palm fruit fibre can be a viable alternative to asbestos, supporting sustainable automotive manufacturing.

Fig. 6a: Palm fruit

Fig. 6b: Palm fruit fiber (ECOTECH, 2025)

Table 3. Physical properties of palm fiber

Fiber	Density (g/cm^3)	Elongation (%)	Tensile Strength (MPa)	Young's Modulus (GPa)
Palm leaf stalk	1.0–1.2	2.0–4.5	97–196	2.5–5.4
Palm leaf sheath	1.2–1.3	2.84	220	4.8
Palm petiole	0.7–1.55	25	248	3.24
Palm fruit	1.09	28	423	6.8
Coir	1.15–1.2	30	175	4.6
Pineapple leaf	0.86–1.6	14.5	144	400–627

Source: (Tegegne & Shiferaw, 2020)

2.7 Hemp fiber

Hemp is one of the oldest known bast fibres (textileblog, 2020). Hemp fibre is derived from cannabis plants (textileblog, 2020). Hemp fibre provides exceptional tensile strength, a high cellulose content, and inherent durability (Manaia et al., 2019; Zimniewska, 2022). It provides reinforcement in polymer matrices, which improves toughness and impact resistance. This is illustrated by the study made by. From the research, the efficacy showcased by the bio-based treatment will no doubt support the utilization of natural fiber in the reinforcement of the BPC, thereby consolidating efforts towards achieving a sustainable and eco-friendly brake pad composite (Lawan et al., 2024). However, hemp's moisture sensitivity necessitates chemical treatment for optimal performance in brake pad systems (Islam & Hasan, 2025).

Fig. 7: Hemp fiber (Himalayan hemp, 2020)

Table 4. Technical properties of hemp fiber

Chemical Properties	Value	Physical Properties	Value
Cellulose (%)	70–75	Specific gravity	1.47
Lignin (%)	3.5–6.0	Fiber length (cm)	0.5–2.0
Hemicellulose (%)	18–23	Moisture absorption (%)	~12
Pectin (%)	4–8	Tensile strength (MPa)	690
Wax (%)	1	Elongation at break (%)	3

Source: (Mydin et al., 2023)

2.8 Coconut husk fiber (Coir) and shell

Coir is coarse, stiff, and highly lignified, offering good toughness and thermal insulation. It improves the structural stability, hardness, and frictional reliability of brake pads (Onyenanu & Uwadibe, 2024). Onyeneke et al. (2014) worked on the production and testing of motor vehicle brake pads using locally available raw materials, which are periwinkle and coconut shell. From the result, "The scratch hardness, bonding strength to the back plate, and wear rate of the specimen were in the range (80-85), (25-27) kg/cm2, (0.03-0.06) mm/min. respectively, and for asbestos brake pad wear rate range from 0.04-0.08mm/min." Similarly, Dirisu et al. (2024), while utilizing the compacting mould technique, developed an asbestos-free friction material using agricultural waste (coconut shell and oil bean stalk) as a filler element, alongside aluminium dross, metal chip industrial wastes, and carbon black. The developed brake pads performed favourably when compared with the existing commercial brake pads. Therefore, the developed materials for brake pads can be considered suitable replacements for asbestos brake pads (Dirisu et al., 2024). From the research made by M. A. Maleque & Atiqah (2013), it was deduced that natural coir fibre can be a potential candidate filler material for the mass-scale fabrication of asbestos-free new brake pads without any harmful effect.

Fig. 8a: Coconut husk fiber (Coir)

Fig. 8b: Coconut shell

2.9 Banana peel ash

Banana peel ash contains silica, potassium, and other minerals (Tsado et al., 2021). It improves thermal conductivity and decreases frictional fading at high temperatures (Ukwu et al., 2024; Onyenanu et al., 2024). Its ash component aids in particle reinforcement and heat resistance, making it appropriate for thermally demanding applications (Mohamed et al., 2023). From the study made, it was indicated that banana peel particles can be effectively used as a replacement for asbestos in brake pad manufacture. According to the findings of Pranay et al. (2023) in their study, banana peel particles may be utilized efficiently as a replacement for asbestos in the fabrication of brake pads.

2.10 Bagasse ash (from sugarcane)

Bagasse ash is a fibrous waste containing silica and alumina, shown in Fig. 9. It increases heat resistance and improves the frictional qualities of composites (Choosri et al., 2019). Its incorporation in brake pad compositions reduces density and increases surface roughness, resulting in increased brake engagement (Vivek & Kanthavel, 2019). Chandradass et al. (2021) developed a low-cost brake pad material using asbestos-free sugarcane bagasse ash hybrid composites. The findings demonstrated that the sample with 10% SCBA as a filler content had low water and oil absorption, high tensile and flexural strengths, and density (Chandradass et al., 2021). Additionally, the results of the impact and hardness tests demonstrated that the material was a suitable material for brake pads (Chandradass et al., 2021).

Table 5a. Physical properties of sugarcane bagasse ash

Property	Value
Fineness modulus	2.12
Specific gravity	2.48

Source: (Vignesh & Poornimabharathi, 2016)

Table 5b. Chemical composition of sugarcane bagasse ash

Oxides	SCBA Mass %
Silica (SiO_2)	68.00
Alumina (Al_2O_3)	3.05
Ferric Oxide (Fe_2O_3)	3.72
Calcium Oxide (CaO)	5.10
Magnesium Oxide (MgO)	1.15
Sulfur Trioxide (SO_3)	0.67
Loss on Ignition	4.50

Source: (Vignesh & Poornimabharathi, 2016)

2.11 Maize husk

Maize husk is an agricultural waste that includes small levels of cellulose and lignin, shown in Fig. 10. It can be used in brake pad composites to reduce production costs while increasing wear resistance. However, its mechanical properties fluctuate, needing constant processing and fibre sizing for consistent use. The development and evaluation of maize husks as asbestos-free friction material for the production of automotive brake pads was carried out by. The result showed that "specimen composite 3 with 30% MH filler content having coefficient of friction, abrasion resistance, water absorption, oil absorption, density, hardness, tensile strength, compressive strength, and thermal conductivity of 0.37, 4.470E-6g/m, 0.725%, 0.660%, 0.852g/cm3, 99.34mPa, 14.407mPa, 6.779mPa and 0.330W/mk respectively was optimum in performance." In contrast to brake pads made of asbestos, composite brake pads are environmentally friendly and do not carry the health risks of asbestosis, mesothelioma, lung conditions, and cancer aggravation that come with using asbestos-bearing components.

Fig. 9: Bagasse ash (from sugarcane) (Ademoh & Olabisi, 2015)

Fig. 10: Maize/corn husk (Ltd, 2018)

3. Brake Pad Composite Structure and Performance Metrics

The design and functional efficacy of automotive brake pads are significantly contingent upon the specific characteristics and combinations of materials utilized within their composite matrix. The four main components of brake pads are binders, fillers, abrasives, and lubricants (Irawan et al., 2022; Raghunathan et al., 2024). Each of these components contributes differently to the structural integrity, thermal properties, and tribological performance of the pad. Nevertheless, the increasing emphasis on sustainable and environmentally friendly materials has prompted an investigation into natural fillers such as plant-derived fibers, seed shells, and agricultural waste ashes as feasible substitutes for asbestos and other synthetic reinforcements. Natural fillers not only provide ecological benefits but also impact essential performance indicators, encompassing wear resistance, frictional properties, hardness, density, and the capacity for moisture and oil absorption. To assess their feasibility, numerous studies have examined the mechanical, thermal, and tribological behaviors of composites formulated with diverse natural fillers across a range of formulations and experimental conditions. Table 6 offers a comprehensive summary of the fundamental components typically incorporated in brake pad composites, detailing their specific functions, pertinent examples of natural fillers, related performance indicators, and standardized assessment methodologies as documented in scholarly literature.

Table 6: Summary of Research Studies on Natural Fillers in Brake Pads

Study Title	Fillers used	Performance Metrics	References
A retrofit for asbestos-based brake pads employing palm kernel fiber as the base filler material	Palm kernel fiber	The result showed that sample C with 40% palm kernel fiber content having hardness, compressive strength, abrasion resistance, specific gravity, water absorption, and oil absorption of 178 MPa, 96.2 MPa, 1.67 mg/m, 1.8 g/cm3, 1.86%, and 0.89%, respectively, had an optimum performance rating.	(Achebe et al., 2019)
Evaluation of palm kernel fibers (PKFs) for the production of asbestos-free automotive brake pads	Palm kernel fibers with epoxy-resin binder	"The results obtained indicated that the wear rate, coefficient of friction, noise level, temperature, and stopping time of the produced brake pads increased as the speed increased. The results also show that porosity, hardness, moisture content, specific gravity, surface roughness, and oil and water absorption rates remained constant with an increase in speed. The result of microstructure examination revealed that worm surfaces were characterized by abrasion wear where the asperities were ploughed, thereby exposing the white region of palm kernel fibers, thus increasing the smoothness of the friction materials."	(Ikpambese et al., 2016)
Development of low-cost brake pad material using asbestos-free sugarcane bagasse ash hybrid composites	Sugar cane bagasse ash (SCBA)	"The results showed that the sample having 10% SCBA as filler content has high tensile strength, flexural strength, density, low water, and oil absorption. Also, the hardness test and impact test results revealed the suitability of SCBA in brake pad material."	(Chandradass et al., 2021)
Development of asbestos-free brake pads using corn husks	Corn husk fibres and silicon carbide were mixed with fixed proportions of graphite, steel dust, and resin	"The result obtained showed that the brake pad produced with the corn husk passing the finer 100 µm screen gave better compressive strength, higher hardness, lower porosity, and lower rate of wear, consequent on the finer distribution of the corn husk particles in the matrix."	(Asotah & Adeleke, 2017)
Development of Eco-Friendly Brake Pads Using Oil Residue Materials: Assessment of Mechanical Properties, Biodegradation, and Environmental Impact	Coconut, groundnut, and sesame.	"Flexural strength improved by 15-20%, with values of about 42.5 MPa, while tensile strength rose by around 18-22%, reaching up to 28.6 MPa. The impact strength was increased by 25-30%, and energy absorption reached 4.9 kJ/m², higher than the 3.7 kJ/m² achieved by conventional alternatives. Superior abrasion performance was shown by an 8-10% rise in Shore D hardness, which reached values of 79-81, and an improvement in wear resistance, with a specific wear ratio decrease of 12-16%."	(Sunil & Edwin, 2025)
Development and Assessment of Composite	Cocoa bean shells	"Based on the investigated properties of the developed brake pad, reducing the filler	(Olabisi et al., 2016)

Brake Pad Using Pulverized Cocoa Bean Shells Filler		content increased the wear rate, tensile strength, and compressive strength, while hardness, density, water absorption, oil absorption, and thermal conductivity varied differently. The coefficient of friction increased with an increase in the filler wt%. The results showed that CBS particles could be effectively used as a replacement for asbestos in automotive brake pad manufacture.”	
Effect of cane wood and palm kernel fibre filler on the compressive strength and density of automobile brake pad	Cane wood and palm kernel	“On optimization, optimal compressive strength and density of 107.3 MPa and 1.73 g/cm^3 were obtained for the composition of 30% resin content, 21.329% palm kernel fibre content, and 40% cane wood content. Thus, the combination of cane wood and palm kernel fibre as filler material for brake pad production will give an automobile brake pad with good compressive strength and density.”	(Obika et al., 2020)
Development of an asbestos-free brake pad using coconut shell powder and coconut shell ash as filler materials with gum Arabic as the binder	Coconut Shell Powder and Coconut Shell Ash as Filler Materials	“The promising values obtained for hardness, density, water, and oil absorption are 186.2 BHN, 1.332g/cm3, 1.353%, 0.700%. Although the sample developed using the 154µm sieve Coconut Shell particles exhibited the highest hardness potential, but it can be seen from the results that all the samples developed using Coconut Shell particles compared brilliantly with that of commercial Brake Pad, hence, it can be used as a good replacement for asbestos based Brake Pad.”	(Shuaibu et al., 2023)
The Development of Vehicle Brake Pad Using Local Materials - (Palm Kernel, Coconut, and Cashew Shells as Base Materials).	Palm Kernel, Coconut, and Cashew Shells	“It was revealed that the co-efficient of friction of the pad material ranged from 0.4-0.65, scratch hardness of 80-85, bonding strength of 25-27Kg/cm2 and wear rate of 0.025mm/min to 0.06mm/min as compared to the conventional brake pad material that has hardness of 80-85, bonding strength of 25-27kg/cm2and wear rate of 0.03-0.08mm/min "	(Anaidhuno et al., 2017)
Production of Eco-Friendly Brake Pad Using Raw Materials Sourced Locally in Nsukka	Palm kernel shell and coconut shell	“The test result showed that the coefficient of friction (static and dynamic) for samples A, B, and C were (0.374, 0351), (0.383, 0354), and (0.362, 0.349) while the commercial pad was (0.388, 0.359). The percentage water absorption for samples A, B, and C was 0.0522, 0.0399, and 0.0470, while the commercial pad was 0.0327. The hardness test results for samples A, B, and C were 3.3, 3.41, and 3.0, while the commercial pad was 2.53. The wear rate test gave	(Egeonu et al., 2015)

		0.00366g/sec, 0.00456g/sec, 0.00334g/sec, 0.00312g/sec for samples A, B, C, and commercial pad, respectively."	
Domestic waste (eggshells and banana peel particles) as sustainable and renewable resources for improving resin-based brake pad performance: Bibliometric literature review, techno-economic analysis, dual-sized reinforcing experiments, for comparison	Eggshells and banana peel particles	The stiffness test, puncture test, wear rate, and coefficient of friction of the specimen were 4.5 MPa, 86.80, 0.093×10^{-4} g/s.mm^2, and 1.67×10^{-4}, respectively.	(Nandiyanto et al., 2022)

4. Comparative Review of Bio-Based Fillers

The efficacy of brake pads composed of natural fillers is fundamentally dependent on essential characteristics such as wear rate, coefficient of friction, hardness, thermal stability, and environmental resistance. Numerous investigations have assessed these fillers under diverse formulations and testing conditions, illuminating not only their relative advantages but also particular limitations. For example, coconut shell powder and palm kernel shell are recognized for their elevated lignin and carbon content, which confer remarkable hardness and wear resistance. In contrast, materials such as banana peel ash and bagasse ash enhance thermal stability and frictional consistency, attributable to their substantial silica content. To facilitate a comparative analysis, Table 7, presented below, delineates a summary of key bio-fillers documented in the literature, emphasizing their mechanical properties, tribological performance, and practical utility in brake pad systems.

Table 7: Comparative Analysis of Bio-Based Fillers for Brake Pads

Filler	Key Properties	Advantages	Limitations
Palm Kernel Shell	High abrasion resistance, thermal resilience, carbon-rich (46-50% C)	Enhances compressive strength (96.2 MPa), wear resistance, and heat stability	Requires surface treatment for optimal resin adhesion
Coconut Shell Powder	High lignin (29.4%), dense structure, excellent thermal stability	Improves hardness (32.3 BHN) and wear resistance	Low flexibility; may increase brittleness
Hemp Fiber	High cellulose (70-75%), tensile strength (690 MPa), lightweight	Superior toughness, impact resistance, and biodegradability	Moisture-sensitive; requires chemical treatment
Sugarcane Bagasse Ash	Silica-rich (68%), low density, high thermal resistance	Reduces frictional fading, improves heat dissipation	Variable particle size distribution
Banana Peel Ash	Silica and potassium content improve thermal conductivity	Low-cost, reduces fading at high temperatures	Limited mechanical strength
Maize Husk	Moderate cellulose/lignin, low density (0.852 g/cm^3)	Cost-effective, reduces wear rates	Inconsistent properties; requires fiber sizing
Groundnut Shell	High lignin (27.7%), moderate strength	Enhances stiffness and wear resistance	Requires alkali treatment for adhesion

5. Conclusion

This comprehensive review substantiates the assertion that natural fillers, including palm kernel shell, coconut shell powder, banana peel ash, sugarcane bagasse ash, and groundnut shells, represent viable and environmentally sustainable alternatives to asbestos in the fabrication of brake pads. The incorporation of these materials markedly enhances thermal stability, wear resistance, frictional performance, and mechanical strength. For example, composites derived from palm kernel fiber exhibited compressive strengths reaching up to 96.2 MPa, whereas formulations utilizing coconut shell attained hardness metrics that are analogous to those of commercially available asbestos-reinforced pads. Furthermore, the inclusion of sugarcane bagasse ash and banana peel ash notably contributed to the enhancement of thermal and frictional characteristics, attributable to their inherent silica content. Collectively, the results delineated herein reinforce the viability of bio-based fillers for the advancement of sustainable brake pad manufacturing, demonstrating commendable mechanical and ecological performance.

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