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Influence of Hybrid Coconut Husk Ash/Periwinkle Shell Ash and Silicon Carbide Reinforcement on Microstructure, Hardness and Wear Properties of Al–Zn Based Matrix Composites

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Abstract

Aluminum is widely used as a structural material in the automotive and aerospace sectors because of its low density and ease of processing. However, its relatively low melting temperature and limited strength restrict its performance in demanding applications. To address these limitations, ceramic reinforcements such as silicon carbide and alumina are commonly introduced due to their effectiveness and affordability. In recent years, attention has shifted toward low-cost and environmentally sustainable alternatives, particularly agro-waste–derived materials. Despite growing interest in such reinforcements, there is limited information on the combined use of Coconut Husk Ash (CHA), Periwinkle Shell Ash (PSA), and Silicon Carbide (SiC) as hybrid reinforcements in Al–Zn alloys. This study therefore examines the microstructural characteristics using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), hardness, ultimate tensile strength, and wear performance of Al–Zn alloy composites reinforced with varying proportions of CHA, PSA, and a constant 2 wt% SiC. The micrograph of the unreinforced alloy revealed a predominantly single-phase structure with zinc-rich dendritic features, along with noticeable voids likely associated with the absence of reinforcement. In contrast, the hybrid composites exhibited a more uniform distribution of reinforcement particles within the

aluminum matrix. Elemental analysis confirmed the presence of constituents such as calcium, manganese, magnesium, silicon, iron, and carbon, which are associated with the added reinforcements and are believed to enhance the observed properties. The reinforced composites consistently demonstrated higher hardness and tensile strength compared to the base alloy, with values increasing as the reinforcement content increased. Similarly, wear resistance improved with increasing reinforcement content, with the best performance recorded for Sample E and at Sample F there is a decline in mechanical properties which might be linked to particle agglomeration, poor interfacial bonding and reduced matrix continuity. Overall, the findings indicate that hybrid reinforcement using CHA, PSA, and SiC significantly enhances the mechanical and tribological performance of Al–Zn alloys. This approach not only improves material properties but also offers an effective means of utilizing agricultural waste, thereby providing both economic and environmental benefits.

Keywords: Al-Zn Alloy, Coconut Husk Ash, Periwinkle Shell Ash, Silicon Carbide, Metal Matrix Composites, Stir Casting, Microstructure, Mechanical Properties.

Introduction

Metal Matrix Composites (MMCs) are engineered materials consisting of a metallic base reinforced with secondary phases such as ceramics, polymers, or other metals. These composites are typically produced by introducing and uniformly dispersing reinforcement particles within a molten or solid metal matrix to achieve improved performance characteristics. The incorporation of reinforcement phases into a metal matrix is primarily aimed at enhancing key properties including strength, stiffness, hardness, and wear resistance. Recent studies emphasize that the addition of suitable reinforcements significantly improves load-bearing capacity and resistance to deformation under service conditions (Kumar *et al.,* 2021; Singh and Chauhan, 2022).

Aluminum and its alloys have attracted considerable attention as matrix materials in MMC development, particularly for automotive and aerospace applications. This is largely due to their low density, good surface finish, corrosion resistance, and compatibility with a wide range of fabrication techniques (Poornesh *et al*., 2017).

Aluminum Matrix Composites (AMCs) have gained widespread acceptance across industries such as transportation, aerospace, and sports equipment manufacturing. Their popularity is attributed to their high specific strength, low coefficient of thermal expansion, excellent high-temperature performance, and superior corrosion resistance when compared with conventional steels (Reddy *et al.,* 2021; Hassan *et al.,* 2022). The performance of AMCs can be further optimized through the development of hybrid composites, which involve the use of two or more reinforcement materials.

Hybridization has been shown to significantly improve hardness, tensile strength, wear resistance, and elastic modulus compared to single-reinforcement composites (Oladele et al., 2021; Sharma *et al.,* 2022). Common ceramic reinforcements such as silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B_4C), and titanium diboride (TiB_2) are widely used due to their high hardness and stiffness. However, challenges such as poor ductility, high density, and weak interfacial bonding with the matrix have limited their overall effectiveness in some applications (Nwigbo and Umoru, 2022).

To overcome these limitations and reduce production costs, recent research has focused on the use of agro-waste and industrial by-products as alternative reinforcement materials in aluminum-based composites. These materials offer advantages such as low cost, reduced density, and environmental sustainability (Olugbenga and Akinwole, 2010).

Several studies have explored the use of agricultural residues such as rice husk ash, bamboo leaf ash, coconut shell ash, maize cob ash, and eggshells, as well as industrial wastes like fly ash and red mud, as reinforcements in aluminum matrices. These materials have demonstrated significant potential in improving mechanical and tribological properties of composites (Oghenevweta *et al.,* 2016; Usman *et al.,* 2014).

Coconut Husk Ash (CHA), obtained from the controlled combustion of coconut husks, is rich in silica and other oxides, making it a suitable candidate for reinforcement in aluminum composites. Its application has been shown to enhance hardness, tensile strength, and wear resistance while promoting sustainable utilization of agricultural waste (Jain *et al.,* 2016).

Periwinkle shell is another abundant waste material, particularly in coastal regions of Nigeria, where it is generated from the consumption of marine snails. After calcination, periwinkle shell ash is primarily composed of calcium carbonate along with silica and other oxides. Its use as reinforcement in MMCs has gained attention due to its ability to improve mechanical strength and wear resistance while reducing environmental waste (Kolawole et al., 2017; Aigbodion *et al*., 2024).

Silicon carbide (SiC) remains one of the most widely used ceramic reinforcements in MMCs due to its exceptional hardness, thermal stability, and mechanical strength. Its addition to aluminum matrices significantly enhances hardness, tensile strength, and wear resistance, making it suitable for high-performance engineering applications (Schubert *et al*.,1999).

The choice of aluminum – zinc alloy (Al-Zn) as the matrix material is due to its inherently favorable combination of high strength to density ratio, low density, high specific stiffness and outstanding corrosion resistance. It generally exhibits better wettability with ceramic particles, castable matrix that bonds well with both synthetic and natural waste derived reinforcements thereby reducing defects like porosity and particle clustering, low melting temperatures ideal for stir casting. The above properties position them as suitable materials for structural components in both automotive and aerospace applications where weight reduction matters (Zhou *et al.,* 2021; Ramesh *et al.,* 2021).

Recent investigations have demonstrated the effectiveness of agro-waste reinforcements in aluminum composites. For instance, Fakorede *et al.* (2024) reported that incorporating up to

16 wt% CHA into aluminum alloys via stir casting resulted in improved hardness and tensile strength, with optimal performance observed at 12 wt% CHA.

Onyechi *et al.* (2015) examined periwinkle shell-reinforced polymer composites and observed notable improvements in tensile, compressive, and wear properties. Likewise, Salawu and Salihu (2023) reported enhanced mechanical performance and uniform particle distribution in Al 7075 composites reinforced with periwinkle shell ash.

Despite these advancements, limited research exists on the combined use of Coconut Husk Ash, Periwinkle Shell Ash, and Silicon Carbide as hybrid reinforcements in aluminum-based composites. This gap highlights the need for further investigation into their synergistic effects. Therefore, this study focuses on the development of Al–Zn alloy composites reinforced with CHA, PSA, and SiC for potential application in the automotive industry.

Materials and Methods

The matrix material employed for the fabrication of the aluminum-based composite was an Al–Zn alloy. Silicon carbide (SiC) particles, with an average particle size of 63 μm, were obtained from the Nigerian Institute of Mining and Geosciences (NIMG), Jos, Plateau State, Nigeria.

Coconut husks were collected from a farm located in Abobo, Okehi Local Government Area of Kogi State, where they had been discarded as agricultural waste. Periwinkle shells were sourced from a local market in the riverine community of Okrika, Rivers State.

The collected coconut husks and periwinkle shells were subjected to controlled combustion to produce ash. The resulting ashes were then sieved using a mechanical sieve shaker to obtain particles with sizes below 63 μm. The chemical compositions of the Coconut Husk Ash (CHA) and Periwinkle Shell Ash (PSA) were determined using X-ray fluorescence (XRF) analysis.

For Scanning Electron Microscopy (SEM) sample preparation, the required materials included a hacksaw with blade for sectioning, emery papers for surface grinding, alumina paste for polishing, and Keller's reagent for etching.

Table 1: Chemical Composition Analysis of the used Aluminum-Zinc Alloy

Element	Al	Si	Fe	Mn	Mg	Zn	Cr	Ti	Cu
Composition	88.17	0.40	0.50	0.3	0.50	9.08	0.20	0.20	0.65

Table 2: Chemical Composition Analysis of Coconut Husk Ash reinforcement

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	MnO	SO_3
Composition	14.34	35.61	0.18	33.27	1.03	19.86	0.21	0.004

Table 3: Chemical Composition Analysis of Periwinkle Shell Ash reinforcement

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	P_2O_5	TiO_2	LOI
Composition	42.32	11.6	5.13	29.54	2.32	0.11	0.43	0.31	0.01	0.042	5.5

The compositional analysis of the base Al–Zn alloy indicates that it is a zinc-rich aluminum system, confirming its classification as a high-zinc aluminum alloy. In addition, the X-ray fluorescence (XRF) results of the reinforcing materials reveal that both Coconut Husk Ash (CHA) and Periwinkle Shell Ash (PSA) are predominantly composed of ceramic oxide phases, including silicon oxide (SiO_2), calcium oxide (CaO), alumina (Al_2O_3), magnesium oxide (MgO), and iron oxide (Fe_2O_3). These oxide constituents are well recognized for their effectiveness as reinforcing agents in aluminum matrix composites due to their contribution to improved mechanical performance (Alaneme *et al.,* 2015).

Preparation of Coconut Husk Ash and Periwinkle Shell Ash

Coconut Husk Ash (CHA) and Periwinkle Shell Ash (PSA) were prepared separately following an established procedure reported in the literature (Joshua *et al.,* 2022), with slight modifications. A perforated metallic drum was employed as the combustion chamber for both materials. Dried coconut husks and periwinkle shells were placed inside the drum and ignited using charcoal as the heat source. The materials were allowed to undergo complete combustion, after which the ashes were left to cool and collected after 24 hours.

To further improve the quality of the ashes by reducing residual carbon and volatile constituents, the collected ash samples were subjected to heat treatment in a muffle furnace at 600 °C for 2 hours. The heat-treated ashes were then sieved using a mechanical sieve shaker to obtain fine particles with sizes less than 63 μm. The chemical compositions of the resulting CHA and PSA were subsequently determined using X-ray fluorescence (XRF) analysis.

Composite Production

The fabrication of the hybrid composites was carried out using a double stir casting technique, as reported in previous studies (Joshua *et al.,* 2022). Based on calculated charge compositions, the required quantities of Coconut Husk Ash (CHA), Periwinkle Shell Ash (PSA), and Silicon Carbide (SiC) particles were measured to produce hybrid composites with reinforcement ratios of 1 wt% CHA/1 wt% PSA/2 wt% SiC, 2 wt% CHA/2 wt% PSA/2 wt% SiC, 3 wt% CHA/3 wt% PSA/2 wt% SiC, 4 wt% CHA/4 wt% PSA/2 wt% SiC, and 5 wt% CHA/5 wt% PSA/2 wt% SiC, as presented in Table 4. An unreinforced Al–Zn alloy was also prepared to serve as the control sample.

Prior to incorporation into the melt, the reinforcement particles (CHA, PSA, and SiC) were preheated to approximately 250 °C. This step was necessary to remove moisture, minimize thermal gradients during addition, and enhance wettability between the particles and the molten matrix.

Melting of the Al–Zn alloy was performed in a gas-fired crucible furnace at a temperature of about 750 ± 30 °C, ensuring complete liquefaction above the alloy's liquidus temperature. The molten alloy was then allowed to cool to a semi-solid state at approximately 600 °C. At this stage, the preheated reinforcement particles were gradually introduced into the melt according

to the specified compositions and manually stirred for about 5–10 minutes to achieve initial distribution.

Subsequently, the slurry was reheated to approximately 780 ± 30 °C, followed by a second, more vigorous stirring process to improve particle dispersion and homogeneity within the matrix. The resulting composite melt was then poured into prepared sand molds and allowed to solidify under ambient conditions.

Sand casting was selected as the fabrication method due to its simplicity, adaptability, and suitability for large-scale production. This technique has also been widely reported in the literature for the production of aluminum-based composites (Alaneme *et al.,* 2020; Joshua *et al.,* 2022; Joshua *et al.,* 2025).

Table 4: Sample Designation and Composite Compositions.

Sample designation	Composite composition
A	Al-Zn
B	Al-Zn + 1.0 wt% CHA/1.0 wt% PSA and 2.0 wt% SiC particles
C	Al-Zn + 2.0 wt% CHA/2.0 wt% PSA and 2.0 wt% SiC particles
D	Al-Zn + 3.0 wt% CHA/3.0 wt% PSA and 2.0 wt% SiC particles
E	Al-Zn + 4.0 wt% CHA/4.0 wt% PSA and 2.0 wt% SiC particles
F	Al-Zn + 5.0 wt% CHA/5.0 wt% PSA and 2.0 wt% SiC particles

Microstructural Analysis of the Aluminum Alloy and Fabricated Composites

Microstructural characterization of the as-cast aluminum alloy and the fabricated composites was carried out using a Carl Zeiss Sigma field emission scanning electron microscope (FE-SEM), equipped with secondary electron (SE) imaging, backscattered electron (BSE) imaging, and energy dispersive spectroscopy (EDS) capabilities.

Prior to analysis, the specimens were prepared following standard metallographic procedures. Each sample was first sectioned to the required dimensions, after which surface preparation was performed through sequential grinding using silicon carbide abrasive papers of progressively finer grit sizes (220, 320, 400, 600, 800, 1200, and 2400).

Subsequent polishing was carried out using alumina paste to obtain a smooth, mirror-like surface finish suitable for microscopic examination. The polished samples were then etched using Keller's reagent to reveal the microstructural features. After etching, the specimens were thoroughly rinsed with water followed by ethanol, and then air-dried prior to SEM observation.

Hardness Test

The hardness of the Al–Zn alloy and the developed composites was evaluated using a Brinell hardness testing machine in accordance with ASTM E18–20 (ASTM, 2020). Prior to testing, the specimen surfaces were properly prepared through grinding and polishing to ensure smooth and uniform contact with the indenter.

During the test, a load of 100 kgf was applied for a dwell time of 10 seconds. Indentations were made at three different locations on each sample to ensure reliability and minimize experimental error. The hardness value for each material was determined by calculating the average of the measured readings obtained from the test points.

Tensile Test

The tensile properties of the developed composites were determined in accordance with ASTM E8/E8M–21 (ASTM, 2021). For each composition, two test specimens were machined to a gauge diameter of 5 mm and a gauge length of 30 mm.

Tensile testing was carried out at room temperature using an Instron universal testing machine (Model 3369) at a constant strain rate of 6×10^{-3} s^{-1}. The mechanical properties were subsequently obtained from the load–displacement curves generated during the test.

Wear Abrasion Test Procedure

Dry sliding wear tests were conducted on the samples using a pin-on-disc apparatus in accordance with ASTM (2022) standards. The procedure followed during the test is outlined below:

1. The initial weight of each specimen was measured using a precision balance.
2. The specimen was mounted securely on the holder of the wear testing machine.
3. Proper alignment was ensured before firmly fixing the specimen in position.
4. A predetermined normal load was applied through the loading mechanism to maintain continuous contact between the pin and the rotating disc surface.
5. The machine was then switched on, allowing the disc to rotate for a fixed number of cycles (20 revolutions).
6. After the test, the specimen was removed, cleaned, and its final weight was recorded.
7. The sliding distance covered during the test was also determined.

$$\Delta w = (w_1 - w_2) \quad (1)$$

Where ΔW = Weight loss of the specimen

W_1 = Weight of the specimen before test

W_2 = Weight of the specimen after test

Volume loss (ΔV) of the specimen is computed in the following way:

$$\Delta V = (w_1 - w_2) \times 1000 \quad (2)$$

Where ρ = Experimental density of the specimen

The Specific wear rate ((Ws) of the specimen is calculated in the following manner:

$$Ws = \Delta V Fn \times Ss \quad (3)$$

Where Ss = Sliding distance (mm), F_N = Normal load (N)

$$\text{Wear resistance} = \text{Sliding Distance (S)Volume (Vloss x 1000)} \quad (4)$$

Results and Discussions

Microstructural Evaluation of the Al–Zn Alloy and Composites

The microstructural features of the as-cast unreinforced Al–Zn alloy were characterized using SEM–EDS. The result Figure 1a indicate a predominantly dendritic structure enriched with zinc-rich phases. Quantitative elemental analysis confirms a zinc content of approximately 7.10 wt%, indicating a high zinc–aluminum alloy system. The micrograph further reveals the presence of voids and micro-porosities, which are typically associated with the absence of reinforcing phases that could otherwise promote densification and microstructural stability.

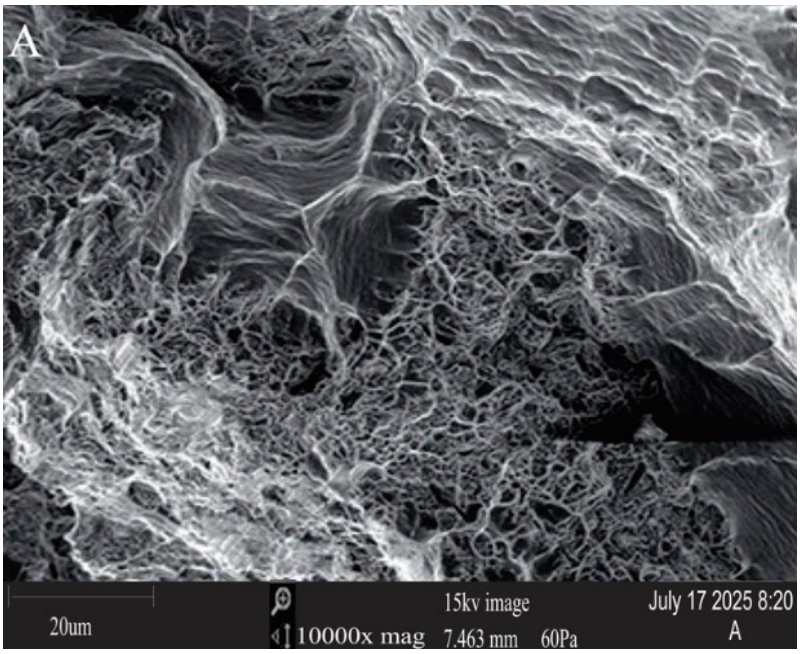
In comparison, the SEM–EDS micrographs of the hybrid composites reinforced with Coconut Husk Ash (CHA), Periwinkle Shell Ash (PSA), and Silicon Carbide (SiC) (Figure 1b–1f) exhibit a heterogeneous distribution of reinforcement particles within the Al–Zn matrix. The particle distribution is relatively non-uniform, with locally coarser clusters observed in some regions. Such microstructural characteristics may influence both wear and mechanical response; however, localized agglomeration can also introduce micro-voids that act as stress concentration sites and potential crack initiation points under applied loading.

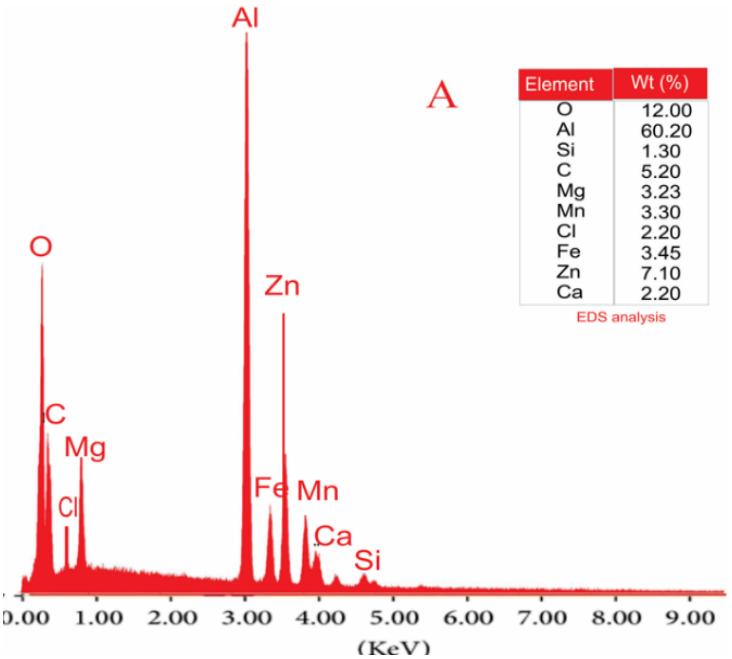
Among all fabricated samples, the microstructure presented in Figure 1e demonstrates the most improved morphology, with a comparatively uniform dispersion of reinforcement phases throughout the matrix. This refinement is reflected in reduced porosity, minimal particle clustering, and improved interfacial bonding between the reinforcements and the Al–Zn alloy. The enhanced interface quality promotes more efficient load transfer and mitigates localized stress accumulation, thereby reducing the tendency for particle pull-out during deformation.

Consequently, the superior microstructural integrity observed in Figure 1e translates to improved overall mechanical stability when compared with Figure 1b–1d. The effective incorporation of hard reinforcement phases within a well-bonded matrix is therefore a key factor contributing to the enhanced performance of the optimally processed composite.

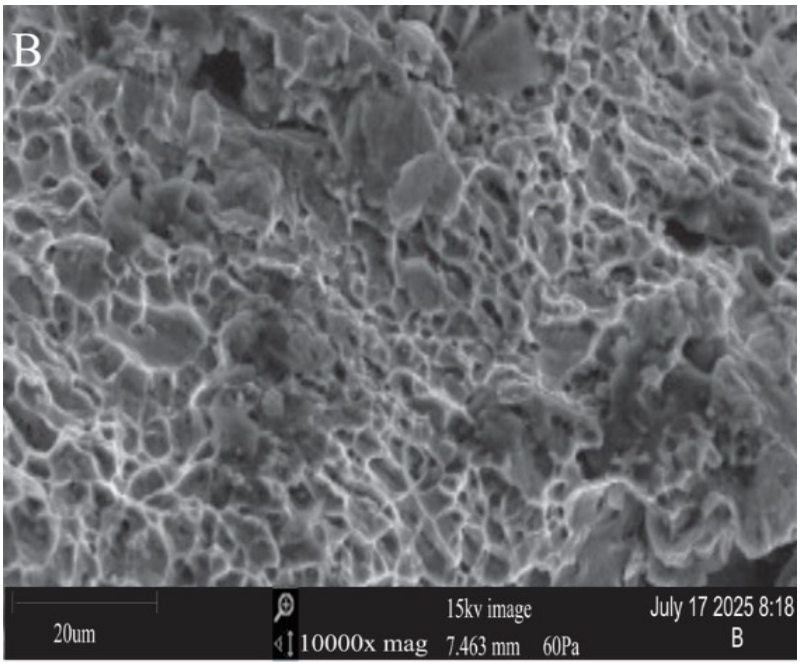
While Figure 1f shows particle agglomeration, increased porosity, poor interfacial bonding, and reduced matrix continuity—factors that collectively introduce stress concentration sites and hinder effective load transfer within the composite—these may cumulatively be responsible for the decline in the recorded hardness and tensile strength values observed after the optimum microstructural and mechanical properties in Figure 1e (Sample e).

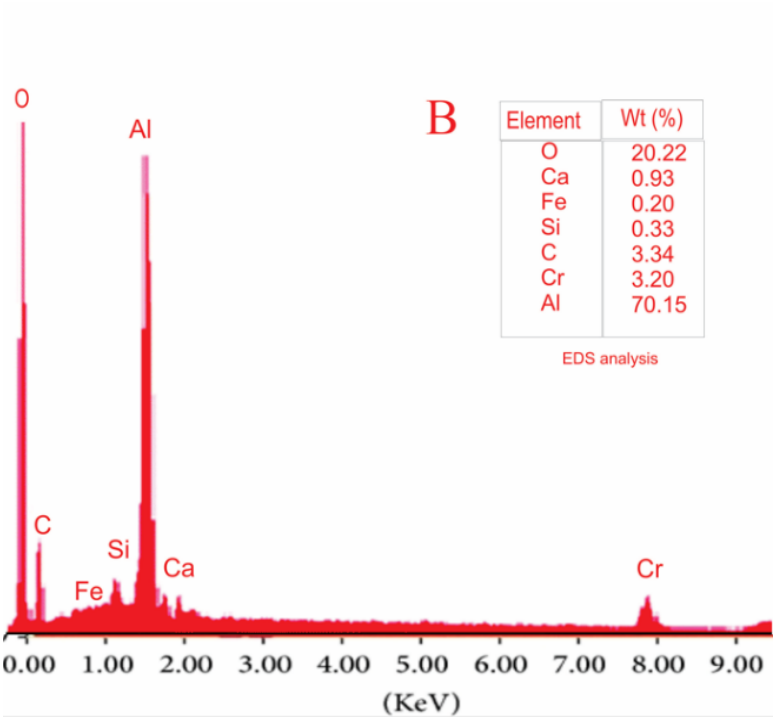
Furthermore, comparative SEM–EDS elemental analysis between the unreinforced alloy and the reinforced composites reveals higher concentrations and migration of elements such as calcium, silicon, magnesium, manganese, and iron from the coconut husk ash and periwinkle shell ash into the Al-Zn matrix, indicating the existence of an active interface in the composites. Chemical reaction occurs at the interface between the reinforcements and the matrix during melting, thereby creating an intermetallic compounds and oxides like $CaAl_2O_4$, Fe_2O_3 which are crucial for bonding and effective stress transfer hence improving the mechanical properties as experienced in this work.



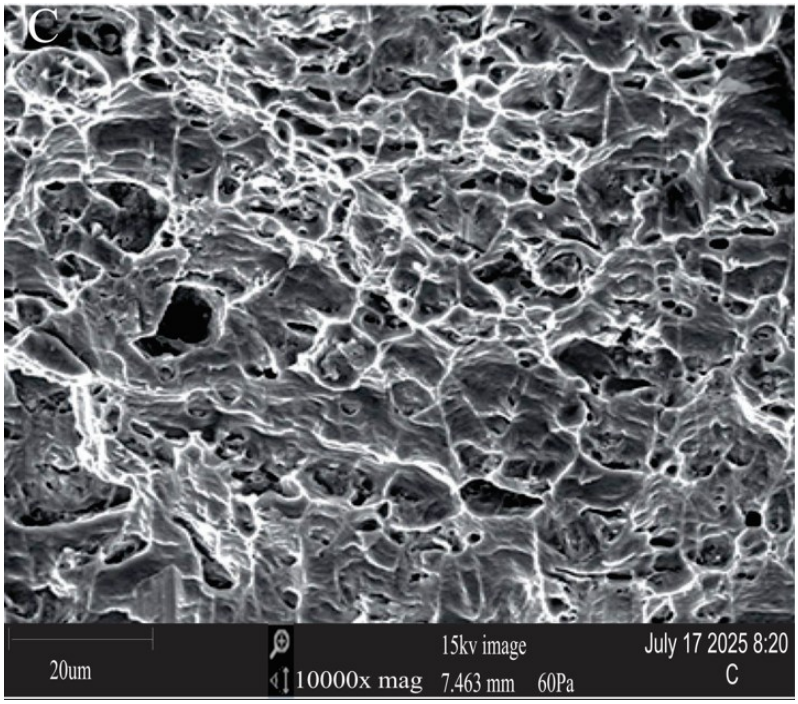


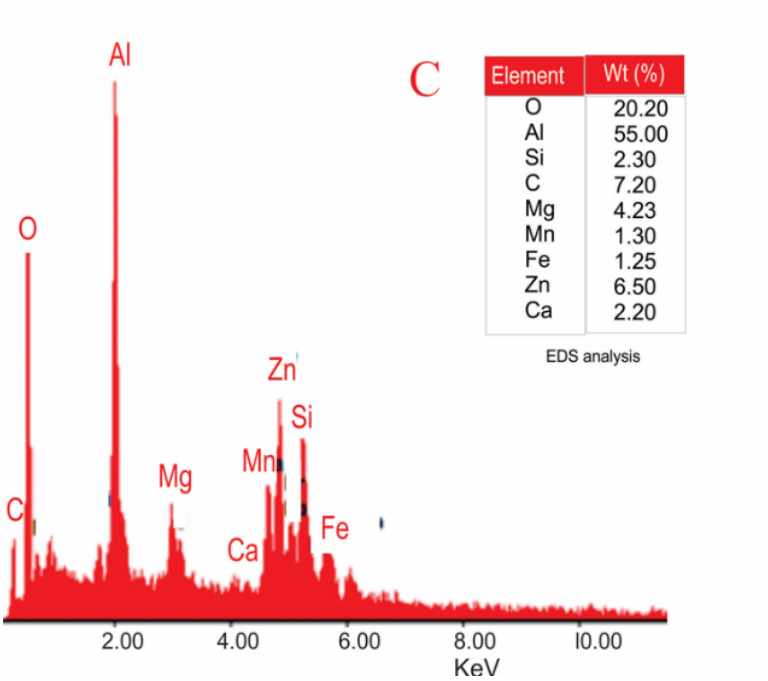
(a) SEM - EDS image of the As - cast Al-Zn alloy



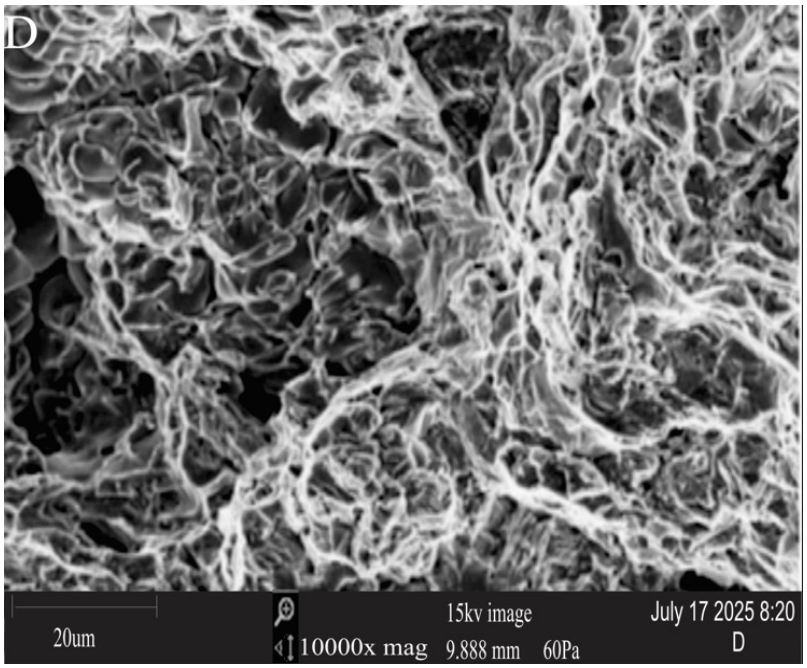


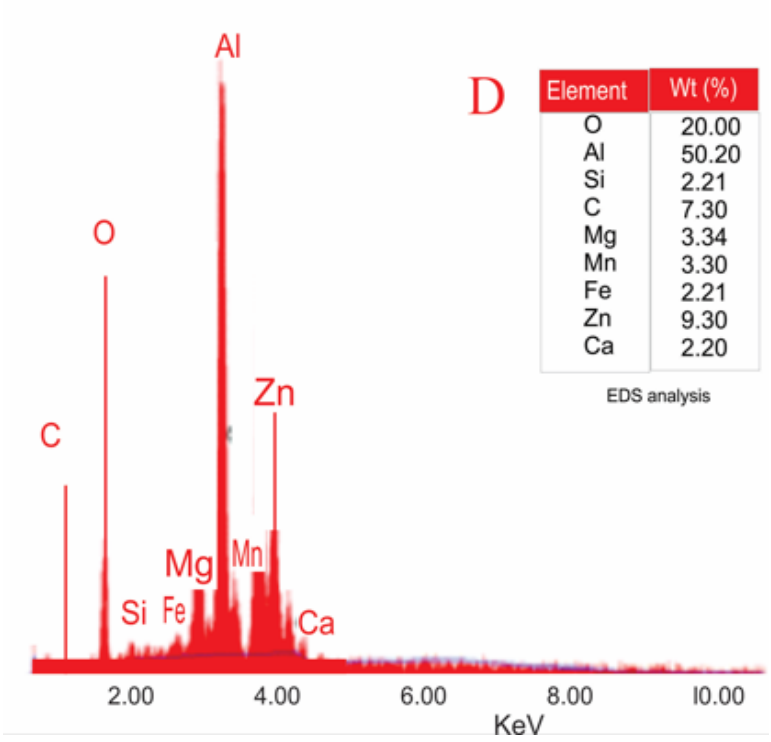
(b) SEM - EDS image of 1% CHA/1% PSA/2% SiC Aluminum Composite



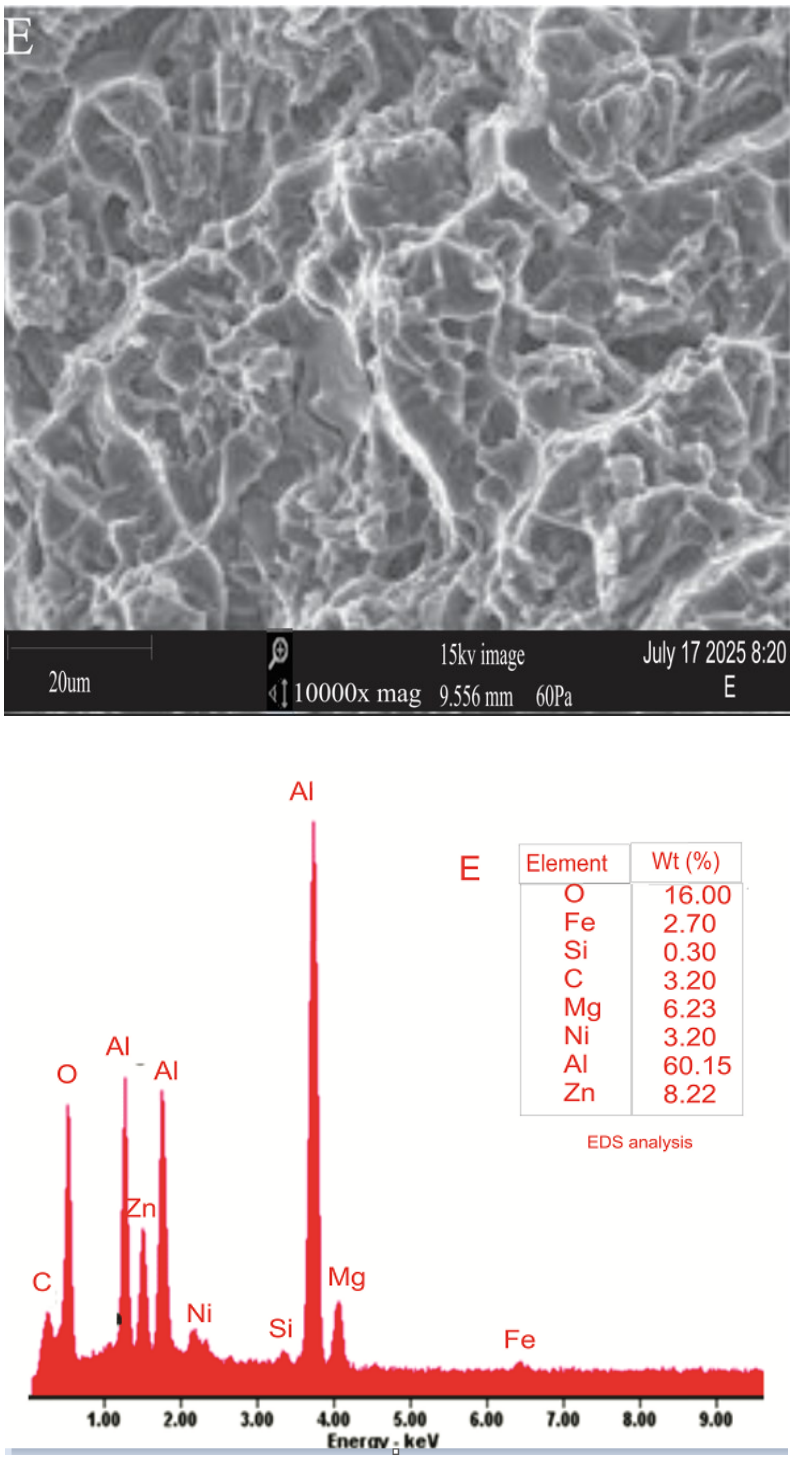


(c) SEM - EDS image of 2% CHA/2% PSA/2% SiC Aluminum Composite

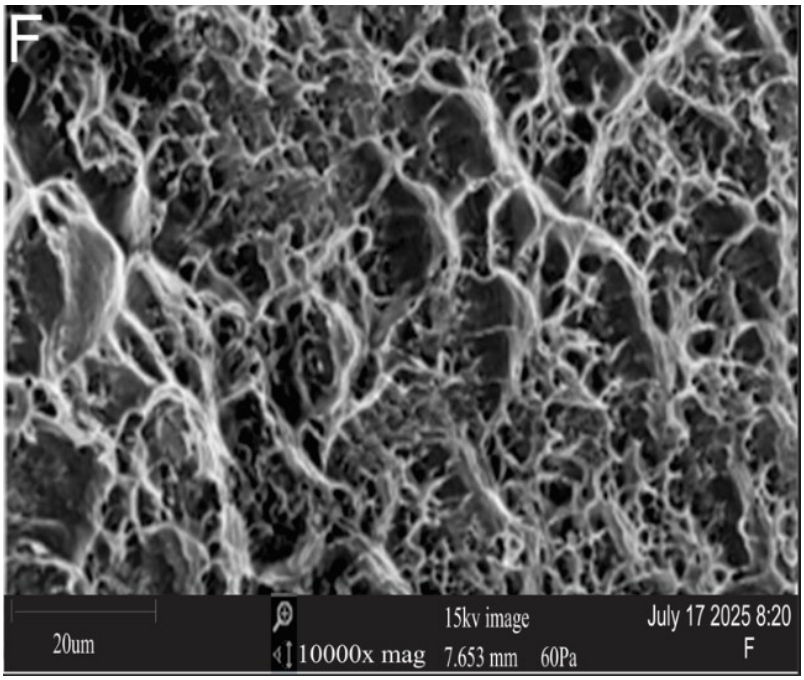


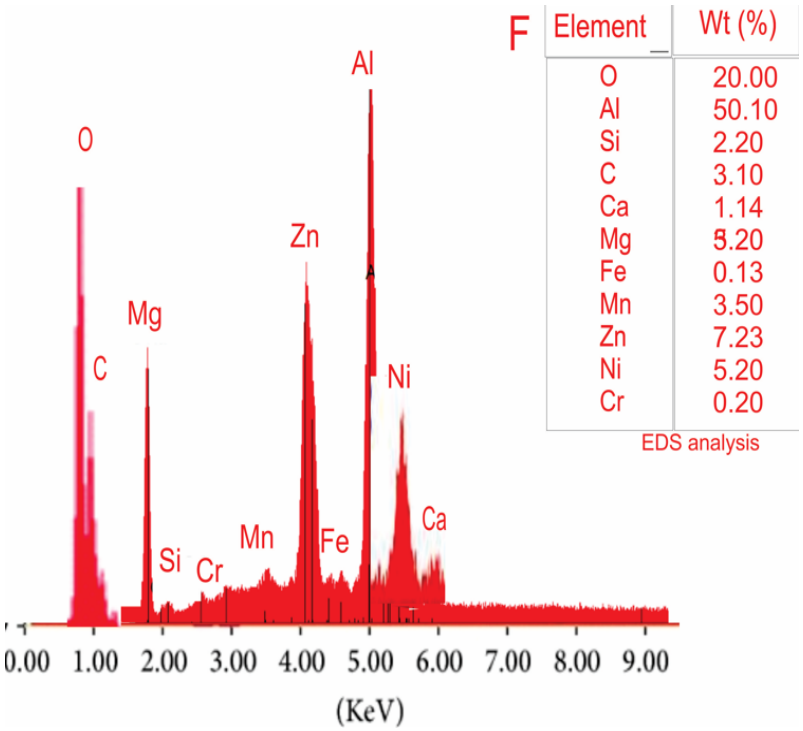


(d) SEM - EDS image of 3% CHA/3% PSA/3% SiC Aluminum Composite



(e) SEM - EDS image of 4% CHA/4% PSA/2% SiC Aluminum Composite





(f) SEM - EDS image of 5% CHA/5% PSA/2% SiC Aluminum Composite

Fig. 1. Representative SEM micrographs of (a) Al–Zn alloy, (b) Al–Zn alloy + 1% CHA+ 1% PSA + 2%SiC, (c) Al–Zn alloy + 2% CHA+ 2% PSA + 2%SiC, (d) Al–Zn alloy + 3% CHA+ 3% PSA + 2%SiC, (e) Al–Zn alloy + 4% CHA+ 4% PSA + 2%SiC, (f) Al–Zn alloy + 5% CHA+ 5% PSA + 2%SiC

Mechanical Behavior

Hardness Test Results

The hardness performance of the Al–Zn alloy reinforced with Coconut Husk Ash (CHA), Periwinkle Shell Ash (PSA), and Silicon Carbide (SiC) is presented in Figure 2. The results show that all the reinforced composites exhibit higher hardness values compared to the unreinforced Al–Zn alloy, indicating the beneficial effect of particle reinforcement on resistance to plastic deformation.

A general increasing trend in hardness was observed with rising weight fractions of CHA and PSA. The base alloy recorded a hardness value of 59.62 HBN, while the highest value of 76.32 HBN was obtained for the composite Sample e containing 4 wt% CHA, 4 wt% PSA, and 2 wt% SiC. This improvement suggests enhanced resistance to indentation, scratching, and surface wear, making the reinforced materials more suitable for tribological applications.

The observed increase in hardness can be attributed to the presence of hard ceramic-rich phases within the reinforcement materials. The oxides present in CHA and PSA, including SiO_2, CaO, MgO, Fe_2O_3, and Al_2O_3, together with SiC particles, contribute significantly to strengthening the matrix. These ceramic constituents promote load transfer and restrict dislocation movement within the aluminum matrix, thereby enhancing overall hardness.

The improvement is consistent with established findings that ceramic reinforcements enhance the hardness of aluminum-based composites through strong interfacial bonding and particle strengthening mechanisms (Aku *et al.,* 2013; Abdulkareem *et al.,* 2019).

While Sample f shows a noticeable decline in hardness after the optimum value recorded in Sample e, this may be linked to particle agglomeration, where the particles interact more with each other than with the Al–Zn matrix alloy.

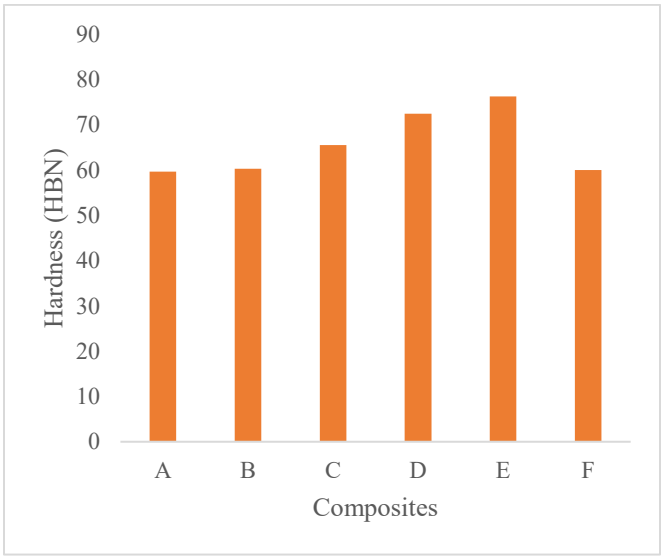


Figure 2: Effect of Coconut Husk Ash/Periwinkle Shell Ash/Silicon Carbide as Hybrid Reinforcement on the Hardness Properties of Al-Zn composite

Ultimate Tensile Strength

In Figure 3, Sample A represents the unreinforced Al–Zn alloy, while Samples B–F correspond to the hybrid composites with increasing reinforcement contents.

The results indicate that all reinforced composites exhibit superior ultimate tensile strength (UTS) compared to the base alloy, which recorded a value of 143.69 MPa. Among the developed materials, the composite containing 4 wt% CHA, 4 wt% PSA, and 2 wt% SiC (Sample E) achieved the highest UTS of 152.71 MPa. This improvement demonstrates an enhanced ability of the material to withstand higher tensile loading prior to fracture, indicating its suitability for structural and load-bearing applications.

The observed increase in tensile strength can be attributed to the presence of hard ceramic phases within the reinforcements, including CaO, MgO, SiO_2, Fe_2O_3, and Al_2O_3, as confirmed by the EDS analysis of the reinforced samples (Figure 1b – 1f). These reinforcing constituents contribute to strengthening by improving load transfer efficiency between the matrix and reinforcement particles.

In addition, the improvement in tensile properties can be explained by established strengthening mechanisms in particle-reinforced aluminum matrix composites. These include effective stress transfer from the ductile matrix to the harder reinforcement particles, as well as the generation of dislocation densities that hinder plastic deformation and enhance resistance to applied tensile loads (Alaneme & Adewale, 2013; Joshua *et al.,* 2022).

Researchers in the past have indicated that the strengthening mechanism in particle reinforced AMCs arises due to load transfer from the matrix material to the particles (direct strengthening) and formation of more dislocations which serve as restraints to plastic deformation (indirect strengthening) (Alaneme and Adewale, 2013; Joshua, *et al.,* 2022).

A decline in strength is observed in Sample f after the optimum value recorded in Sample e, which may be attributed to a weak interface and debonding under load. This arises from the higher reinforcement content of coconut husk ash and periwinkle shell ash, which hinders proper wetting of the aluminum–zinc matrix with the reinforcement.

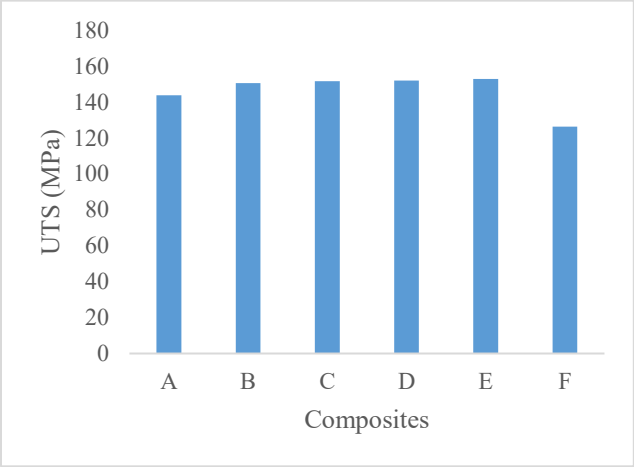


Figure 3: Effect of Coconut Husk Ash/Periwinkle Shell Ash/Silicon Carbide as Hybrid Reinforcement on the Ultimate Tensile Strength of Al-Zn composite.

Wear Properties

The specific wear rate (mm³/Nm) and wear resistance (mm³/mm or mm/mm³ as applicable) of the developed composites are presented in Figures 4 and 5. The results indicate a clear improvement in wear performance with increasing proportions of Coconut Husk Ash (CHA) and Periwinkle Shell Ash (PSA), ranging from 1 wt% to 5 wt%, while the Silicon Carbide (SiC) content was maintained at 2 wt% across all hybrid compositions.

All reinforced samples demonstrated superior wear resistance compared to the unreinforced Al–Zn alloy. The control sample exhibited the highest specific wear rate of 0.0109 mm³/Nm and the lowest wear resistance value of 9.1895 mm³/mm³, indicating poor resistance to material loss under sliding conditions. In contrast, the composites showed reduced wear rates and improved resistance, confirming the beneficial effect of reinforcement addition.

Among the developed materials, Sample e (4 wt% CHA/4 wt% PSA/2 wt% SiC) recorded the best performance, with a wear resistance value of 26.0288 mm³/mm³. This suggests that an optimal reinforcement level exists, beyond which wear performance improvement may not be as significant.

The enhancement in wear behavior can be attributed to the presence of hard ceramic phases within the reinforcements, including CaO, SiO_2, MgO, Fe_2O_3, and Al_2O_3. These phases contribute to increased surface hardness, which in turn improves resistance to abrasion, micro-cutting, and plastic deformation during sliding contact. The improved hardness observed in earlier results further supports the reduction in material loss under tribological loading conditions (Alam *et al.,* 2018; Joshua *et al.,* 2022).

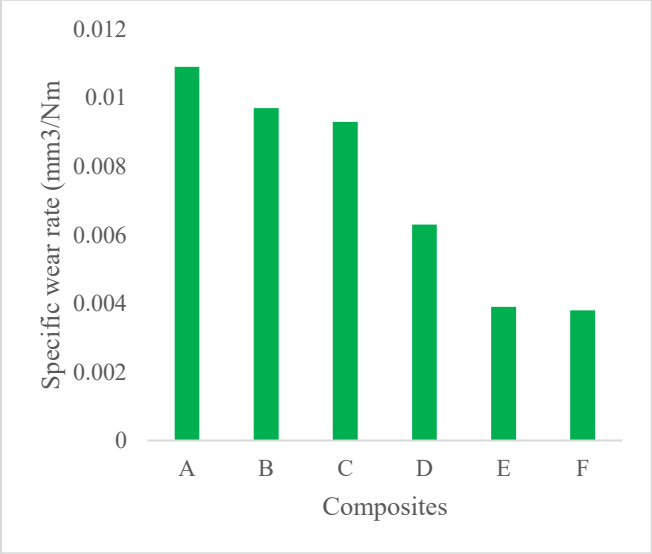


Figure 4: Effect of Coconut Husk Ash/Periwinkle Shell Ash/Silicon Carbide reinforcement on the Specific Wear Rate of Al-Zn Composite

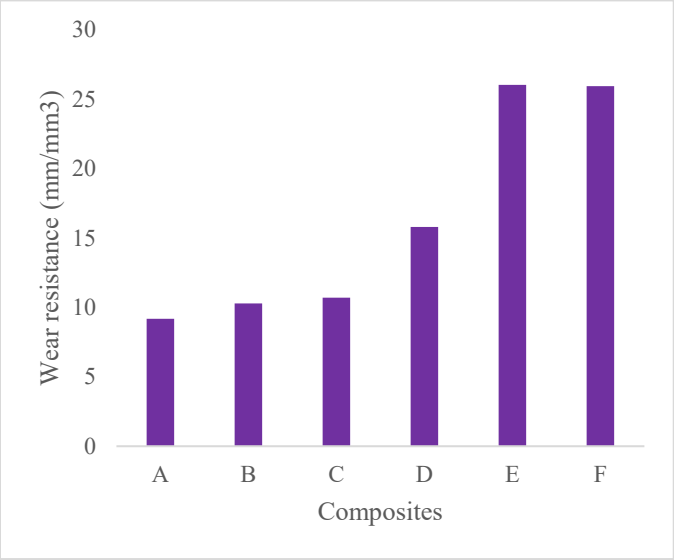


Figure 5: Effect of Coconut Husk Ash/Periwinkle Shell Ash/Silicon Carbide reinforcement on the Wear Resistance of Al-Zn Composite

Conclusions

This study investigated the structural, mechanical, and tribological performance of Al–Zn alloy composites reinforced with hybrid combinations of Coconut Husk Ash (CHA), Periwinkle Shell Ash (PSA), and Silicon Carbide (SiC). The composites were fabricated using a double stir casting technique with reinforcement contents ranging from 1 wt% CHA/1 wt% PSA/2 wt% SiC to 5 wt% CHA/5 wt% PSA/2 wt% SiC. Based on the experimental findings, the following conclusions are drawn:

- The hybrid reinforcement particles were successfully incorporated into the Al–Zn matrix using the double stir casting route, confirming the effectiveness of the fabrication process.
- SEM–EDS analysis of the unreinforced alloy revealed a predominantly single-phase microstructure characterized by zinc-rich dendritic formations. In contrast, the reinforced composites exhibited a more heterogeneous structure with reasonably distributed reinforcement particles within the matrix. Elemental analysis further confirmed the presence of key reinforcement-derived elements such as Ca, Mg, Si, Fe, Mn, and C in the composites.
- The mechanical properties of the composites improved progressively with increasing reinforcement content. Both hardness and ultimate tensile strength showed a positive correlation with the weight fraction of CHA and PSA, with the optimum values recorded for Sample E (4 wt% CHA/4 wt% PSA/2 wt% SiC).
- A significant reduction in wear rate was observed with increasing reinforcement additions, while wear resistance improved correspondingly. Sample E again demonstrated the best tribological performance among all the developed materials.

Overall, the study confirms that the incorporation of CHA, PSA, and SiC particulates into Al–Zn alloy enhances its mechanical strength and wear resistance. This indicates that the developed hybrid composites are suitable for lightweight engineering applications where improved structural and tribological performance is required.

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