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## DEVELOPMENT AND PERFORMANCE EVALUATION OF PALM KERNEL SHELL/RAFFIA PALM SEED REINFORCED EPOXY COMPOSITES FOR AUTOMOTIVE BRAKE PAD APPLICATIONS

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### Abstract

*The development of sustainable friction materials has become increasingly important as a result of the environmental and health concerns related to asbestos and metallic based brake pads. This research presents fabrication and characterization of palm kernel shell (PKS) combined with raffia palm seed (RPS) reinforced epoxy composites as eco-friendly alternatives for automotive brake pad applications. Four composite formulations (Samples A–D) were produced with varying proportions of PKS, RPS, and aluminum chips in an epoxy matrix, and evaluated for physical, mechanical, and tribological performance. Density and hardness tests revealed that increasing reinforcement content enhanced material compactness and strength, with Sample B achieving the highest hardness (70.91 Hv). Water absorption was generally low across all samples, with Sample B recording the lowest uptake (0.0319%). Wear tests indicated superior resistance in Samples C and D, which also exhibited stable coefficients of friction (0.45–0.55) suitable for braking performance. SEM micrographs confirmed improved filler–matrix bonding and uniform dispersion in optimally reinforced samples, while XRD analysis showed no harmful or radioactive elements. Generally, Samples C and D demonstrated the most favorable balance of properties, highlighting the potential of PKS/RPS composites as cost-effective, sustainable, and high-performing alternatives to conventional brake pad materials. an optimal balance of mechanical and physical properties for semi-structural applications.*

**Keywords:** Palm kernel shell, Raffia palm seed, Epoxy matrix composites, Brake pad material, Mechanical properties, Wear resistance.

### Introduction

The growing necessity for environmentally friendly and sustainable engineering materials has spurred investigation into natural fiber-reinforced composites, particularly for application in automotive industry. Conventional brake pads, typically composed of metallic or asbestos-based materials, have caused environmental and health challenges because of their possible toxicity and lack of biodegradability [1], [2], [3]. Therefore, there is an growing interest in creating environmentally friendly substitutes that offer comparable or superior performance without adverse environmental impact.

Palm kernel shell (PKS) and raffia palm seed (RPS) are abundant agro-waste byproducts in tropical regions, especially in Africa and Southeast Asia. These lignocellulosic materials possess favorable mechanical characteristics, including high strength and low density, rendering them promising contenders for reinforcement in polymer matrix composites [4]. The incorporation of

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such agricultural wastes not only addresses disposal issues but also enhances the sustainability and cost-effectiveness of composite materials.

Epoxy resin is widely employed as a matrix during composite fabrication because of its excellent mechanical properties, thermal stability and adhesion characteristics. When reinforced with natural fillers like PKS and RPS, epoxy-based composites can be tailored for applications involving excessive wear resistance such as brake pads. The prospect of natural fiber reinforced epoxy composites in tribological applications has been shown in previous studies, emphasizing the significance of filler-matrix interactions and impact of fiber content on performance [5], [6], [7], [8], [9], [10], [11].

These increasing environmental concerns and the need for sustainable materials have driven significant research into development of environmentally friendly composite materials for engineering application, involving automobile brake systems. Traditional brake pads are commonly manufactured using asbestos or synthetic fibers and metallic constituents, which pose health hazards and environmental risks [12]. Natural fiber-reinforced polymer (NFRP) composites have therefore become viable substitutes because of their outstanding mechanical characteristics, affordability, and biodegradability [13].

Palm kernel shell (PKS), an agricultural waste byproduct from palm oil industry, has drawn interest as a possible filler in polymer composites because of its high carbon content, hardness, as well as availability [14]. Studies have shown that PKS-reinforced epoxy composites exhibit commendable thermal resistance, wear behavior, and mechanical integrity, making them viable for tribological applications such as brake pads [15]. In addition to PKS, raffia palm seed (RPS), another agricultural waste, possesses lignocellulosic characteristics that can enhance the toughness and energy absorption capacity of polymer matrices [16]. While RPS remains relatively underexplored in composite applications, its compatibility with epoxy resins and potential reinforcement ability presents a novel opportunity for hybrid composites. The combination of PKS and RPS is anticipated to offer a synergistic reinforcement effect, improving mechanical strength and tribological behavior while maintaining cost-effectiveness and sustainability.

Hybridization of fillers in epoxy composites has been reported to enhance wear performance and moisture resistance, which are critical for brake pad reliability [17]. Several researchers have emphasized the role of fiber-matrix interfacial bonding, particle dispersion, and filler treatment in determining the performance of such hybrid composites [18]. Furthermore, water absorption characteristics are essential, as excessive moisture uptake can deteriorate mechanical properties and reduce the lifespan of brake pads [4].

While individual use of PKS in brake pad development has been studied extensively, limited literature exists on the hybrid reinforcement of PKS with raffia palm seed. This research is aimed at filling this discrepancy by developing and assessing performance of a novel PKS/RPS-reinforced epoxy composite for brake pad applications, focusing on its physical, mechanical, and microstructural characteristics.

## **Materials and Methods**

### ***Materials and Sample Production***

The primary constituents utilized in this study were epoxy resin (LY 556) and hardener (HY 951), both provided by a local chemical distributor. Palm kernel shells (PKS) and raffia palm seeds (RPS) were sourced from agro-processing facilities in Benue state, Nigeria. The materials were chosen because of their availability, cost-effectiveness and mechanical potential as reinforcement agents in polymer composites. Other materials used include abrasives (aluminium chips), mold release agents, distilled water, and ethanol.

The process of developing the brake pad material started with raw material selection, followed by weighing, blending, compacting, and bonding. There were four compositions with varying

amounts of powdered raffia palm seed and palm kernel shell. Classification was done by variation in palm kernel shell powder, raffia palm seed powder, epoxy resin, catalyst/hardener and aluminium chips material in the formulation. The detailed formulations of four distinct types of novel materials are displayed in Table 1.

**Table 1.** Formulation of Brake Pad Material

S/No.	MATERIALS	SAMPLES (g)			
		A	B	C	D
1	Epoxy Resin	65.38	58.10	50.51	42.52
2	Catalyst/Hardener	38.65	29.05	25.21	21.77
3	Palm kernel shell powder	5.23	10.48	15.72	20.97
4	Raffia palm seed powder	3.92	7.43	11.16	14.89
5	Aluminum chips	2.63	4.25	6.40	10.63

***Preparation of Samples***

The palm kernel shell and raffia palm seed were collected from cracked palm kernel shell and raffia palm seed respectively. Ethanol was used to remove the contaminants from the gathered raw materials. Following a thorough washing with ethanol and sun drying for seven days, the palm kernel shell and raffia palm seed were crushed using ball mill and sieved to powder within 100-200 µm range. The powdered reinforcements were stored in sealed containers to prevent moisture absorption prior to composite fabrication. Four different combinations (samples A, B, C, D) were formulated by varying palm kernel shell powder and raffia palm seed powder compositions (Table 1). The base materials were powdered palm kernel shell and raffia palm seed, the abrasives were aluminium chips, and the binder was epoxy resin.

Each sample was prepared by thoroughly mixing palm kernel shell, raffia palm seed, and aluminium chips until a uniform and homogeneous blend was achieved. Epoxy resin was introduced to the mixture and the components thoroughly blended, resulting in a paste-like consistency. A catalyst/hardener at a ratio of 1:1000 was subsequently added, after which the blended mixture was transferred into the pre-prepared mould. The moulded mixture was allowed to remain for 24 hours, after which gelation occurred, accompanied by a noticeable increase in surface temperature indicating an exothermic reaction. At this stage, a pressure of 16.75 kN/m<sup>2</sup> was applied and maintained for 6 hours, to ensure complete curing, after which excess material was removed from the samples using abrasive machining.

***Density Measurement***

The fluid displacement method was employed to determine the volume of samples. Samples were submerged in a 1000 mL graduated cylinder containing distilled water at ambient temperature. The volume of water before and after submersion was recorded, and the difference between the two readings was taken as volume of the sample. The mass of samples was determined using a Mettler E200 electronic balance with an accuracy of ±0.01 g. The thickness of samples A, B, C, D was determined with micrometer by taking measurements at three positions (both ends and the center), then calculating the mean value.

***Water absorption***

Water absorption testing was performed following ASTM 570-98 [19]. The samples, cut to dimensions of 30 mm × 30 mm × 10 mm, were weighed and subsequently submerged in a container of water for 24 hours at ambient temperature. The samples were weighed using a Mettler E200 electronic balance. After immersion, they were removed and surface moisture was wiped off before reweighing. The difference in mass represented the quantity of absorbed water, and the percentage water absorption (based on dry mass) was calculated using Equation 1.

$$\% \text{ water absorption} = \frac{\text{Wet mass} - \text{Dry mass}}{\text{Dry mass}} \times 100 \quad (1)$$

### ***Microstructural Analysis***

Microstructural images of samples were obtained using Scanning Electron Microscope (SEM) (Model: Zeiss 540 Ultra) equipped with Energy Dispersive X-ray Spectroscopy (EDS) in high vacuum (HV) mode at accelerating voltage of 20 kV from Ahmadu Bello University, Zaria, Nigeria. The EDS system was used for bulk elemental analysis of the composite, while the linear intercept method with ImageJ software was employed to determine the average grain size.

### ***X-ray diffraction Analysis***

Phase analysis of samples was carried out using X-ray diffractometer (XRD) (Model: RAYONS X) at the Institute for Nano-Engineering Research (INER), Tshwane University of Technology, Pretoria. Measurements were performed with a D/max-250 diffractometer using Cu-K $\alpha$  radiation ( $\lambda = 1.54 \text{ \AA}$ ) at 30 kV and 20 mA with 1°/min scanning rate. Crystal structures and peak intensities were identified using X'Pert HighScore Plus software integrated with the RAYONS X system.

### ***Hardness Test***

The microhardness of the samples (15 mm  $\times$  15 mm) was determined using the Vickers method in accordance with ASTM E-834 at INER in Tshwane University of Technology, Pretoria. A microhardness tester (Model: FM-800) was used with an applied load of 50 g and a dwell time of 15 s. Three measurements were taken for each condition, and the reported value represents the average of indentations spaced 0.20 mm apart.

### ***Wear Test***

Dry sliding wear behavior was evaluated using a tribometer (Serial No: 10000392309, Version: 8.1.8) with a ball-on-disc configuration in accordance with ASTM G-99 at the Surface Engineering Laboratory, Tshwane University of Technology, Pretoria. Tests were performed at 20 °C and 48.24% relative humidity. Specimens (20 mm  $\times$  10 mm) mounted in resin were slid against a 6 mm zirconia ball (62 HRC hardness, 0.3  $\mu\text{m}$  surface roughness) at 130 rpm. Tests were performed under a load of 5 N, sliding speed of 1 m/s, with sliding distance of 282.09 m along a 120 mm diameter track. Wear rate was determined by the weight loss technique using microbalance, while coefficient of friction ( $\mu = F_f/P$ ) was gotten from the recorded frictional force ( $F_f$ ) and applied load ( $P$ ). Three specimens were tested to ensure repeatability, and the average values were reported.

## **Results and Discussions**

### ***Density***

The density values of the palm kernel shell/raffia palm seed composites, as presented in Figure 1, indicate a notable variation across the samples, ranging from 2.54 g/cm<sup>3</sup> to 3.14 g/cm<sup>3</sup>. Sample D showed the highest density of 3.14 g/cm<sup>3</sup>, suggesting a compact structure or higher filler content compared to the others. Conversely, Sample A had the lowest density of 2.54 g/cm<sup>3</sup>, which implies a less dense packing or lower filler-to-matrix ratio. These variations in density are critical in composite applications, as higher densities often correlate with enhanced mechanical strength and wear resistance, particularly important for brake pads [20], [21]. Moreover, the observed trend aligns with findings in previous studies, where increasing reinforcement content or reducing porosity tends to improve composite density and performance [22].

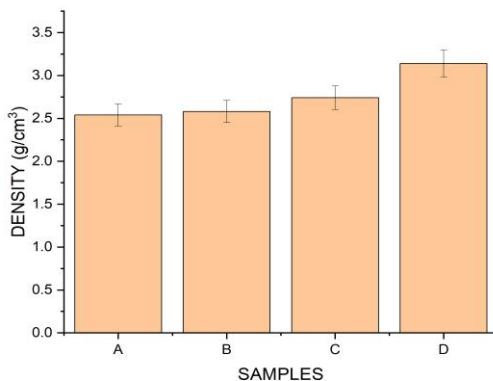


Fig. 1. Variation of Density with the PKS/RPS Composite Samples

**Water absorption**

The water absorption behavior of palm kernel shell/raffia palm seed composite samples (A–D) as shown in Figure 2 indicates varying levels of hydrophilicity, which is crucial in assessing their suitability for moisture-sensitive applications. Sample A exhibited the highest water absorption at 0.1038%, while Sample B had the lowest at 0.0319%, suggesting that the composite composition or structure in Sample A may have more voids or less effective bonding between the matrix and reinforcement, facilitating higher water uptake. The trend in water absorption for samples A > D > C > B implies that minor variations in filler content, dispersion, or interfacial adhesion can significantly affect the composite's resistance to moisture ingress. Generally, lower water absorption is desirable for better dimensional stability and mechanical performance in moist environments [4], [23]. The relatively low absorption values across all samples align with the hydrophobic nature of epoxy matrices and the partially lignocellulosic characteristics of the reinforcements, which, when properly treated or well dispersed, can limit moisture uptake [24].

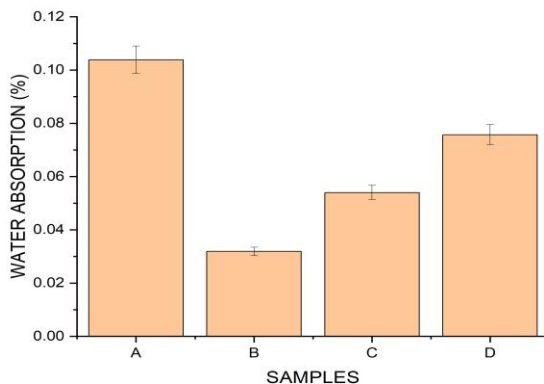
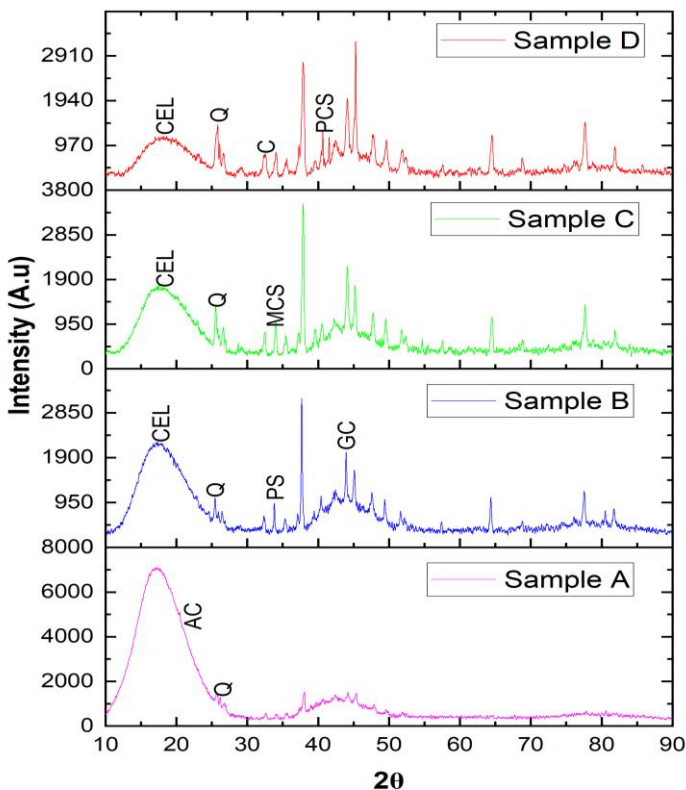


Fig. 2. Variation in Water Absorption with the PKS/RPS Composite Samples

**X-ray diffraction**

The XRD patterns of the palm kernel shell/raffia palm seed composites are presented in Figure 3, while the corresponding major diffraction peaks and inter-planar distances are summarized in Table 2. The diffractograms revealed noticeable variations in the crystalline and amorphous

phases present in Samples A–D, indicating progressive mineralogical transformations within the composites. Sample A exhibited a broad diffraction bulge within the 20–25° region, characteristic of amorphous carbon (AC), together with a distinct quartz (Q) peak at 26.5° corresponding to an inter-planar spacing of 3.36 Å. The dominance of the broad bulge indicates a largely amorphous structure with limited crystalline arrangement. Sample B showed improved crystallinity with several well-defined diffraction peaks. The peak at 21.8° (4.08 Å) was attributed to cellulose (CEL), while the strong reflection at 26.6° (3.35 Å) corresponded to quartz (Q). Additional peaks observed at 30.1° (2.97 Å) and 43.0° (2.10 Å) were assigned to potassium silicate (K<sub>2</sub>SO<sub>3</sub>) identified as (PS) and graphite carbon (GC), respectively. The appearance of graphite-related reflections suggests partial graphitization of the carbonaceous structure during processing.



**Fig. 3.** X-ray diffraction of the PKS/RPS Composite

For Sample C, the diffraction peak at 16.1° (5.50 Å) corresponded to cellulose (CEL), whereas the peak at 21.9° (4.06 Å) further confirmed the presence of cellulose-rich crystalline domains. The prominent quartz peak (Q) was identified at 26.5° (3.36 Å), while the reflections at 30.0° (2.97 Å) and 32.1° (2.79 Å) were associated with mixed carbonates/silicates (MCS) phases. The coexistence of silicate and carbonate minerals indicates increasing mineral complexity within the composite matrix. Sample D displayed diffraction peaks at 16.3° (5.43 Å) and 22.4° (3.97 Å), both corresponding to cellulose (CEL) phases, while the peak at 26.6° (3.35 Å) was assigned to quartz (Q). The diffraction reflection observed at 29.5° (3.02 Å) corresponded to calcite (C), whereas the potassium calcium silicate phase (K<sub>2</sub>CaSO<sub>4</sub>) also known as (PCS) was identified at approximately 38–40°. The sharper and more intense peaks observed in Sample D indicate enhanced crystallinity relative to the other samples.

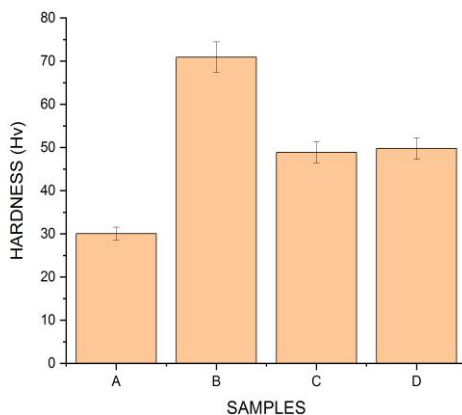
Generally, the XRD mineralogical analysis confirmed that the palm kernel shell/raffia palm seed composites predominantly contain carbon, oxygen, silicon, potassium, and calcium-bearing phases. The absence of detectable heavy or radioactive mineral phases suggests that the composites are unlikely to contain hazardous or radioactive constituents, thereby indicating their suitability for environmentally safe applications. This finding is coherent with observations reported in previous studies [25], [26].

**Table 2.** Diffraction Peaks and their inter-planar distances in PKS/RPS Composite

Sample A		Sample B		Sample C		Sample D	
Major diffraction peaks (°)	Inter-planar distance (Å)	Major diffraction peaks (°)	Inter-planar distance (Å)	Major diffraction peaks (°)	Inter-planar distance (Å)	Major diffraction peaks (°)	Inter-planar distance (Å)
20-25	Broad hump 3.36	21.8	4.08	16.1	5.50	16.3	5.43
26.5		26.6	3.35	21.9	4.06	22.4	3.97
		30.1	2.97	26.5	3.36	26.6	3.35
		43.0	2.10	30.0	2.97	29.5	3.02
						32.1	2.79

**Hardness**

The hardness characteristics of the composites is as indicated in Figure 4. It was noted that the composition of samples significantly affects their hardness. Sample B has the highest hardness of 70.91 Hv with a mixture composition of 58.10g epoxy resin, 29.05g hardener, 10.48g palm kernel shell powder, 7.43g raffia palm seed powder and 4.25g aluminium chips. This level of hardness is desirable for brake pads as it indicates the ability to maintain structural integrity under repeated braking stress and heat cycles. According to studies, increased hardness in composite brake materials typically correlates with improved lifespan and stable frictional performance [27]. This is followed by sample D having 49.78 Hv with 20.97g palm kernel shell powder and 14.89g raffia palm seed powder. Also, sample C has a hardness of 48.90 Hv and the lower hardness is recorded in sample A having 30.05 Hv with 5.23g palm kernel shell powder and 3.92g raffia palm seed powder. The hardness ability of the samples could be related to the presence chemical compounds such as Fe<sub>2</sub>O<sub>3</sub>, CaO, SiO<sub>2</sub>, which is present in palm kernel shell and raffia palm seed powders as well as their closed packed together with resin and hardener [28]. The hardness values obtained for the samples are consistent with those reported for similar materials in previous studies [29], [30].



**Fig. 4.** Variation in Hardness with the PKS/RPS Composite Samples

## Wear Behaviour

### *Wear Depth*

The wear depth of the composite is as indicated in Figure 5. Results revealed significant differences in wear resistance across the samples. Samples A and B, with wear depths of 258.088  $\mu\text{m}$  and 257.252  $\mu\text{m}$  respectively, recorded the highest values, indicating poor wear resistance. This confirmed that these samples had lower reinforcement content and weaker filler–matrix interfacial bonding, which is a critical factor in tribological performance. According to Onuoha et al. [31] increased filler loading especially with hard, abrasive-resistant natural fillers can significantly improve wear resistance. Therefore, the high wear depths of A and B is as a result of insufficient reinforcement or suboptimal dispersion of fillers within the epoxy matrix. Conversely, Samples C and D exhibited markedly lower wear depths of 52.440  $\mu\text{m}$  and 30.382  $\mu\text{m}$ , respectively, indicating superior resistance to wear. This performance can be linked to an optimal blend of PKS and RPS particles, which enhanced hardness and interfacial bonding, reducing material removal under abrasive conditions. This result aligns with findings by Aigbodion et. al. [25], who emphasized that hybrid composites reinforced with agro-waste fillers showed improved wear properties when the filler content and size were appropriately controlled. Moreover, the high wear resistance of sample D suggests it possess the most favorable formulation for brake pad applications, combining both hardness and interfacial integrity to minimize wear during braking.

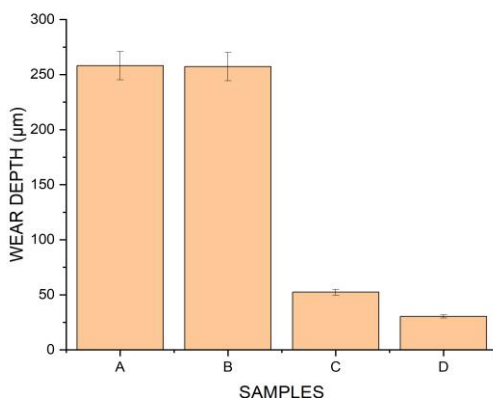


Fig. 5. Variation in Wear Depth with the PKS/RPS Composite Samples

### *Wear Rate*

The wear rate values obtained revealed an overall improvement in wear resistance with increasing filler content as shown in Figure 6. Samples A and B, which recorded wear rates of  $8.62\text{E-}6 \text{ mm}^3/\text{N}\cdot\text{m}$  and  $8.59\text{E-}6 \text{ mm}^3/\text{N}\cdot\text{m}$  respectively, exhibited relatively higher wear losses compared to samples C and D. The values, while still within acceptable limits for brake pad materials, indicate a less optimized formulation in terms of tribological behavior. The presence of hard and well-bonded fillers considerably improves wear resistance of composite materials used in tribological applications, pointing to the importance of filler–matrix bonding and homogeneity [32]. Samples C and D showed superior wear resistance, implying that their formulation had a more effective reinforcement contribution from both PKS and RPS. The close similarity between the two values suggests a point of optimal filler ratio or dispersion that contributed to reduced surface degradation during sliding contact.

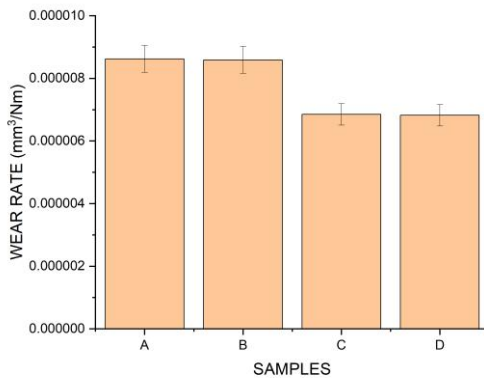


Fig. 6. Variation in Wear Rate with the PKS/RPS Composite Samples

**Coefficient of Friction**

The coefficient of friction (COF) results revealed notable variations among the samples (A to D) over time (Figure 7). Sample A exhibited the highest COF, averaging around 0.6 to 0.63, which is indicative of insufficient abrasive filler content or excessive matrix dominance, reducing surface grip. In contrast, Sample B showed a fluctuating but similarly high COF with intermittent peaks beyond 0.65, pointing to aggressive frictional behavior that could lead to noise or wear under real-life conditions. This fluctuation may be due to heterogeneous filler dispersion or inadequate bonding within the matrix, where poor filler-matrix compatibility led to unstable tribological behavior [33]. Sample C presented a moderate COF, averaging around 0.55, with relatively fewer fluctuations than Sample B. This suggests a balance between adequate friction and stable performance, likely due to an optimal ratio of PKS and RPS particulates. Sample D, however, showed the lowest COF, consistently around 0.45 to 0.48, which is indicative of excellent frictional performance suitable for brake applications. This stability suggests a consistent interfacial contact between the composite and the friction surface, which is essential for reliable braking. In general, the reduction in coefficient of friction with increasing filler content in both samples can be associated with the influence of mechanical properties and the wear system on friction behavior [34].

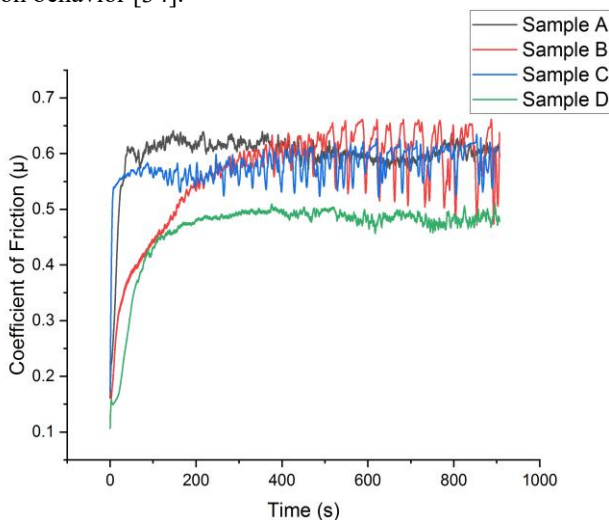


Fig. 7. Variation in Coefficient of Friction among PKS/RPS Samples over Time

### Microstructural Analysis of PKS/RPS Composites

The micrographs of the composites by SEM/EDS revealed the impact of increasing reinforcement contents on the morphology of epoxy matrix as shown in Figs. 8 - 11. The white areas show the dispersion of PKS/RPS particles, whilst the black regions show the resin. In Sample A (Fig. 11), the surface appears smooth with fewer reinforcement particles. This suggests a resin rich matrix and weak interfacial bonding, which could lead to reduced wear resistance.

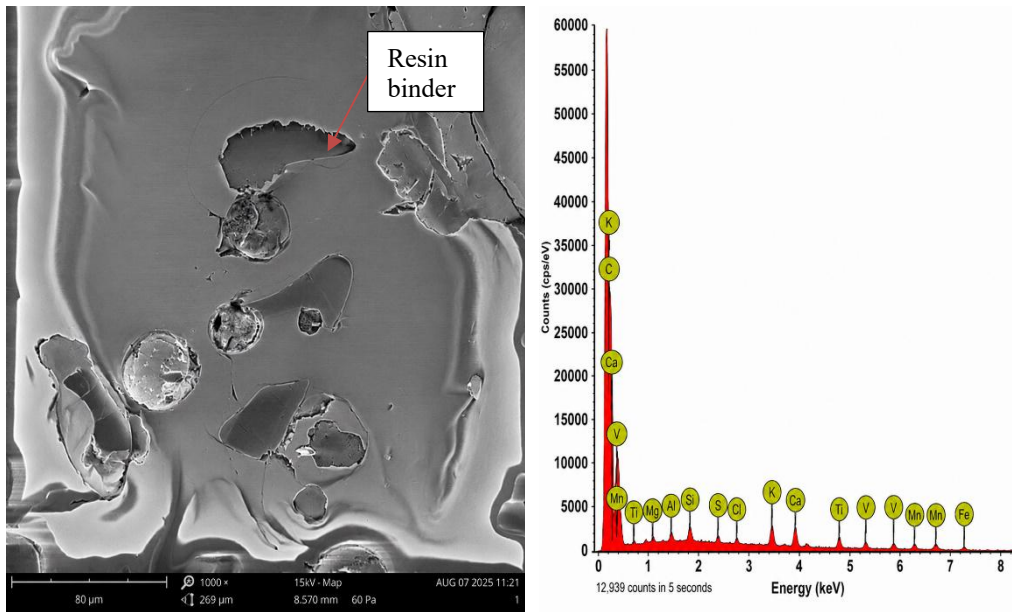


Fig. 8. SEM/EDS Images for Composition of Sample A

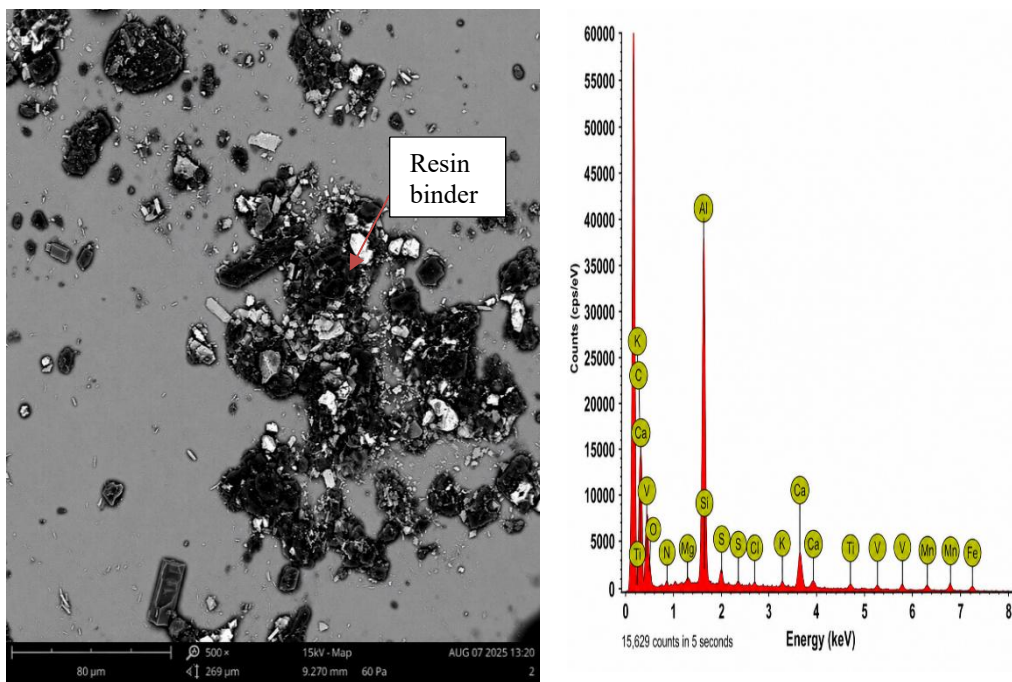
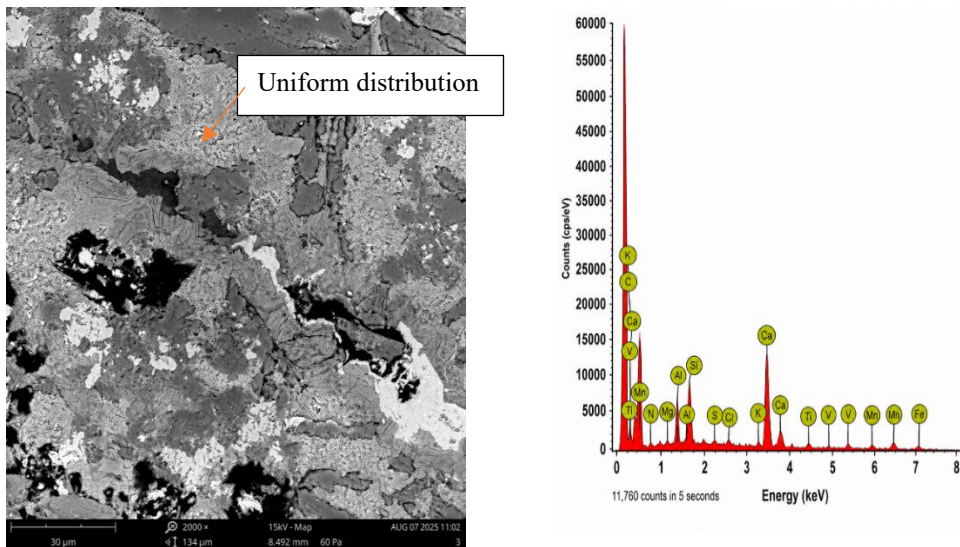
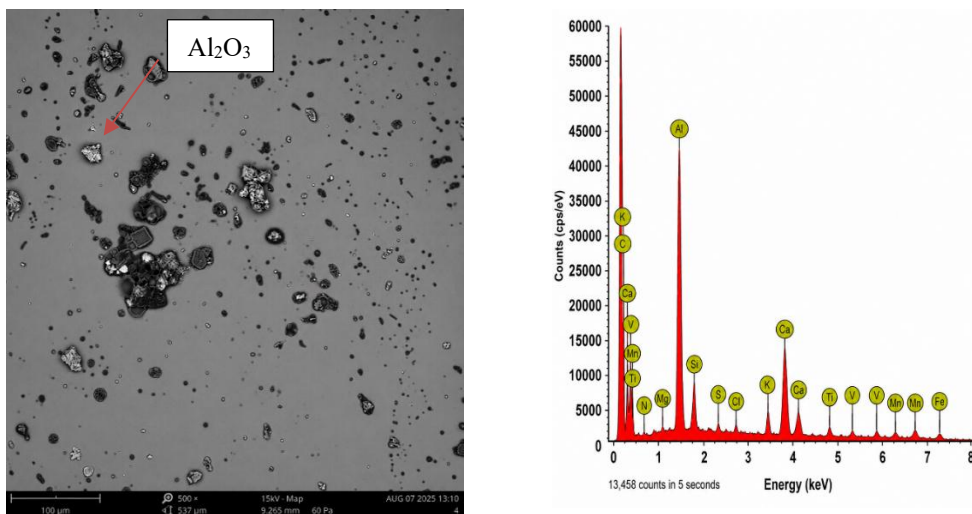


Fig. 9. SEM/EDS Images for Composition of Sample B

As the reinforcement content increases in Sample B (Fig. 12), more palm kernel shell and raffia palm seed particles are observed within the matrix, indicating improved particle dispersion and stronger interfacial adhesion. Sample C (Fig. 13) exhibits a more uniform distribution of reinforcements with fewer voids, signifying enhanced load transfer capability and mechanical stability. This homogeneity is expected to boost the tribological characteristics of the composite, in agreement with earlier reports that good particle matrix adhesion enhances brake pad performance [35], [36]. In Sample D (Fig. 14), the highest reinforcement content results in dense particle concentration with some evidence of agglomeration.



**Fig. 10.** SEM/EDS Images for Composition of Sample C



**Fig. 11.** SEM/EDS Images for Composition of Sample D

While this contributes to increased hardness and frictional stability, clustering may introduce microcracks and stress concentration zones, thereby reducing toughness [25], [37].

## Conclusions

This study demonstrated the successful development of palm kernel shell/raffia palm seed reinforced epoxy composites as sustainable alternatives for brake pad applications.

The results indicated that density increased with reinforcement, from 2.54 g/cm<sup>3</sup> in sample A to 3.14 g/cm<sup>3</sup> in sample D, while water absorption remained low across all samples, with the least uptake of 0.0319% recorded in sample B.

Hardness improved significantly with filler content, peaking at 70.91 Hv in sample B, compared to 30.05 Hv in sample A. Wear performance also improved, as wear depth decreased from 258.09 µm in Sample A to 30.38 µm in sample D, with corresponding wear rate reductions.

The coefficient of friction stabilized with higher reinforcement, with sample D exhibiting the most desirable range of 0.45 - 0.48, compared to unstable high values (~0.60) in sample A. SEM analysis confirmed enhanced filler-matrix bonding and uniform dispersion in samples C and D, correlating with their superior performance.

Generally, while the use of agro-waste reinforcements provides a cost-effective, environmentally friendly substitute to traditional asbestos and metallic-based brake pad materials, samples C and D exhibiting the most balanced mechanical and tribological properties.

## Conflict of Interest

The authors disclosed no potential conflicts of interest.

## Acknowledgement

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## Authorship Contribution Statement

Oryina Mbaadega INJOR: Development of ideas, Approach, Analysis, Writing—original draft. Moipone Linda TEFFO: Development of ideas, Resources, Supervision, Writing—revision & editing. Emmanuel Rotimi SADIKU and Victor Ugbetan AGBOGO: Resources, Writing—revision & editing.

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