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Effect of Snail shell Ash Reinforcements on the Microstructural and Mechanical Properties of AA6063 Aluminium Alloy

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Abstract: Aluminium matrix composites (AA6063/SSA), consisting of an AA6063 aluminum alloy matrix reinforced with low-cost, 63 μm snail shell ash (SSA) particles, were successfully fabricated using the stir-casting method. The microstructural, tensile strength, hardness, wear resistance, and flexural strength tests of composites containing 0, 3, 6, 9, 12 wt.% SSA in the AA6063 matrix were carried out. Microstructural analysis showed uniform SSA particle dispersion and progressive grain refinements up to 9 wt.%, while at 12 wt.% SSA loading there were particle agglomeration and porosity. Mechanical properties improved with increasing SSA content up to 9 wt.%, with peak performance observed at this composition (ultimate tensile strength ≈ 99 MPa, Brinell hardness ≈ 95 HBS, minimum wear rate, and flexural strength 159.16 MPa). These properties reduced at 12 wt.% SSA, due to defects and weak particle–matrix bonding. Single-factor ANOVA indicated that SSA reinforcement had a significant influence on all assessed properties of AA6063 composites, except ultimate tensile strength, with peak enhancements in flexural strength, hardness, fracture strain, yield stress, and wear occurring at 9 wt.% SSA. The study demonstrates that 9 wt.% SSA offers an optimal balance between reinforcement and matrix integrity and confirms SSA as a sustainable reinforcement for AA6063 matrix composites.

1. Introduction

Metal matrix composites (MMCs) are a class of advanced engineering materials produced by combining a metal matrix with reinforcing phases in order to improve mechanical and physical properties (Velmurugan *et al.*, 2022; Kumar *et al.*, 2024; Latifi *et al.*, 2025). The demand for materials with high strength-to-weight ratio (Kumar *et al.*, 2024), improved wear resistance (Kumar *et al.*, 2022; Abouri *et al.*, 2025), and enhanced thermal properties (Sidhu *et al.*, 2016) has driven the development of MMCs for various applications including aerospace, automotive, and structural components (Singh *et al.*, 2021; Sharma *et al.*, 2020; Koli *et al.*, 2015). Traditional monolithic metallic materials often lack the combination of properties required for these modern engineering applications (Yu *et al.*, 2023). Aluminium is one of the most widely used matrix materials for MMCs because of its low density, excellent corrosion resistance, high thermal conductivity, and good formability (Venugopal *et al.*, 2023). Aluminium matrix composites (AMCs) are produced by incorporating reinforcement particles into an aluminium matrix to enhance properties such as hardness, stiffness, strength, and wear resistance (Kumar *et al.*, 2024 ; Igwe *et al.*, 2025-1; Alami *et al.*, 2026). Conventional reinforcement materials such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) (Karabulut *et al.*, 2023; Boobalan *et al.*, 2022) are commonly used. However, their high cost and limited availability in developing countries restrict their widespread application (Gashaw *et al.*, 2025). In recent years, the utilization of agro-waste and bio-waste materials as reinforcement in metal matrix composites has gained considerable attention (Sonker *et al.*, 2024). Materials such as rice husk ash (Dixit *et al.*, 2022; Igwe *et al.*, 2025-2), palm kernel shell ash (Abolusor *et al.*, 2025), coconut shell ash (Kumar *et al.*, 2023), and snail shell ash (Saravankumar *et al.*, 2025) have been investigated for their potential to improve composite performance while reducing environmental pollution. Snail shells are commonly discarded as waste after consumption in many regions (Potorti *et al.*, 2024). These shells consist mainly of calcium carbonate ($CaCO_3$) along with small amounts of silica and other mineral compounds (Nugroho *et al.*, 2023). When subjected to high-temperature calcination, snail shells decompose to form calcium oxide and other stable oxide phases, producing snail shell ash that can serve as reinforcement particles in aluminiums composites. Snail shell ash has attracted attention as a reinforcement material in metal matrix composites due to its low cost, availability, and environmentally friendly nature. The ash contains calcium-based compounds that can improve hardness, wear resistance, and microstructural stability while simultaneously providing a sustainable route for recycling agricultural waste (Adepitan *et al.*, 2025; Kishore *et al.*, 2026; Igwe *et al.*, 2025-3). The performance of aluminium–SSA composites depends largely on the fabrication method used to incorporate the reinforcement particles into the metal matrix (Kishore *et al.*, 2026; Zhang *et al.*, 2024). Among the various fabrication techniques available (Igwe *et al.*, 2025-4; Igwe *et al.*, 2025-5), stir casting is one of the most widely adopted methods due to its simplicity, low cost, and suitability for mass production (Sankhla *et al.*, 2022; Udensi *et al.*, 2024). The stir casting process involves mechanical stirring of reinforcement particles into molten aluminium to achieve uniform dispersion before casting into moulds. Proper control of stirring parameters and particle preheating is essential to prevent particle agglomeration and ensure good interfacial bonding between the matrix and reinforcement (Raj *et al.*, 2024). This study focuses on the development of aluminium metal matrix composites reinforced with snail shell ash using the stir casting method. The aim of the research is to evaluate the influence of SSA reinforcement on the microstructure and mechanical properties of aluminium composites and to assess the potential of snail shell ash as a sustainable reinforcement material for engineering applications. This study investigates the production of lightweight aluminium matrix composites reinforced with snail shell ash (SSA), using a liquid metallurgy technique, specifically stir casting. The research examines the influence of SSA reinforcement on the microstructural characteristics and mechanical properties of the aluminium matrix. Furthermore, the study evaluates the feasibility of utilizing snail shell ash as a sustainable, low-cost reinforcement material for engineering applications, contributing to the development of environmentally friendly and resource-efficient composite materials.

2. Methodology

2.1 Sourcing and preparation of materials

The matrix material used in this study was aluminium alloy AA6063, obtained in billets form, from Nigerian Aluminium Extrusion Limited (NIGALEX), Oshodi, Lagos, Nigeria. AA6063 was selected due to its excellent castability, relatively low density (~2.7 g cm^{-3}), high thermal conductivity (~200 W m^{-1} K^{-1}), and favourable mechanical properties, including tensile strength of approximately 250 MPa - depending on temper, and shear strength of about 150 MPa (Ramesha *et al.*, 2025; Mishra *et al.*, 2025; Kula *et al.*, 2024). Snail shells used as reinforcement material were collected from local market, in Owerri, Imo state, Nigeria, before being discarded as waste. Other materials required for the casting process included moulding sand, fluxing agents, and polishing materials used during sample preparation.

2.2 Preparation of Snail Shell Ash

The collected snail shells were thoroughly washed with copious amounts of clean water to remove dirt, organic matter, and other impurities. The shells were subsequently rinsed with deionized water and dried under the sun to remove residual moisture. They were then crushed into smaller fragments, calcined at 700 °C for 2 hours, ground using a hammer mill for 10 minutes, and sieved through a 63 µm sieve in accordance with ASTM E 11-81 (Sheikh *et al.*, 2025).

2.3 Fabrication of AA6063/ SSA Composite

The AA6063/SSA composite was produced using the stir casting technique by applying the rule of mixtures to determine the appropriate proportions of the matrix and reinforcement materials, as expressed in **Eqn. 1:**

$$\rho_c = \rho_m v_m + \rho_r v_r \qquad \textbf{Eqn. 1}$$

The AA6063 melt in the open-hearth furnace was stirred at 300 rpm, a speed suitable for achieving uniform dispersion of the micron-sized SSA particles without causing vortex formation or air entrapment. Stirring was maintained until the reinforcements at weight fractions of 0%, 3%, 6%, 9%, and 12% were fully wetted and evenly distributed throughout the molten matrix. The molten composite was then poured into pre-prepared moulds and allowed to cool and solidify.

2.4 Microstructural Tests

Metallographic optical analysis was performed on the AA6063/SSA composites to examine their microstructures. Sections of the stir-cast specimens were mounted in epoxy resin for easier handling. The mounted specimens were ground sequentially using silicon carbide abrasive papers of progressively finer grit sizes (240, 400, 600, 800, and 1200). The ground surfaces were then polished with alumina suspension to obtain a mirror-like finish and etched in Keller's reagent (95 mL water, 2.5 mL HNO_3, 1.5 mL HCl and 1 mL HF) to reveal the microstructural features of the aluminium matrix. After etching, the specimens were rinsed with distilled water and examined under a metallurgical optical microscope at magnifications of 200× and 500× to observe the grain structure of the aluminium matrix and the distribution of snail shell ash particles within the composite.

2.5 Tensile Tests

The tensile tests of the AA6063/SSA specimens were done in an Instron universal testing machine at $\mathbf{10^3\ s^{-1}}$ strain rate under room temperature conditions. Machined specimens measuring 12 mm in diameter and 60 mm gauge length were tested according to ASTM E8M – 15a (Sheikh *et al.*, 2025). The tensile properties investigated include; ultimate tensile strength, yield strength and fracture strength.

2.6 Hardness Tests

The hardness of the test specimens was determined using an ATI B3000-2 Brinell hardness tester equipped with a 2.5 mm diameter hardened steel ball indenter. A load of 62.5 kgf was applied with a dwell time of 30 seconds to ensure stable deformation, in accordance with ISO 6506/ASTM E10 standard for testing materials with coarse microstructures (Smirnov *et al.*, 2025). The indentation diameter was measured along two perpendicular axes, averaged, and compared with a Brinell hardness (BHN) table to determine the specimen's hardness accurately.

2.7 Wear (Abrasion Tests

The dry sliding wear behaviour of AA6063/SSA cylindrical composite specimens (2 cm thick, 10 cm diameter) was evaluated using 220-grit abrasive paper (Idusuvi *et al*., 2019). The specimens were rotated at 600 rpm under a constant load of 20 N for 600 seconds at room temperature. Initial weights were measured using a high-precision electronic balance (least count 0.0001 g). After testing, the specimens were cleaned with acetone, dried, and reweighed to determine weight loss. Wear rates were calculated from the difference in weight before and after testing.

2.8 Flexural Strength Tests

The flexural strength of the AA6063/SSA composites was determined using a three-point bending test in accordance with ASTM D790 test procedure (Kumar *et al*., 2017). The test specimens measuring 240 mm × 40 mm × 40 mm, were placed on two supports, and a load applied at the midpoint until fracture. The flexural strength (Fs) was calculated using the **Eqn. 2.**

$$F_s = \frac{3FL}{2BD^2} \qquad \text{Eqn. 2}$$

Where F = flexural force at fracture (kN), L = support span length (mm), B = specimen breadth (mm) and D = specimen thickness (mm).

3. Results and Discussion

3.1 Microstructural results

The sectioned AA6063 billet and calcined snail shell ash used in this study are shown in figure 1(A) and figure 1(B) respectively. Also, the stir-cast AA6063 disc (9% SSA) and cylindrical rods (0-. 3-. 6-. 9- and 12 wt % are shown in figure 1(C) and figure 1(D) respectively. The optical micrographs of the AA6063 matrix without (0%) and with SSA reinforcements (3%, 6%, 9% and 12%) are respectively shown in figure 2(A - E) at 500× magnification. Figure 2(A) shows that the matrix has homogeneous microstructure with minimal presence of second-phase particles, consistent with the microstructure expected for as-cast AA6063 alloys. The absence of reinforcement results in unrestricted grain growth during solidification (Chandrashekar *et al.*, 2009). With 3% SSA (figure 2B) reinforcement of AA6063, a noticeably good interfacial bonding between the matrix and reinforcement is observed. The presence of these particles provides heterogeneous nucleation sites during solidification, leading to partial grain refinement compared with the control sample (Greer *et al.*, 2016).

The specimen with 6% SSA reinforcement (figure 2C) shows existence of voids and SSA particles agglomeration, particularly at the grain boundaries. These agglomerates may be due to inadequate wetting or insufficient stirring during composite fabrication, resulting in localized particle segregation. While the presence of reinforcement contributes to strengthening, excessive agglomeration may lead to localized stress concentration sites within the matrix (Ali *et al.*, 2020).Figure 2(D and E) are the micrographs of 9% and 12% SSA reinforcements respectively. Figure 2(D) shows that the SSA particles were homogeneously dispersed, with minimal void in the specimen, while figure 2(B) shows SSA particle agglomeration and moderate grain refinement at the grain boundaries. The improved distribution of reinforcement particles noticed in figure 2(D) promotes better load transfer between the matrix and the reinforcement phase (Greer *et al.*, 2016; Ali *et al.*, 2020). Such microstructural characteristics are generally associated with enhanced mechanical properties, including increased hardness and improved wear resistance.

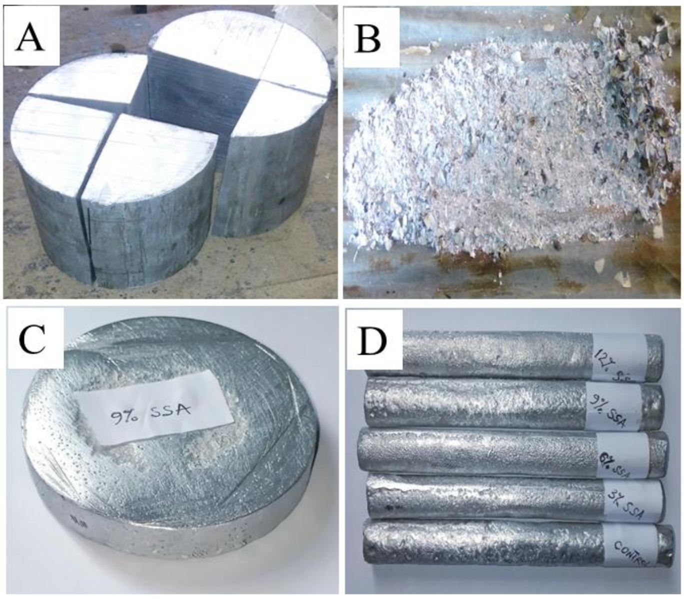

Figure 1. (A) Sectioned AA6063 billet and **(B)** calcined snail shell used this study. **(C)** The as-produced stir-cast AA6063/SSA composite disc (10 cm diameter and 2 cm height) and **(D)** the as-produced stir-cast AA6063/SSA cylindrical rods (1.5 cm diameter and 15 cm height)

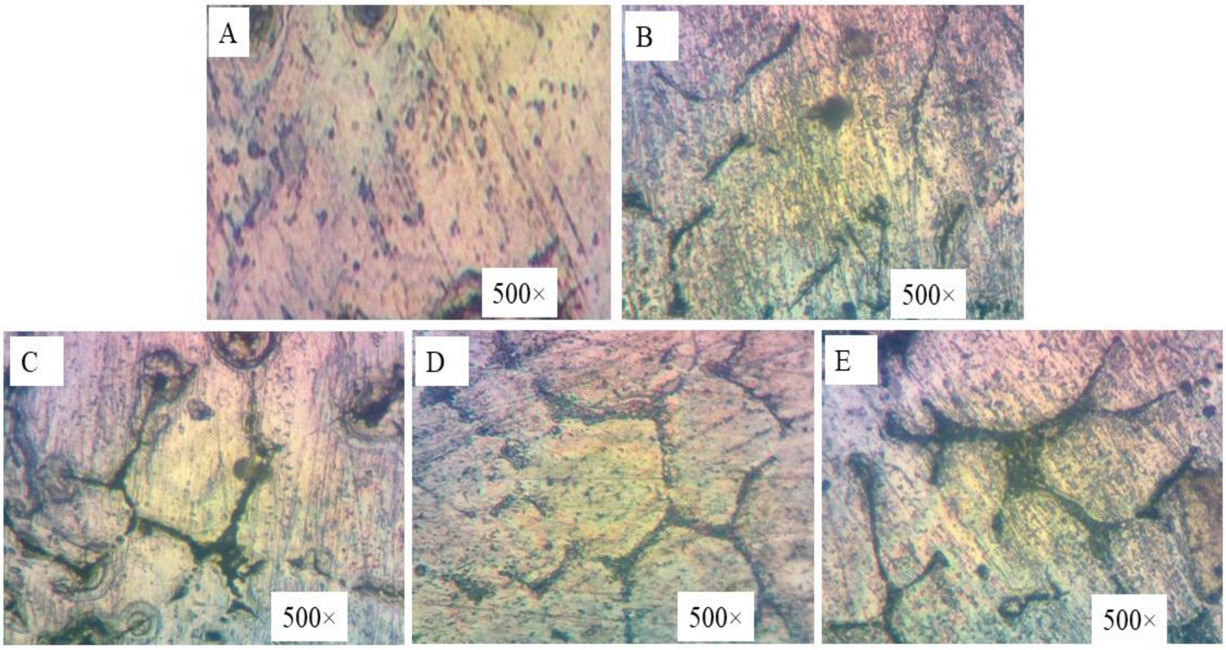

Figure 2. The optical micrographs of **(A)** the unreinforced AA6063 matrix and the reinforced AA6063 matrix with **(B)** 3% SSA, **(C)** 6% SSA, **(D)** 9% SSA, and **(E)** 12% SSA

Overall, the addition of SSA to AA6063 modified the microstructure through particle-induced grain refinement and reinforcement dispersion. However, the effectiveness of the reinforcement depends strongly on the uniformity of particle distribution. Regions with well-dispersed SSA particles exhibit improved structural integrity, while areas with particle agglomeration may adversely affect the composite's mechanical performance.

3.2 Tensile results

The tensile test results of the unreinforced AA6063 and SSA reinforced AA6063 matrix specimens are tabulated in Table 1 and illustrated in Figure 3 and Figure 4.

Table 1. Tensile Properties of the stir-cast AA6063/SSA composites with varying SSA reinforcements.

SSA (wt.%)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Fracture Strain (mm/mm)
0%	92 ± 3	35 ± 2	0.055 ± 0.003
3%	95 ± 3	38 ± 2	0.055 ± 0.002
6%	97 ± 3	42 ± 2	0.065 ± 0.003
9%	99 ± 4	50 ± 3	0.095 ± 0.004
12%	96 ± 4	45 ± 3	0.060 ± 0.003

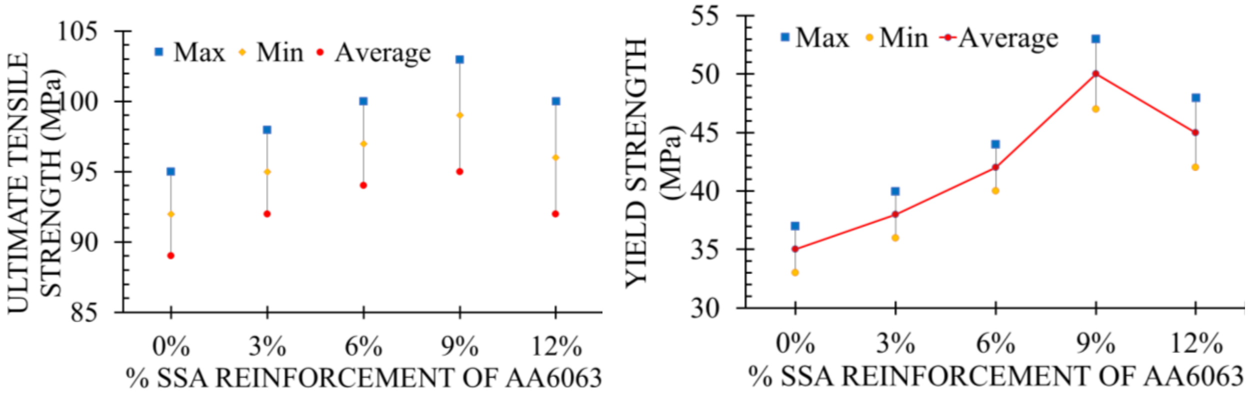

Figure 3. Ultimate tensile strength (MPa) versus %SSA weight contents (right) and Yield strength (MPa) versus %SSA weight contents (left) of the stir-cast AA6063/SSA composites.

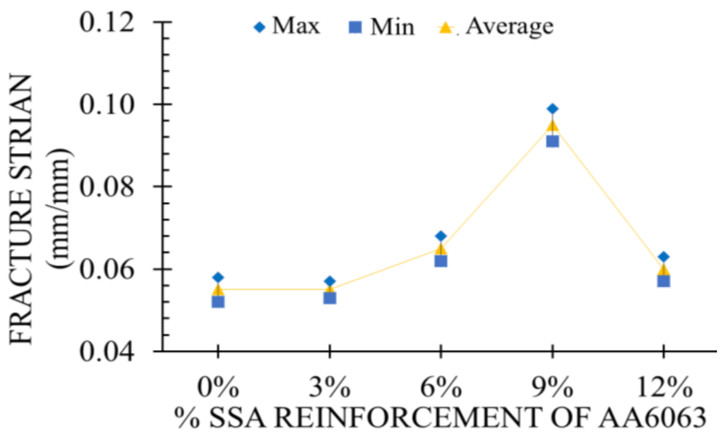

Figure 4. Variation of fracture strain (mm/mm) with %SSA weight contents of the stir-cast AA6063/SSA composites.

The test results were taken in triplicates and showed an increased tensile strength, yield strength and fracture strength with SSA addition up to 9%, followed by a slight decrease at 12%. The 3% SSA composite exhibited moderate yield strength (38 MPa) and ultimate tensile strength (95 MPa) with reasonable ductility (fracture strain ~0.055 mm/mm) (Schmidt *et al.*, 2018). Integration of 6% and 9% SSA significantly improved mechanical performance, with the 9% SSA composite achieving the highest UTS (99 MPa) and fracture strain (0.095 mm/mm), indicating optimal load transfer between the aluminium matrix and the SSA (Garces *et al.*, 2007). The depression in mechanical performance at 12% SSA loading is thought to be due to increased porosity or casting defects.

3.3 Hardness results

The Brinell hardness results obtained from the tests are shown in table 2 and illustrated in figure 5. The results show increasing Brinell hardness number (BHN) with increasing SSA weight percent, which peaked at 95.10 HBS 2.5/62.5/30 at 9 wt.% SSA and dropped to 76.03 HBS 2.5/62.5/30 at 12 wt.% SSA.

Table 2. Brinell hardness numbers of the stir-cast AA6063/SSA Composites with varying SSA weight contents.

SSA (wt. %)	Diameter of Indentation (mm)	Brinell Hardness Number (BHN)
0	0.978	81.17
3%	0.952	85.10
6%	0.931	89.10
9%	0.903	95.10
12%	0.997	76.03

This improvement can be attributed to the reduction in the number of pores present with increased SSA addition (Imran *et al.*, 2016). During indentation, the reinforcement particles helped in resisting localized deformation, thereby increasing the resistance of the material to penetration. At 12 wt.% SSA increased agglomeration and lack of proper SSA wetting lead to the reduced value (Tran *et al.*, 2011).

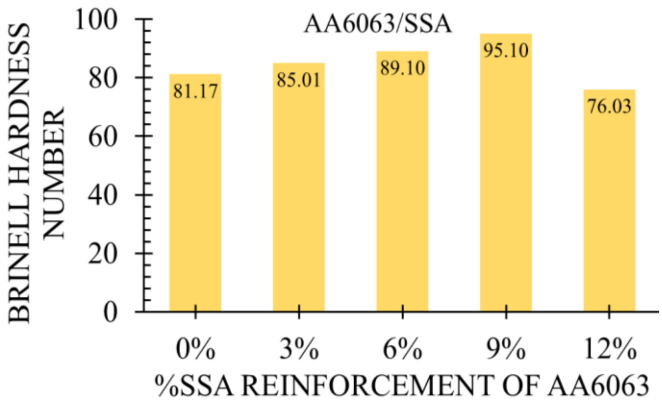

Figure 5. Variation of Brinell hardness number with %SSA weight contents of the stir-cast AA6063/SSA composites.

3.4 Wear (Abrasion) results

The wear characteristics of the AA6063/SSA composites with varying SSA content (0–12 wt.%) are presented in Table 3. The wear results show that SSA addition significantly influences the tribological performance of the composite. The unreinforced AA6063 exhibited a wear volume of 47.4 mm^3 and wear rate of 0.0251 mm^2/Nm. With increasing SSA content from 3 to 9 wt.%, the wear volume and wear rate progressively decreased, reaching optimum values at 9 wt.% SSA, with the lowest wear volume (40.4 mm^3) and wear rate (0.0215 mm^2/Nm), which corresponds to the highest wear resistance of 46.6 Nm/mm^2. This improvement is attributed to enhanced load-bearing capacity and resistance to material removal provided by the reinforcing SSA particles (Bhushan *et al.*, 2003). However, at 12 wt.% SSA, wear performance deteriorated due to possible particle agglomeration and weak AA6063 matrix–reinforcement bonding, resulting in increased wear (Fukuchi *et al.*, 2022). These results corroborate the previously mentioned hardness data.

Table 3. Wear test results of the stir-cast AA6063/SSA composites showing weight loss, wear volume, wear rate, and wear resistance at varying SSA weight reinforcements.

SSA	Weight			Wear		
(wt%)	Initial (g)	Final (g)	loss (g)	volume (mm^3)	rate (mm^2/Nm)	resistance (Nm/mm^2)
0	440.3	439.9	0.1577	47.4	0.0251	39.8
3	308.6	308.5	0.1519	45.2	0.0240	41.7
6	318.5	318.4	0.1465	43.2	0.0229	43.7
9	261.5	261.4	0.1392	40.4	0.0215	46.6
12	206.9	206.8	0.1665	50.6	0.0268	37.3

3.5 Flexural strength results

The flexural strength of the stir-cast AA6063/SSA composites as shown in figure 6 increases with SSA reinforcement from 146.67 MPa (0 wt.%) to a maximum of 159.16 MPa (9 wt.%) before dropping to 142.22 MPa (12 wt.%). The improvement up to 9 wt.% is attributed to effective load transfer, dislocation hinderance at the grain boundaries, and possible grain refinement due to well-dispersed SSA particles (Raj *et al*., 2023). This indicates that 9 wt.% represents an optimal reinforcement level with a favourable balance between matrix continuity and particle distribution.

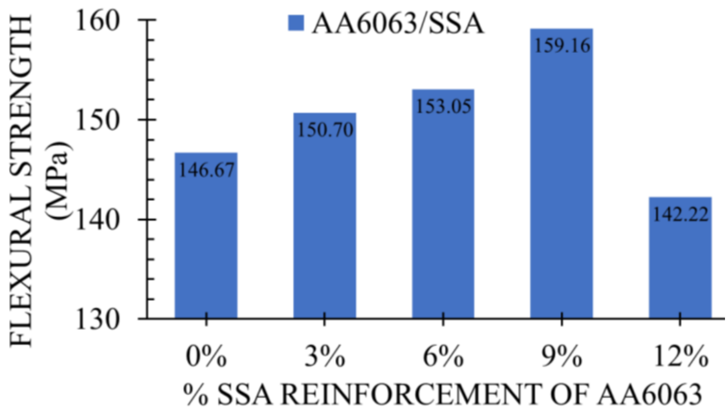

Figure 6. Variation of flexural strength with %SSA weight content of the stir-cast AA6063/SSA Composites.

However, at 12 wt.% the reduction in flexural strength is likely due to particle agglomeration, increased porosity, and weakened interfacial bonding (Saravanakumar et al., 2018). Consequently, the mechanical response transitions from a strengthening-dominated regime to a defect-dominated regime at higher SSA contents.

3.6 Anova analysis

Statistical validation of the experimental tests was performed using single-factor ANOVA (Sudha *et al*., 2019) to evaluate the effect of SSA reinforcement on AA6063 composites' mechanical and wear properties. The results showed that at least one reinforcement group differed significantly in all the tested properties, as $F_{calculated}$ exceeded $F_{critical}$ (Santa Rosa *et al*., 2025), except for the ultimate tensile strength, where no significant difference was observed. Enhancements were noticed in flexural strength, Brinell hardness, fracture strain, yield stress, and wear peaked at 9 wt.% SSA, with a slight decline at 12 wt.%, while differences between 3 and 6 wt.% were negligible. The unchanged ultimate tensile strength across 3 - 12 wt.% suggests that improving tensile strength may require compromises that could influence other AA6062/SSA composites' properties (Miller *et al*., 2002).

Conclusion

AA6063 composites reinforced with snail shell ash (SSA) were successfully fabricated via stir casting, demonstrating SSA as a sustainable, low-cost reinforcement. Microstructural analysis showed grain refinement and good particle-matrix bonding at 9 wt.% SSA, while 12 wt.% loadings led to agglomeration and porosity. Mechanical properties - including tensile strength, hardness, wear resistance, and flexural strength - improved with SSA addition up to 9 wt.% and declined at 12 wt.% due to defects. The statistical analysis confirms that SSA reinforcement significantly influences most mechanical and wear properties of AA6063/SSA composites, with optimal performance achieved at 9 wt.% reinforcement, except that of UTS. The absence of significant improvement in UTS across all reinforcement levels suggests that application of this material should be where its not subjected to tensile loading. Overall, 9 wt.% SSA provides the optimal balance between reinforcement and matrix integrity for enhanced composite performance.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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