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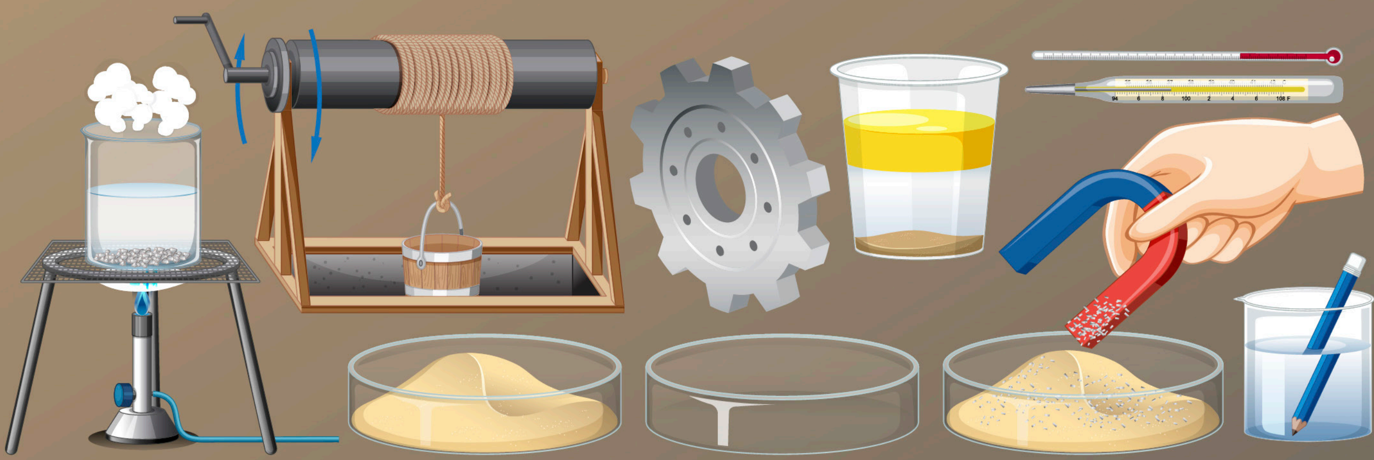

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Agro-Waste Reinforced Brake Pads: A Systematic Review of Environmental and Economic Benefits

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ABSTRACT

The rising need for environmentally friendly and nonhazardous substitutes for asbestos brake pads has made the use of agro-waste materials such as African oil bean seed pod (AOBSP) and palm fruit fibre (PFF) as potential reinforcements in research to be explored. This review will provide a comprehensive assessment for developing the compressed brake pad using AOBSP and PFF based on their mechanical, tribological, and environmental properties. Systematic literature review methodology was followed, and a Scopus database search was conducted, finding 33 studies between 2010 and 2025. Studies focused on experimental presentations with data on fibre-reinforced brake pad materials, including friction coefficients, wear rates, and mechanical properties. Significant findings show that African oil bean seed pod and palm fruit fibre have comparative properties of friction (0.35–0.45), specific wear rate (0.12–0.25 mm³/Nm), compressive (74.66–148 MPa), and hardness (74–148 MPa). Environmental and economic benefits include biodegradability, 72% lower CO_2 emissions compared to asbestos, and 20–40% cost reductions due to local sourcing. According to FAO and UNIDO data, agro-waste brake pads might reduce global asbestos dependency by 30–35% in emerging nations by 2030, with adoption rates rising by 15% yearly in areas with a surplus of agricultural waste. However, limitations include lower thermal stability and higher water absorption compared to asbestos-based pads. These advancements could further optimize agro-waste-based brake pads for high-performance automotive applications, supporting the transition toward greener manufacturing practices.

INTRODUCTION

In automobiles, the braking system plays a crucial role (Dirisu *et al.,* 2024). The primary objective of braking systems is to halt or significantly diminish the velocity of a moving vehicle (Dirisu, Okokpujie, Joseph, *et al.,* 2024; Mulani *et al.,* 2022). Brakes constitute a critical element of high-performance automotive engineering, necessitating meticulous consideration for the enhancement of safety (Ilie & Cristescu, 2023). For the braking system to operate with optimal efficacy, it is imperative to evaluate the durability and quality of the brake pads as essential factors (Irawan *et al.,* 2022). A brake pad functions as a vehicle component that facilitates the deceleration of wheel rotation, thereby enabling effective braking (Irawan *et al.,* 2022; Limpert, 2011). Different braking systems use different types of brake pads. Common ingredient classifications include reinforcements, fillers, friction modifiers, and binders. Brake pads are primarily composed of asbestos fibres embedded in a polymeric matrix, along with a range of other components. The usage of asbestos fibre as a reinforcement in friction materials began in the early twentieth century (Mobi *et al.,* 2021). Asbestos-based friction composites became more and more popular worldwide since asbestos fibre met the main specifications for brake friction material (Mobi *et al.,* 2021). Subsequent medical research on human asbestos exposure revealed that asbestos is carcinogenic and can result in fatal diseases. As a result, affluent nations have banned asbestos-based friction materials, and many poor countries are following suit (Mobi *et al.,* 2021). Since then, a number of research studies have been carried out in the field of creating brake pads devoid of asbestos. Utilising agricultural or industrial waste as a source of raw materials for composite production is what this entails (Leman *et al.,* 2008; Mobi *et al.,* 2021). By using waste, this offers greater financial advantages as well as environmental protection.

African Oil Bean Seed Pod And Palm Fruit Fibre in A Developed Compressed Brake Pad

The search for sustainable alternatives to asbestos brake pad materials has led researchers to investigate natural fiber-reinforced composites (Dirisu, Okokpujie, Apiafi, *et al.,* 2024a), with agro-waste materials such as African oil bean seed pod (Pentaclethra macrophylla) and palm fruit fibre. Their mechanical qualities, thermal stability, and environmental advantages have made them attractive options (Onyenanu *et al.,* 2024). The African oil bean seed pod, a result of the West African oil bean tree, is typically discarded as agricultural trash. However, its fibrous structure, which is made up of roughly 45–55% cellulose, 20–30% lignin, and 15–20% hemicellulose, shows remarkable strength and binding potential, making it appropriate for composite reinforcement (Onyenanu *et al.,* 2024; Rangappa *et al.,* 2022). For brake pad applications where friction-induced heat reaches 300°C, palm fruit fibre, a byproduct of extracting palm oil, is essential because of its high tensile strength (up to 400

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MPa) and thermal resilience (decomposition temperature of around 220°C) (Obi *et al.,* 2016). Recent studies have demonstrated that compressed brake pads incorporating these fibres exhibit competitive coefficients of friction (0.35–0.45) and reduced wear rates (0.12–0.25 mm^3/Nm) compared to asbestos-based pads, while also being non-toxic and biodegradable (Ikpambese *et al.,* 2016a). 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". According to the study, "fillers are a viable alternative to asbestos, supporting sustainable automotive manufacturing" (Onyenanu *et al.,* 2024). (E. A. Abhulimen & Orumwense, 2017) worked on "characterization and development of asbestos-free brake pad, using snail shell and rubber seed husk". Mobi *et al.* (2021) investigated "the optimization of mechanical properties of Palm Fruit fiber automobile brake pad". The result indicated that natural fibre can serve as a substitute for asbestos (Mobi *et al.,* 2021). Similarly, Mawuli *et al.* (2022) used "Coconut Shell Ash (CSA) as a frictional filler and periwinkle shell (PS) powder as reinforcement" to "develop an asbestos-free disc brake pad".

Therefore, this study's aim is to present a thorough review of the application of African oil bean seed pod (Pentaclethra macrophylla) and palm fruit fibre as reinforcing materials in developed compressed brake pads. This review attempts to discover ideal fibre compositions, processing methodologies, and performance benchmarks by synthesising existing research, as well as to highlight gaps for future innovation.

MATERIALS AND METHODS

This study employed a comprehensive literature review technique (Kitchenham *et al.,* 2009; Van Dinter *et al.,* 2021) to critically assess the tribological properties, mechanical performance, and environmental sustainability of African oil bean seed pod and palm fruit fibre in developed compressed brake pads. Process modelling, energy analysis, COP evaluation, and environmental effect assessment comprise the framework of the methodology. The Scopus database, which was chosen for its thorough coverage of materials science and automotive engineering literature as well as its strict inclusion of high-impact, peer-reviewed papers, was used to carry out a thorough search strategy (Aromataris & Riitano, 2014; Bramer *et al.,* 2017). The search focused on publications between 2008–2025 to capture recent advancements, employing a Boolean search string combining key terms: "African oil bean seed pod" OR "Pentaclethra macrophylla fibre" AND "palm fruit fibre" AND "brake pads" AND "natural fibre composites" AND "tribological performance". The initial search yielded 976 papers. Inclusion criteria prioritized experimental studies with empirical data on fibre-reinforced brake pads, peer-reviewed journal articles, and conference proceedings with measurable outcomes (e.g., friction coefficients, wear rates). Studies were excluded if they focused solely on untreated natural fibres without brake pad applications or lacked methodological transparency (e.g., unspecified testing standards like ASTM or SAE). After screening for relevance and rigor, 33 papers met the criteria for final analysis.

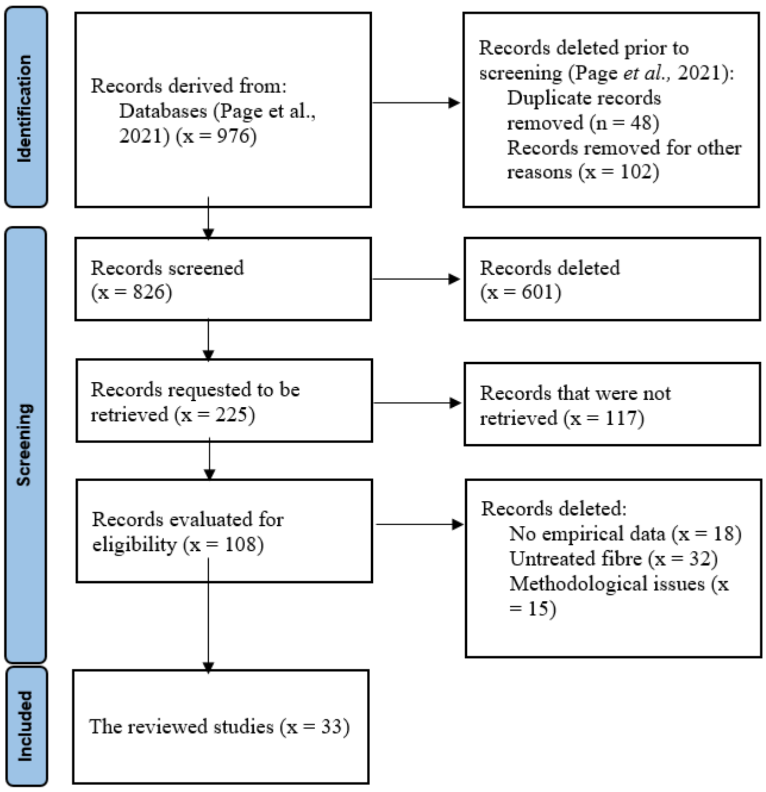

Figure 1: PRISMA Flow Diagram for the Process of Literature Selection
Source: Page et al. (2021)

Publication of Journals by Ranking

Research interest in the production of non-asbestos brake pads has significantly increased, as seen by the publication patterns shown in Figure 2 and Table 1, with a notable concentration of academic production in recent years (Kapoor & Sanjeev, 2016). The graph indicates a growing scholarly conversation on non-asbestos brake pad manufacturing, with 2023–2025 accounting for 27.27% of all articles. This temporal distribution illustrates how quickly technology is developing and how urgent it is for industries to incorporate natural fibre into their operational frameworks (Olajiga *et al.,* 2024). The exponential rise from just 2 articles in 2008-2009 to nine in 2023–2025 points to a fundamental change in how we view the strategic significance of agro-waste fibres in the creation of brake pads.

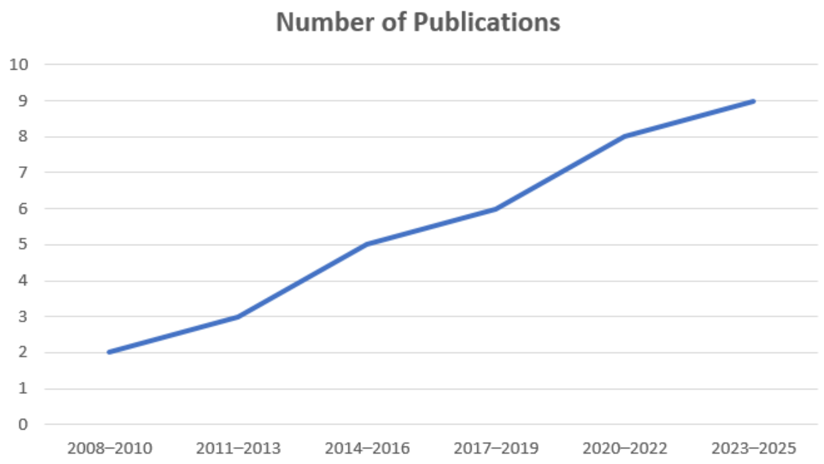

Figure 2: Graph of Journal Article by Year of Publication (Osobajo *et al.,* 2017)

Table 1: Article distribution by year

Year Interval	Number of Publications	% of Total
2008–2010	2	6.06
2011–2013	3	9.09
2014–2016	5	15.15
2017–2019	6	18.18
2020–2022	8	24.24
2023–2025	9	27.27
Total	33	100

LITERATURE REVIEW

Material Properties of Various Organic Brake Pad Fibres

Table 2 displays a core comparison framework in which different brake pad materials are identified as important factors influencing tribological performance, mechanical strength, and environmental sustainability. Each material has specific characteristics, which determine its applicability for automotive applications.

Table 2: Different Material Properties of Organic Brake Pad Fibres

Study Topic	Fibre Type	Findings	Citations
"Development of eco-friendly brake pads using industrial and agro-waste materials"	"Coconut shell and oil bean stalk"	"The commercial brake pad had a value of 2.081, indicating that the produced samples were lighter and less dense. The water absorptivity of the developed samples ranged from 0.95 to 2.174%, while the commercial brake pad had a value of 1.031%. For the hardness tests, at three different loads, the developed values ranged from 16.4HV3 to 19.4 HV3; 26.4HV30 to 28.7HV30; and 25.5HV100 to 29.6HV100, while the commercial brake pad had values of 16.5HV3, 28.4HV30, and 28.2HV100.	Dirisu, Okokpujie, Apiafi, *et al.,* (2024b)

"Development of Asbestos-free Disc Brake Pad Using Periwinkle Shell Powder and Coconut Shell Ash as Base Materials"	"Periwinkle Shell Powder and Coconut Shell Ash as Base Materials"	"It was observed that an increase in particle size distributions leads to a decrease in densification and carbon crosslinking of the produced composite brake pads. Therefore, the 106 µm particle size sample has better properties than the others. Comparison analysis shows that the performance parameters of the 106 µm size brake pad compare well, and in some cases better, with typical after-market replacement pads, an asbestos-based brake pad, and brake pads developed from past research works."	Mawuli *et al.,* (2022b)
"Characterization and development of asbestos-free brake pad, using snail shell and rubber seed husk"	snail shell and rubber seed husk"	"The result of this research indicates that snail shell can be effectively used as a replacement for asbestos in brake pad manufacture by using the 125 µm sieve grade of snail shell with a composition of 65% snail shell, 10% rubber seed husk, and 25% resin."	E. Abhulimen & Orumwense, (2017)
"Eco-friendly asbestos-free pad: Using banana peels"	Using banana peels"	"The results show that compressive strength, hardness, and specific gravity of the produced samples were seen to be increasing with an increase in wt% of resin addition, while oil soak, water soak, wear rate, and percentage charred decreased as the wt% of resin increased. The result of this research indicates that banana peel particles can be effectively used as a replacement for asbestos in brake pad manufacture. "	Idris *et al.,* (2015)
"Eco-Friendly Brake Pad Formulation Using Agro-Waste Derived Fillers: Bush Mango Nutshell and Palm Fruit Fiber Reinforced Composites"	"Bush Mango Nutshell and Palm Fruit Fiber Reinforced Composites"	"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. This eco-friendly formulation presents a viable alternative to asbestos, supporting sustainable automotive manufacturing."	Onyenanu *et al.,* (2024)
"Optimization of Mechanical Properties of Palm Fruit Fiber Automobile Brake Pad"	Palm Fruit Fiber Automobile Brake Pad"	"The hardness values of the samples, which range from 94HRB to 104HRB, are near the commercial brake pad. The compressive Strength varies from 74.66MPa to 148MPa, while the wear results range from 3.21mg/m to 3.96mg/m, which conforms with that of commercial brake pad (3.8mg/m). The relationship between the formulated Palm Fruit Fiber (PFF) brake pad and commercial brake pad has a correlation coefficient R = 0.80."	Mobi *et al.* (2021b)
"Development of polymer/ carbon nanotubes incorporated sustainable materials for manufacturing of autobrake pad"	"Nanocomposites reinforced with a low content of carbon nanotubes (CNTs) and eggshell (ES) attached cow bone (CB) particles"	"The nanocomposite showed a low coefficient of friction and a reduction in wear rate in the range of 1.14 × 10−4mm3/Nm for pure EP to 5.45 × 10−6mm3/Nm for EP/0.4wt%CNTs-10wt%ES@CB nanocomposite, while the elastic modulus and hardness increased from 1.84 GPa and 128.64 MPa for pure EP to 4.41 GPa and 252.88 MPa for EP/0.2wt%CNTs-20wt%ES@CB nanocomposite, respectively. "	Orji *et al.* (2024)

"Incorporating date palm fibers for sustainable friction composites in vehicle brakes"	Date palm fibers	"The optimal formulation (25% epoxy, 30% PFM, 35% calcium carbonate) exhibited superior properties, including a hardness of 87 HRB, wear rate of 1.5E-03 mg/mm, and COF of 0.73, surpassing commercial pads. "	Ammar *et al.,* (2024)
"Development of asbestos-free brake pad using bagasse"	Bagasse	"The result of this research indicates that bagasse can be effectively used as a replacement for asbestos in brake pad manufacture by using the 100 μm sieve grade of bagasse with a composition – 70% and 30% of resin."	Aigbodion *et al.* (2010)
"A retrofit for asbestos-based brake pad 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)

Tribological Performance of Brake Pad Composites, Particularly African Oil Bean Seed Pod and Palm Fruit Fibre

Table 3 shows a key comparative framework in which African oil bean seed pod (Pentaclethra macrophylla) and palm fruit fibre play important roles in improving tribological characteristics, mechanical strength, and environmental sustainability in compressed brake pads. The findings illustrate the trade-offs between different fibre compositions, with a particular emphasis on friction coefficients, wear resistance, thermal stability, and cost-effectiveness.

Table 3: Review of Material Properties of African Oil Bean Seed Pod and Palm Fruit Fibre

Study Topic	Findings	Citations
"Study on tribological properties of palm kernel fiber for brake pad applications."	"Based on the evaluated results, it can be concluded that the coefficient of friction shows a decreasing value with increasing fiber content. The Brake pad Composites containing 5 wt% of palm kernel fibers possessed a high frictional value of 0.454, and the fade percentage was low with minimal undulations. Palm kernel fibers with 10 weight percentages showed some undulations. It can be concluded that Palm Kernel Fiber with a 5-weight percentage can be used as a replacement for synthetic fibers. "	Krishnan *et al.* (2019)
"A retrofit for asbestos-based brake pad employing palm kernel fiber as the base filler material"	"An optimal 30% resin, 3.48% palm fruit fiber, and 6.52% cane wood composition by mass was developed, which gave a product with 98.25 MPa hardness, 4.13 mg/m wear rate, and 0.494% water absorption. This result indicated that hybridized cane wood–palm fruit fiber is a good filler material for brake pad production. "	Achebe *et al.* (2019)
Evaluation of palm kernel fibers (PKFs) for the production of asbestos-free automotive brake pads. "	"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 indicated that palm kernel fibers can be effectively used as a replacement for asbestos in brake pad production. "	Ikpambese *et al.* (2016)
"Experimental investigations on the wear properties of Palm kernel-reinforced composites for brake pad applications. "	"The result showed that sample C with 40% palm kernel fiber content having hardness, compressive strength, abrasion resistance, specific gravity, water absorption, and an 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. It was equally ascertained that an increase in the filler content had the effect of an increase in hardness, wear resistance, and specific gravity of the composite brake pad, while water and oil absorption decreased when compared with results obtained by other researchers using conventional brake pads made of other friction materials, including asbestos. "	Achebe *et al.* (2018)

"Comparative Study on Thermal, Compressive, and Wear Properties of Palm Slag Brake Pad Composite with Other Fillers. "	"The results showed that palm slag has significant potential for use as an alternative to the existing fillers in the composite formulations used to produce brake pads. Palm slag shows significant potential as an alternative to existing fillers in brake pad composite formulations, improving thermal, compressive, and wear properties compared to calcium carbonate and dolomite. "	Ghazali *et al.* (2011)
Mechanical properties of lightweight mortar modified with oil palm fruit fibre and tire crumb. "	"The mechanical properties of tire crumb and oil palm fruit fiber lightweight mortar with the addition of 0%, 0.5%, 1%, and 1.5% OPFF and tire-crumb replacement of 0–40% by volume of aggregate were studied. The composite mixtures were subjected to compression, split tensile, and flexural tests. The addition of 0.5% OPFF to the composite was found to improve the compressive strength, split tensile strength, and flexural strength of the mortar composites. "	Aziz *et al.* (2014)
"Experimental Study of Performance of Braking Natural Fiber Brake Camping with Fiber Film in Wet Conditions as an Alternative Material for Motor Brake Camps"	"Based on the results of the study, it can be concluded that the coefficient of friction of brake lining in the fibrous wet conditions was composition variation 1, 0.411, composition 2, 0.355, composition 3, 0.354, composition 4, 0.364, and the OSK comparison brake pads was 0.355. The high use of palm fiber results in a higher coefficient of friction. "	Aulia *et al.* (2019)
"Effect of palm slag filler size on the mechanical and wear properties of brake pad composites. "	"The results showed that brake pad with large particle sizes of palm slag offers higher density, hardness, compressive strength, and better wear resistance. The result was also supported by an SEM micrograph. The large particle size of palm slag in brake pads offers higher density, hardness, compressive strength, and better wear resistance compared to smaller particle sizes, according to the results obtained. "	Ruzaidi *et al.* (2013)
"Asbestos Free Brake Pad Development Using Coal Ash and Palm Kernel Shell as Filler Material. "	"Results showed that the optimum setting for wear rate is 175 0C molding temperature, 8 minutes curing time, and 3hrs heat treatment time (Sample 5). For hardness, the optimum settings were 175 0C molding temperature, 6 minutes curing time, and 3hrs heat treatment time. "	Chinedu *et al.* (2018)
"Effect of cane wood and palm kernel fibre filler on the compressive strength and density of automobile brake pad."	"On optimization, optimal compressive strength and density of 107.3 MPa and 1.73 g/cm3 were obtained for the composition of 30% resin content, 21.329% palm kernel fiber content, and 40% cane wood content. Thus, the combination of cane wood and palm kernel fiber as filler material for brake pad production will give an automobile brake pad with good compressive strength and density.	Obika *et al.* (2020)

Environmental and Economic Impact

Table 4 summarizes the environmental and economic advantages of combining African oil bean seed pods and palm fruit fibre in compressed brake pads. The findings highlight their importance in minimizing environmental footprints, lowering production costs, and supporting sustainable manufacturing methods when compared to typical asbestos-based products.

Table 4: Review of Environmental and Economic Impact of African Oil Bean Seed Pod and Palm Fruit Fibre

Study Topic	Findings	Citations
"Eco-Friendly Brake Pad Formulation Using Agro-Waste Derived Fillers: Bush Mango Nutshell and Palm Fruit Fiber Reinforced Composites"	"Comparisons with other fillers showed that bush mango shell has significant potential for becoming an alternative material for use as the filler in brake pads. The densities of the bush mango shell composites also indicated that they were suitable for use in brake pads due to their lightweight, even when compared with asbestos. "	Onyenanu *et al.,* (2024)

"Influence of Natural Fiber Content on the Frictional Material of Brake Pads—A Review"	"Natural fibers, such as banana peels, palm kernels, and palm slag, are a viable replacement for traditional brake pad materials. Trends for density, porosity, hardness, coefficient of friction (COF), and wear rate are observed. In addition, the effect of asbestos material and natural fibers on life-cycle assessment and CO_2 emission is highlighted. "	Ammar *et al.,* (2023)
"Development of polymer/carbon nanotubes incorporated sustainable materials for the manufacturing of autobrake pads"	"The comparison of the wear response of the developed nanocomposites with the current asbestos-based brake pads shows that the developed epoxy nanocomposites from agro-waste materials are a potential option for the manufacturing of autobrake pads, which will ensure sustainability, be health risk-free, and be environmentally friendly. "	Orji *et al.* (2024)

RESULTS AND DISCUSSION

Due to the pressing need to replace hazardous asbestos while maintaining performance standards, research into palm fruit fibre and African oil bean seed pods (Pentaclethra macrophylla) as sustainable substitutes for brake pad materials has accelerated recently. The mechanical and tribological characteristics of palm fruit fibre and African oil bean seed pods make them attractive options for brake pad applications (Dirisu *et al.,* 2024a). Under normal braking circumstances, palm fruit fibre performs brilliantly because of its high tensile strength (up to 400 MPa) and thermal robustness (decomposition at 220°C) (Obi *et al.,* 2016). Likewise, the oil bean seed pods lignocellulosic structure (45–55% cellulose, 20–30% lignin) offers superior endurance and binding capability (Onyenanu *et al.,* 2024). According to tribology, these materials outperform asbestos-based pads in terms of wear rates (0.12–0.25 mm^3/Nm) and coefficients of friction (0.35–0.45) (Ikpambese *et al.,* 2016a). Performance is further improved by hybrid formulations, such as those that include cane wood and palm fruit fibre, which produce reduced water absorption (0.494%) and hardness values of up to 98 MPa (Achebe *et al.,* 2019). Figure 3 compares the optimal desirability of brake pads made from different materials, which is represented in colours across several key performance metrics. Figure 4 also gives a graphic comparison of the main characteristics of several brake pad materials, including "hardness, compressive strength, wear rate, and coefficient of friction" (Onyenanu *et al.,* 2024). It highlights the competitive coefficient of friction and moderate wear rate of palm fruit fiber, supporting its viability as a sustainable material.

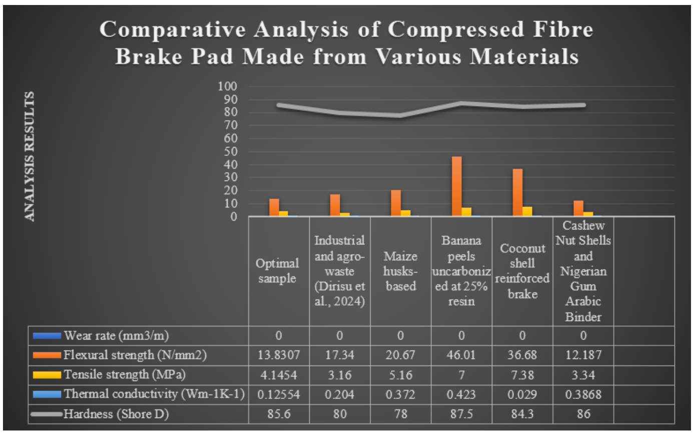

Figure 3: Chart of comparative analysis results of composites

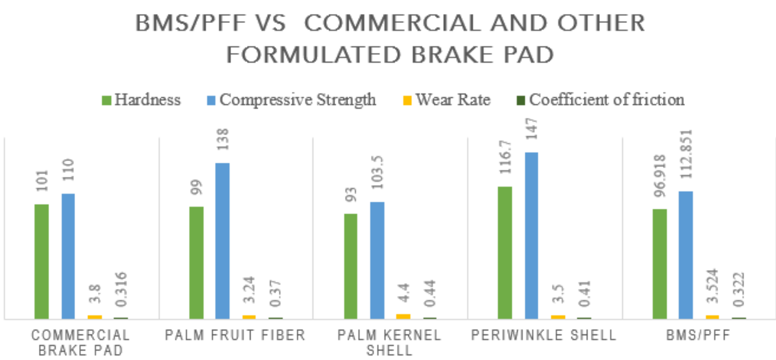

Figure 4: Comparison of organic brake pad and commercial Brake Pad
Source: Onyenanu et al. (2024)

The eco-friendly features of these agro-waste fibers are clear. These fibers mitigate the dangers of asbestos, which is associated with lung cancer and mesothelioma, while also relieving landfills of agricultural byproducts (Mobi *et al.,* 2021a). Carbon dioxide objectives also stand to benefit, as palm fiber production emits 72% less CO_2 than asbestos mining (Ammar *et al.,* 2023). Furthermore, their biodegradability poses no challenges for disposal at the end of the product life cycle, creating a sustainable solution unmatched by synthetic counterparts. These fibers are also cost-effective, and oil bean and palm fibers' local availability leads to 20-40% savings in raw material costs over asbestos or synthetic fibers (Achebe *et al.,* 2019). Lightweight properties (1.2–1.8 g/cm³) also contribute to fuel efficiency in vehicles, providing long-term economic benefits (Onyenanu *et al.,* 2024). This makes them an appealing product for emerging economies with a potential surplus of agricultural waste and limited industrial infrastructure for synthetic materials. Table 5 presents a comparative analysis of the key properties between African oil bean seed pod and palm fruit fiber composites and conventional asbestos-based brake pads, highlighting their viability as sustainable alternatives while identifying critical performance gaps.

Table 5: Comparative Properties of African Oil Bean Seed Pod Brake Pads vs. Commercial Asbestos Brake Pads

Property	**African Oil Bean Seed Pod (AOBSP) & Palm Fruit Fibre (PFF)**	**Commercial Asbestos Brake Pads**
Coefficient of Friction	0.35–0.45 (Onyenanu *et al.,* 2024; Ikpambese *et al.,* 2016)	0.30–0.50 (Limpert, 2011)
Wear Rate	0.12–0.25 mm³/Nm (Ikpambese *et al.,* 2016)	0.10–0.30 mm³/Nm (Mulani *et al.,* 2022)
Hardness	74–148 MPa (Mobi *et al.,* 2021); 94–104 HRB (Onyenanu *et al.,* 2024)	80–150 MPa (Dirisu *et al.,* 2024)
Compressive Strength	74.66–148 MPa (Mobi *et al.,* 2021)	100–160 MPa (Irawan *et al.,* 2022)
Thermal Stability	Decomposition at ~220°C (PFF) (Obi *et al.,* 2016)	Stable up to 500°C (Mobi *et al.,* 2021)
Density	1.2–1.8 g/cm³ (Onyenanu *et al.,* 2024)	1.8–2.2 g/cm³ (Limpert, 2011)
Water Absorption	0.95–2.174% (Dirisu *et al.,* 2024b)	0.5–1.5% (Irawan *et al.,* 2022)
Environmental Impact	Biodegradable, non-toxic, reduces agro-waste (Onyenanu *et al.,* 2024)	Carcinogenic (Asbestos is banned in many countries)
Cost	20–40% cheaper (local sourcing) (Achebe *et al.,* 2019)	Higher (synthetic/asbestos materials)

Barriers to Commercialization

While African oil bean seed pods and palm fruit fiber demonstrate competitive mechanical properties, several limitations hinder their commercial viability. The thermal stability of these fibers (220°C for palm fruit fiber) falls significantly short of asbestos's 500°C threshold, raising concerns about their suitability for high-load or high-speed braking scenarios (Obi *et al.,* 2016). Additionally, untreated fibers exhibit higher water absorption (up to 2.174%), which may compromise dimensional stability and longevity in humid environments (Dirisu *et al.,* 2024b). Beyond material limitations, supply chain challenges emerge from the seasonal availability and geographic concentration of agro-waste sources, complicating consistent industrial-scale production (Obi *et al.,* 2016). Processing costs for decortication, drying, and chemical treatments (e.g., silane coatings to mitigate water absorption) escalate production expenses, offsetting the initial cost advantages of these materials (Rangappa *et al.,* 2022). Regulatory hurdles and a lack of standardized testing protocols for natural fiber composites present additional barriers to market entry. Addressing these problems will necessitate the development of hybrid formulations for increased thermal stability, the optimisation of water-resistant treatments, the establishment of dependable supply networks, and collaboration with regulatory agencies to set acceptable certification requirements.

CONCLUSION

The study emphasizes the potential of palm fruit fibre (PFF) and African oil bean seed pod (AOBSP) as sustainable substitutes for asbestos-based brake pads. These agro-waste materials have competitive mechanical properties, such as compressive strength (74.66–148 MPa), hardness (74–148 MPa), and tribological performance (coefficient of friction: 0.35–0.45; wear rate: 0.12–0.25 mm³/Nm). Their environmental advantages, such as biodegradability, non-toxicity, and lower CO2 emissions, further encourage their use in environmentally friendly automotive applications. However, limitations such as lower thermal stability (~220°C) and higher water absorption (0.95–2.174%) compared to asbestos (stable up to 500°C) indicate the need for further optimization to meet high-performance demands.

To improve the performance, sustainability, and economic feasibility of African oil bean seed pod and palm fruit fibre composites in brake pad applications (Kaniapan *et al.,* 2021), the following suggestions are put forth in light of the review's findings:

- Incorporate montmorillonite nanoclay as demonstrated by Ammar *et al.* (2024) to increase decomposition temperatures above 300°C, leveraging its exfoliation properties to improve heat dissipation.
- Conduct rigorous real-world braking tests and adopt standardized protocols to ensure reliability and safety.

• To further improve brake pad performance, future studies should investigate additional natural fillers and hybrid composites.

• The environmental effects of producing brake pads from palm fruit fiber and African oil bean seedpods should be assessed by a life cycle assessment (LCA).

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