
EFFECT OF DOUBLE PRESSING AND DOUBLE SINTERING ON THE MECHANICAL AND TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX REINFORCED RICE HUSK ASH COMPOSITES

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

This study investigates the effect of double pressing and double sintering (DPDS) on the mechanical and tribological properties of aluminum matrix composites reinforced with rice husk ash (RHA). Aluminum–RHA composites containing 0–15 wt.% RHA were fabricated using powder metallurgy through three processing routes: single pressing–single sintering (SP–SS), single pressing–high-pressure sintering (SP–HPS), and double pressing–double sintering (DPDS). Hardness, wear rate, and coefficient of friction (COF) were evaluated, with representative values obtained under stable sliding conditions used to establish physically meaningful correlations. The DPDS route produced higher hardness values for both pure aluminum (69.9 HV) and the 5 wt.% RHA composite (78.0 HV), with the corresponding lowest specific wear rates of $(8.33 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m})$ and reduced coefficients of friction (COF) of 0.195 and 0.203, respectively. A clear inverse relationship between hardness and specific wear rate was observed for pure aluminum and the 5 wt.% RHA composites, consistent with classical tribological principles. However, composites containing 10–15 wt.% RHA exhibited increased wear and friction despite their relatively higher hardness, which was attributed to particle agglomeration, weak interfacial bonding, and abrasive wear associated with the silica-rich RHA particles. These findings demonstrate that DPDS is an effective processing route for improving the tribological performance of aluminum–RHA composites, with 5 wt.% RHA providing the best combination of hardness, wear resistance and coefficient of friction under the investigated conditions. The use of locally sourced RHA in this study promotes agricultural waste valorization and sustainable materials development, supporting the global goal of advancing environmentally responsible engineering solutions.

Keywords: Aluminum matrix composites; Rice husk ash; Double pressing-Double sintering; Hardness; Wear; Powder metallurgy

1. INTRODUCTION

The incorporation of hard ceramic reinforcements can further enhance the hardness, load-bearing capacity, and wear resistance. Aluminum matrix composites (AMCs) have attracted significant research attention due to its lightweight and superior mechanical properties compared to conventional aluminum alloys (Chak et al., 2020; Kumar et al., 2024). Aluminum's low density (approximately 2.7 g/cm³), combined with its high specific strength, makes it an attractive matrix material for lightweight structural applications (Singhal, Shelly, Rawat, et al., 2025; Singhal, Shelly, Saxena, et al., 2025). of aluminum matrix composites, thereby improving their performance under sliding wear conditions (Singhal, Shelly, Saxena, et al., 2025). Recently, agro-waste materials particularly rice husk ash

(RHA) have attracted increased interests due to their high silica content, abundance, and environmental benefits (Islam et al., 2024; Taiye et al., 2024). Incorporating RHA into aluminum matrices not only enhances mechanical properties like hardness and wear resistance but also supports eco-friendly material development from agricultural waste (Singh Karam et al., 2022).

Rice husk is unusually high in ash compared to other biomass fuels in the range of 10-20%. Rice husk ash typically contains more than 80% silica, highly porous and light-weight, with high external surface area when properly calcined. Flach et al. (2022) highlighted that RHA enhances hardness, reduce density, and promotes wear resistance in composite. However, the effectiveness of RHA as a reinforcement is strongly dependent on processing conditions. Challenges such as particle agglomeration, poor interfacial bonding, and residual porosity often limit the mechanical and tribological performance of aluminum– Rice husk ash (Al-RHA) composites fabricated using conventional powder metallurgy routes (Akgümüş Gök et al., 2024; Shaikh, Arif, et al., 2019).

Conventional SP–SS often result in high porosity, weak interfacial bonding, incomplete densification, leading to increased wear and unstable friction behavior (Shaikh, Raja, et al., 2019). DPDS involve an initial pressing and pre-sintering, followed by re-pressing and a final sintering cycle, thereby promoting better particle rearrangement, enhanced neck growth, and reduced porosity. Literature shows that DPDS significantly improves hardness and tensile strength (Mechanical properties), while enhancing tribological performance (Alem et al., 2020; Hammes et al., 2014; Liu et al., 2023). Although double pressing and double sintering (DPDS) has been investigated for aluminum-based composites reinforced with synthetic and carbon-based reinforcements, its application to rice husk ash (RHA)-reinforced aluminum remains comparatively less explored. Previous studies have demonstrated the potential of DPDS to improve the consolidation and mechanical performance of aluminum composites; however, limited attention has been given to the combined influence of RHA content and the DPDS processing sequence on the hardness and tribological response of Al–RHA composites (Alaneme & Sanusi, 2015). In particular, the present study compares conventional single pressing–single sintering routes with a DPDS route involving initial compaction, pre-sintering, re-pressing and final sintering using the same Al–RHA compositions. The single press and single sinter process suffers from limited green density due to work hardening and friction, leaving high residual porosity after sintering. This porosity severely weakens mechanical properties and corrosion resistance. Double pressing and double sintering use a second high-pressure press on a sintered part to crush pores that the first press couldn't eliminate, resulting in a much denser and stronger final component (Alem et al., 2020).

Therefore, this study evaluates the DPDS route for the fabrication of Al–RHA composites containing 0, 5, 10, and 15 wt.% RHA, with particular emphasis on the influence of the additional pressing–sintering cycle on their hardness and tribological performance. The findings provide insight into the processing–property relationships of Al–RHA composites and contribute to the development of sustainable aluminium-based composites with improved mechanical and tribological performance.

2. METHODOLOGY

2.1 Materials

The materials and reagents used in this study included commercially pure aluminium powder (99.99% purity), which served as the matrix material. Rice husk ash (RHA), derived from the calcination of rice husk particles obtained from a rice mill in MTD, Zaria, Kaduna State, Nigeria, was used as the reinforcement. Ethanol was employed as the mixing medium during powder blending, while zinc stearate powder was used as a die lubricant during compaction to reduce friction between the powder compact and die wall and facilitate the ejection of the green compact.

2.2.1 Sample Preparation

The rice husk obtained from the rice mill was initially purified by removing impurities such as sand, dust and organic residues through winnowing. The rice husk was subsequently washed thoroughly with water to remove adhering dirt and dried under sunlight to facilitate moisture removal. The dried rice husk was then placed in a furnace and calcined at 700 °C for 6 hours. After calcination, the resultant rice husk ash (RHA) was removed from the furnace and allowed to cool to room

temperature in air. The cooled ash was subsequently pulverized using a ball mill to reduce its particle size and passed through a 75 μm sieve. The sieved RHA was collected and stored in sealed polyethylene bags to minimize moisture absorption and contamination prior to further processing and characterization.

2.3 Composite Fabrication

The experimental variables investigated in this study were the RHA content and powder-metallurgy processing route. The mixing conditions were kept constant for all compositions. Aluminum powder and RHA were blended at RHA contents of 0, 5, 10 and 15 wt.%, as presented in Table 1. For each composition, the experiment was performed using the three processing routes described in Table 2. The powder mixtures were ball-milled at a constant rotational speed of 200 rpm for 1 hour using a ball-to-powder ratio of 10:1

Table 1: Percentage composition of samples

Al	RHA
100	0
95	5
90	10
85	15

2.3.1 Powder Mixing

Aluminum powder and varying weight percentages of rice husk ash (5%, 10%, and 15%) were measured using a digital weighing balance. The powders were mixed using a ball mill at 200 rpm for 1 hour to ensure uniform distribution of rice husk ash within the aluminum matrix. Homogeneous dispersion was achieved through wet ball milling using a ball-to-powder ratio (BPR) of 10:1. A total of 0.5 mL of ethanol, which served as a process control agent (PCA), was added to the mixture and subsequently evaporated in a furnace.

2.3.2 Powder Compaction and Sintering

The 1 g powder mixtures were compacted into cylindrical billets using a uniaxial hydraulic press. Two processing routes were employed: SP–SS, representing the conventional powder metallurgy route, and DPDS, the novel processing route. For the SP–SS route, the powders were compacted once at either 3 MPa (Route 1) or 5 MPa (Route 2), followed by sintering at 594 °C for 2 hours in an electric muffle furnace. The sintered samples were then cooled outside the furnace to room temperature. For the DPDS route, the powder mixture was initially compacted at 3 MPa, followed by pre-sintering at 300 °C for 1 hour to promote preliminary diffusion and particle bonding. The pre-sintered compact was subsequently repressed at 5 MPa to improve particle rearrangement and reduce porosity, followed by final sintering at 594 °C for 2 hours. The sintering temperature was selected based on the melting point of aluminum (approximately 660 °C), corresponding to about 90% of its melting temperature, and was maintained across all RHA contents to provide consistent processing conditions. Similar sintering temperatures have been employed in previous powder-metallurgy studies of Al–RHA composites, supporting their suitability for promoting solid-state diffusion and interparticle bonding while remaining below the melting temperature of aluminum (Mohamed Ariff et al., 2022).

However, the addition of RHA may influence the thermal and interfacial behavior of the composites. Therefore, the use of a fixed temperature of 594 °C across the 0–15 wt.% RHA range represents a controlled processing condition rather than an assumption that it is the optimum sintering temperature for every composition. After sintering, the specimens were allowed to cool outside the furnace to room temperature. The DPDS route was adopted to enhance densification, reduce porosity, and improve the mechanical properties of the fabricated Al–RHA composites. Samples were labeled according to their RHA content and processing route. Table 2 provides details of the powder metallurgy routes adopted for the fabrication of the samples.

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Table 2: *Description of the powder metallurgy routes adopted for the sample fabrication*

Route	Processing Description	Abbreviation
Route 1	Single pressing at 3 MPa → sintering at 594 °C	SP–SS (Single Pressing and Single Sintering)
Route 2	Single pressing at 5 MPa → sintering at 594 °C	SP–HPS (Single Pressing–Higher Pressure Sintering)
Route 3	Double pressing and double sintering: 3MPa pressing → pre-sintering at 300 °C → re-pressing at 5 MPa → final sintering at 594 °C	DPDS (Double Pressing and Double Sintering)

2.4 Hardness

The hardness tests were performed using a Vickers micro hardness testing machine, ASTM E384. A diamond indenter was used with an applied load of 0.3kgf, and a dwell time of 8 seconds. To account for sample inconsistencies, three readings were taken at different spots. The average hardness value was then determined from these readings.

2.5 Wear and Coefficient of Friction

The wear test was conducted on the samples according to ASTM 99-95a test standard for wear testing of materials. Using ball-on-disk tribometer machine (model version R0.01), an 8N load was applied over a 30 m sliding distance, with the test duration of 30 minutes for all the samples. The corresponding average sliding speed was 1.0 m/min (0.0167 m/s). The counter-body has a ball diameter of 6mm. The wear track radius was 3mm, and the specimen mass is 1g. The tests were conducted under dry ambient laboratory conditions at 27 °C and 55% relative humidity. The coefficient of friction (COF) was automatically recorded by the ball-on-disk tribometer during the wear tests, while the specific wear rate was calculated using Equation (1).

$$\text{Specific wear rate} = \frac{\text{Wear Volume}}{\text{Load X Sliding Distance}} \quad (1)$$

3. RESULTS AND DISCUSSION

Table 3: *Properties Al-RHA composite processed via different powder metallurgy route*

Composition	Processing Route	Hardness (HV)	Wear Rate (mm ³ /N.m)	Coefficient of Friction
100% Al	SP–SS (3 MPa)	48.9	2.50×10^{-5}	0.273
100% Al	SP–HPS (5 MPa)	57.1	5.00×10^{-6}	0.217
100% Al	DPDS	69.9	8.33×10^{-7}	0.195
95% Al + 5% RHA	SP–SS (3 MPa)	63.1	3.33×10^{-6}	0.239
95% Al + 5% RHA	SP–HPS (5 MPa)	65.5	8.33×10^{-7}	0.228
95% Al + 5% RHA	DPDS	78	8.33×10^{-7}	0.203
90% Al + 10% RHA	SP–SS (3 MPa)	69.4	1.89×10^{-3}	0.277
90% Al + 10% RHA	SP–HPS (5 MPa)	73.7	1.24×10^{-3}	0.414
90% Al + 10% RHA	DPDS	77.4	5.96×10^{-4}	0.319
85% Al + 15% RHA	SP–SS (3 MPa)	84.6	9.76×10^{-4}	0.281
85% Al + 15% RHA	SP–HPS (5 MPa)	91.5	1.66×10^{-3}	0.42
85% Al + 15% RHA	DPDS	75.9	8.53×10^{-4}	0.41

3.1 Hardness

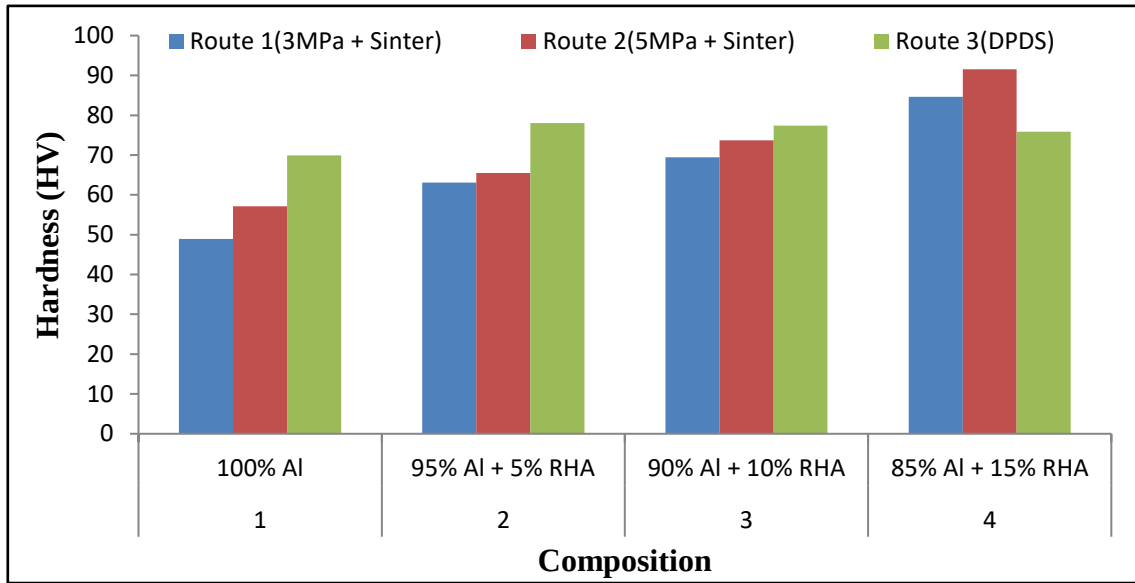


Figure 1: Hardness characteristics of AL- RHA Content under Different Processing Routes

As shown in Table 3 and Figure 1, hardness was influenced by the compaction pressure and sintering conditions. For pure aluminum, hardness increased from 48.9 HV for SP–SS to 69.9 HV for DPDS. A similar improvement was observed for the 5 wt.% RHA composites, where DPDS produced the highest hardness of 78.0 HV. For the DPDS route, hardness increased from pure aluminum to 5 wt.% RHA, reaching a maximum of 78.0 HV, and subsequently decreased slightly at 10 wt.% (77.4 HV) and 15 wt.% RHA (75.9 HV). The reduction at higher RHA contents may be associated with less effective particle packing, possible particle agglomeration, and weaker matrix–particle interaction. These mechanisms are proposed as possible explanations rather than confirmed microstructural effects, since detailed microstructural characterization was not performed in the present study. Overall, the hardness trend followed the order DPDS > SP–HPS > SP–SS for pure aluminum, 5 wt.% RHA composites. However, at 15 wt.% RHA, this trend was reversed, with SP–HPS producing the highest hardness (91.5 HV), while DPDS exhibited the lowest hardness (75.9 HV). This result suggests that the beneficial effect of multiple pressing and sintering cycles on hardness was not maintained at the highest RHA content. Nevertheless, hardness alone was insufficient to guarantee improved tribological performance at higher reinforcement levels.

3.2 Wear Behaviour

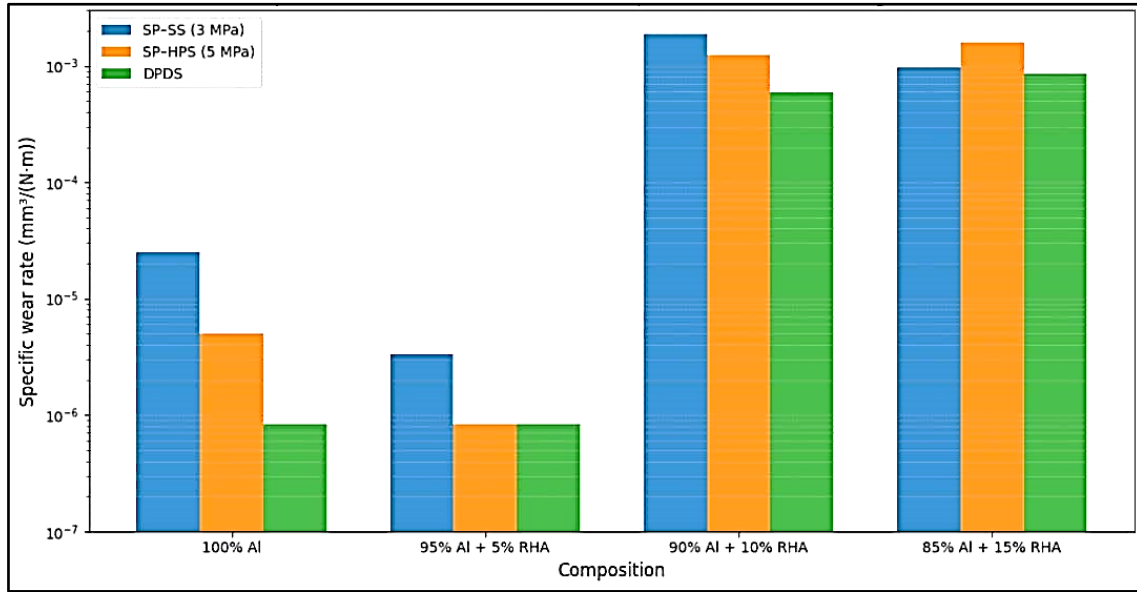


Figure 2: Effect of rice husk ash content and processing route on the wear rate of Aluminum-RHA composites

Figure 2 illustrates the influence of reinforcement content and processing route on wear behavior, showing a significant reduction in wear rate for DPDS-processed pure aluminum and 5wt. % RHA. A clear inverse relationship between hardness and wear rate was observed. The DPDS-processed pure aluminum sample exhibited the lowest wear rate of $8.33 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, compared with $2.50 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ for the SP-SS condition. Similarly, the 5 wt. % RHA composites processed via DPDS showed a wear rate of $8.33 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$, indicating excellent wear resistance. In contrast, composites containing 10 and 15 wt. % RHA displayed significantly higher wear rates despite increased hardness. For example, the 10 wt. % RHA composites processed via SP-SS recorded a wear rate of $1.89 \times 10^{-3} \text{ mm}^3/\text{N}\cdot\text{m}$, while the DPDS condition reduced wear to $5.96 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$ but did not eliminate severe wear behavior. These results suggest that excessive RHA content promotes particle agglomeration, interfacial decohesion, and abrasive particle pull-out, leading to accelerated material loss. However, these mechanisms are proposed as possible explanations rather than confirmed effects, as detailed microstructural and worn-surface characterization was not performed in the present study.

3.3 Coefficient of Friction

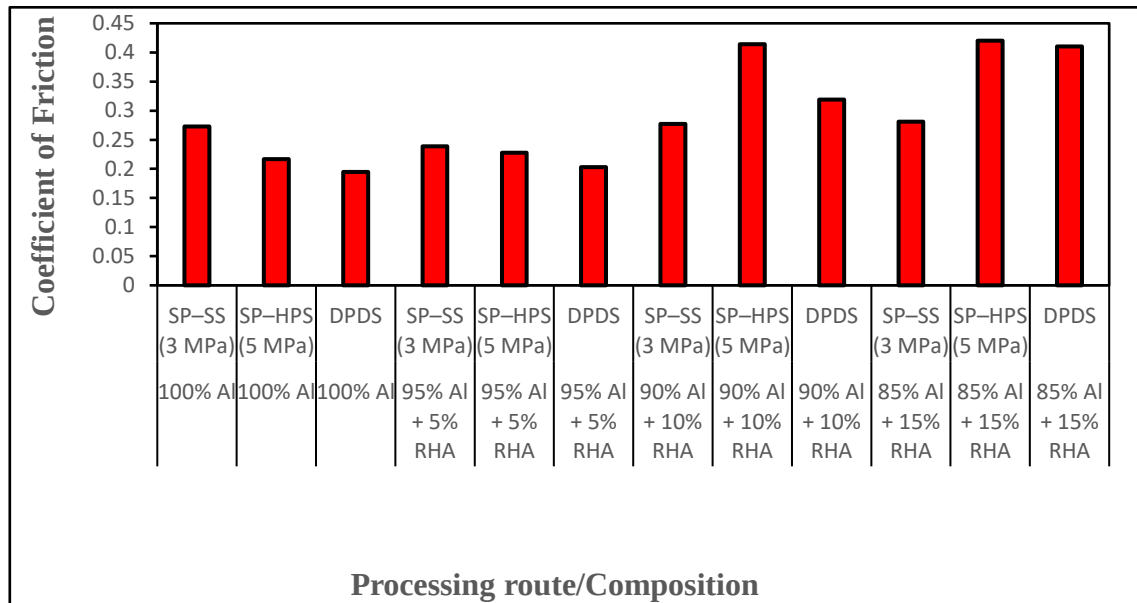
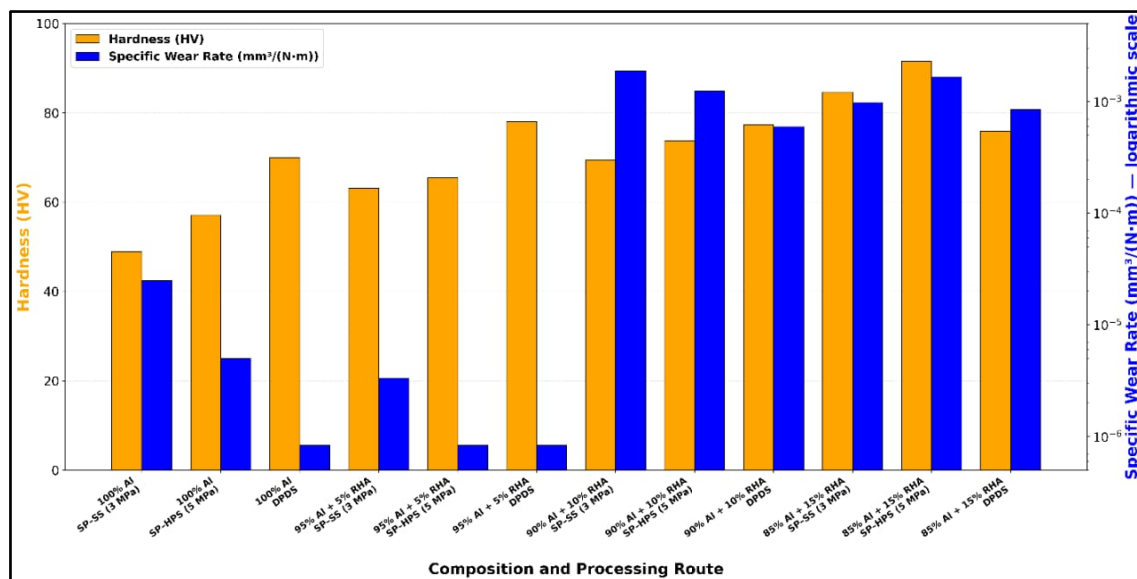


Figure 3: Effect of rice husk ash content on Aluminum-RHA composites processed via different routes

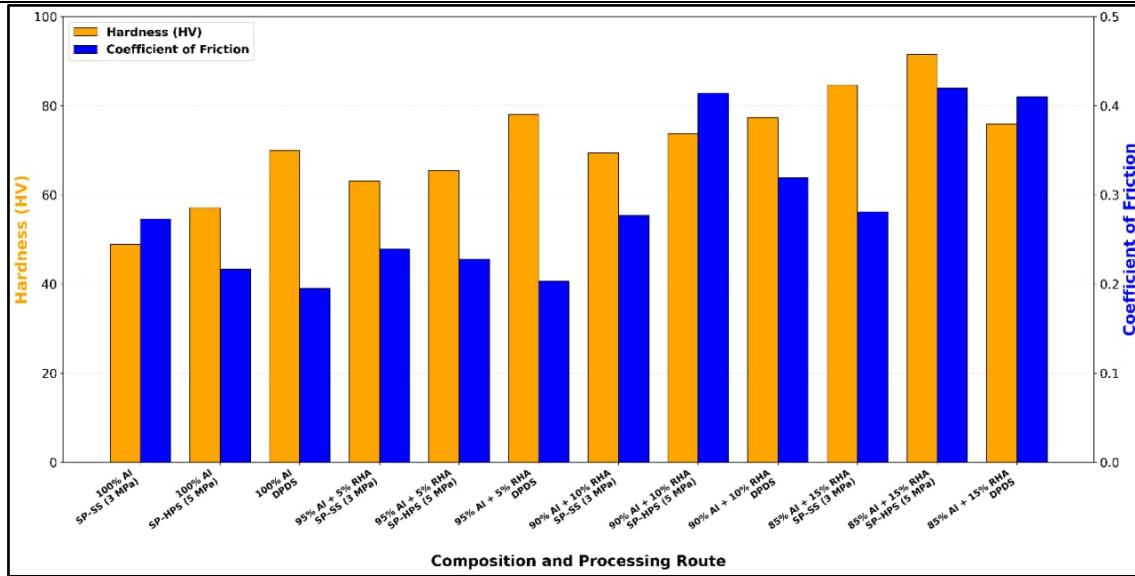
The coefficient of friction followed trends similar to the wear rate (see Figure 3). Lower wear rates were associated with reduced friction values, particularly for DPDS-processed samples. Pure aluminum processed via DPDS exhibited a COF of 0.195, while the 5 wt. % RHA composites showed a COF of 0.203. These values indicate stable sliding conditions with reduced adhesive and abrasive interactions. Higher COF values were recorded for 10–15 wt. % RHA composites, reaching 0.414–0.420 for some SP-HPS samples. The higher friction values observed at some of the higher RHA contents may be associated with the presence of hard silica-rich particles, which can act as third-body abrasives and promote ploughing and micro-cutting at the sliding interface. However, these interpretations are proposed as speculative mechanisms because the particle distribution and worn-surface morphology require further confirmation through surface and microstructural characterization.

3.4 Correlation between Hardness and Tribological Performance



(a)

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(b)

Figure 4: Comparison of hardness with (a) wear rate and (b) coefficient of friction

Figure 4a and b show the relationships between hardness and wear rate, and between hardness and COF for the fabricated Al–RHA composites, respectively. The results show an inverse relationship between hardness and specific wear rate, particularly for pure aluminum and the 5 wt.% RHA composites (See Figure 4a). For these compositions, the DPDS route produced higher hardness values accompanied by lower wear rates. This behavior can be attributed to the improved resistance of the harder material to plastic deformation and surface material removal during sliding. The observed trend is consistent with Archard’s wear law, which identifies material hardness as an important factor influencing wear resistance. However, at higher RHA contents of 10 and 15 wt.%, the relationship between hardness and wear rate becomes less consistent. This suggests that the wear behavior is influenced not only by hardness but also by microstructural characteristics such as porosity, particle agglomeration, weak matrix–RHA interfacial bonding, and particle pull-out. These defects can promote crack initiation, surface damage, and third-body abrasion, thereby increasing the wear rate despite the presence of a relatively hard reinforcement phase. Figure 4b compares hardness and COF, showing that the DPDS-processed pure aluminum and 5 wt.% RHA composites exhibit higher hardness alongside lower COF values. The reduction in COF with increasing hardness suggests that the improved surface resistance reduces asperity deformation and severe adhesive interactions during sliding, resulting in more stable sliding contact. Nevertheless, the relationship is not strictly linear across all RHA contents as earlier discussed in Section 3.4.

Figure 4 demonstrates that increased hardness generally contributes to improved tribological performance, as reflected by lower wear rate and COF. However, this relationship depends on the reinforcement content, as observed in this study. The consistent improvement observed for the DPDS-processed pure aluminum and 5 wt.% RHA composite indicates that the DPDS route effectively enhanced hardness while simultaneously reducing wear rate and COF. In contrast, the improvements in hardness at higher RHA contents did not consistently translate into reduced wear rate and COF, suggesting that other factors associated with increasing reinforcement content may influence the tribological behavior. These results therefore indicate that an optimum reinforcement content and appropriate processing route are essential for achieving a balanced combination of high hardness, low wear rate, and low COF in Al–RHA composites.

4. CONCLUSION

The effects of DPDS on the hardness and tribological performance of Al–RHA composites were investigated. Both RHA content and processing route influenced the material properties, with 5 wt.% RHA processed by DPDS providing the best overall balance of hardness, wear resistance, and

coefficient of friction. At 15 wt.% RHA, SP–HPS produced the highest hardness (91.5 HV) but also the highest COF (0.420), whereas DPDS produced the lowest wear rate ($8.53 \times 10^{-4} \text{ mm}^3/\text{N}\cdot\text{m}$) at the same composition. This confirms that higher hardness does not necessarily result in improved tribological performance. The lack of microstructural characterization limits verification of the mechanisms underlying these trends; future studies should therefore incorporate SEM/EDS and surface roughness analyses. The use of locally sourced RHA in this study promotes agricultural waste valorization and sustainable materials development, supporting locally driven and environmentally responsible engineering solutions in Nigeria. Overall, DPDS shows potential for sustainable Al–RHA composite development, with 5 wt.% RHA providing the most favorable overall performance under the investigated conditions.

Acknowledgements The authors would like to express their sincere appreciation to the Tertiary Education Trust Fund (TETFund) for supporting this research through the NRF 2021 SETI, Batch 8 research grant, awarded to Engr. Prof. U. A. Abdullahi, Department of Mechanical Engineering, Bayero University, Kano, Nigeria.

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