

Comparative Analysis on The Mechanical Properties and Microstructure of Al-Mg-Si Composites Reinforced with Groundnut Shell Ash, Palm Kernel Shell Ash, Avocado Pear Seed Ash and Alumina Particles

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Abstract: This study looks at the mechanical properties and microstructural aspects of Al-Mg-Si alloy matrix composites that are reinforced with Groundnut Shell Ash (GNSA), Palm Kernel Shell Ash (PKSA), Avocado Pear Seed Ash (APSA), and aluminium oxide (Al_2O_3) particles. The composites were fabricated using stir casting and analyzed for porosity, hardness, tensile properties, and fracture behaviour. The percentage porosities increased for all reinforcements, with APSA showing the highest (31.1% increase) and PKSA the lowest (18.1% increase), while all values stayed within the acceptable limit for cast aluminium. Significant enhancements in hardness were observed, particularly in GNSA-reinforced composites (43.1% increase), confirming improved wear resistance. Al_2O_3 exhibited the most significant improvement in ultimate tensile strength (39.2% increase), succeeded by PKSA (30.0% increase), demonstrating successful reinforcement. The specific strength reached its zenith with Al_2O_3 reinforcement (60.1% increase), underscoring its exceptional load-bearing capability. In contrast, ductility, shown by strain to fracture, decreased in Al_2O_3 (57.98% decrease) but dramatically increased with GNSA (80.8% increase) and APSA (69.8% increase), demonstrating enhanced energy absorption in agro-based composites. Fracture toughness significantly diminished in all samples, especially in APSA (274.3% decrease) and Al_2O_3 (136.6% decrease), indicating increased brittleness due to the reinforcements. SEM examination demonstrated uniformly distributed particles throughout all matrices, reducing clustering and enhancing consistent mechanical performance. Agro-waste reinforcements exhibited commendable efficacy in improving mechanical properties while minimizing environmental impact; however, compromises in toughness should be acknowledged in design considerations.

Keyword: Al-Mg-Si alloy; AA6061; groundnut shell ash; palm kernel shell ash; Avocado pear seed ash and alumina

I. Introduction

The demand for lightweight materials, particularly aluminium, has increased due to their energy-saving properties. However, traditional methods for increasing aluminium strength have limitations. Metal matrix composites (MMCs) offer superior tensile strength, wear resistance, and resistance to corrosion and heat effects. These composites can reduce thermal expansion, increase hardness, and reduce weight, making them ideal for applications in automotive and other fields. MMCs, which incorporate non-metallic reinforcements, offer enhanced thermal conductivity, abrasion resistance, creep resistance, and dimensional stability, demonstrating superior efficacy at elevated temperatures [1-9].

Chandla *et al.* (2020), study aimed to create a lightweight metal matrix composite using Al 6061 as the matrix and alumina and bagasse ash as reinforcements. The hybrid reinforced metal matrix composite (HRMMC) showed significant improvements in mechanical properties, including compressive strength, hardness, and tensile strength, compared to the single reinforced metal matrix composite (SRMMC). The composite's density was found to be inferior to SRMMC, but it showed increased porosity with increasing reinforcement weight [10].

Dwivedi *et al.* (2020), looked into using waste spent alumina catalyst and agro-waste rice husk ash as reinforcement materials along with scrap aluminium alloy wheel matrix. The findings of their investigation indicated that the RHA and SAC were homogeneously dispersed within a recycled aluminium alloy matrix, as per microstructural behavior. RHA and SAC were simultaneously employed as reinforcing agents in the matrix material of SAAWs to enhance mechanical properties, including hardness, ductility, compressive strength, and tensile strength [11]. The effects of agricultural waste RHA and SAC on recycled aluminium alloy were assessed by thermal expansion behavior, soil degradation tests, and corrosion loss observations.

“A systematic review of the mechanical parameters (tensile strength and modulus, flexural strength and modulus, impact strength, and hardness) of metal matrix composites” was conducted by [12]. This encompasses the processing methods, reinforcement mechanisms, and applications of MMCs, along with suggestions for future study and challenges. The mechanical performance of MMCs is significantly influenced by the characteristics of the reinforcement and matrices, interfacial bonding, particle dispersion

within the matrix, particle morphology and dimensions, particle volume fraction, and processing techniques. This review analysis demonstrates that MMCs provide significant potential for effectively addressing present and future demands [12].

Gupta and Gupta (2020), investigated the mechanical performance of single reinforced metal matrix composites and monolithic Al alloys utilizing a hybridization approach. Gupta and Gupta (2020), found that hybrid composites with micro-particles had better tensile, flexural, and hardness properties, as well as less impact energy and porosity, than Al alloy and single reinforced metal matrix composites. The hybrid composite (B50A50) had the maximum tensile strength and modulus, surpassing the Al alloy by 40% and 52.12%, respectively [13]. Furthermore, in comparison to the Al alloy, the composite B50A50 exhibited a 105.72% enhancement in flexural strength and a 23.88% reduction in impact energy [13]. Applications for the presently developed hybrid metal matrix composites encompass components for construction and vehicles [13].

“The processing and performance assessment of agro-waste reinforced bio-based epoxy hybrid composites” was examined by [14]. The mechanical properties of the manufactured composites were influenced by the structure (coarser or finer) of the fillers and their chemical makeup. The mechanical analysis of the composites indicated that the inclusion of wood apple shell fillers led to the highest increases in tensile strength (23.97%), impact strength (16.81%), and interlaminar shear strength (31.64%). Conversely, the addition of pine cone fillers resulted in the greatest enhancement of flexural strength, as well as Young’s modulus (35.4%) and flexural modulus (32.81%) [14]. The addition of both types of fillers resulted in a decrease in moisture absorption up to a specific filler loading, and the studies indicated a significant improvement in the mechanical and physical properties of the produced composites when reinforced with micron-sized fillers [14].

“The morphological and mechanical characterisation of Al-4032/granite powder composites” was examined by [15]. The morphological analysis of the composites indicates that the reinforcing particles (GP) are nearly equally dispersed inside the matrix phase. The mechanical properties of the AMCs are superior to those of the unreinforced alloy [15]. The manufactured Al-4032-GP composites are anticipated to be advantageous for automotive components such as pistons, disc brakes, high-speed equipment, and high-speed rotating elements, among others.

A thorough examination was conducted on “sophisticated natural fibre-based entirely biodegradable and renewable composites and nano-composites” by [16]. Naghdi (2021) noted that the composites exhibited distinctive combination features of bio-fibres and offered this novel class of bio-composites as a versatile alternative to existing petrochemical composite materials. Significant efforts are currently being made to leverage the synergistic effects of integrating natural reinforcements with plant-derived polymers for the development of high-performance green composites and nanocomposites [16].

“Research on the microstructural evolution and mechanical properties of innovative Al 6061/7075–granite–SiC metal matrix composites, produced using two-stage stir casting”, was conducted by [17]. The microstructural characterization, encompassing optical microscopy (OM), scanning electron microscopy (SEM), and X-ray diffraction (XRD), corroborates the existence of grain refinement and microstructural strain in the composites [17]. The tensile strength, hardness, impact energy, and wear resistance of the composites highlight their superior performance; SEM-based fractography analysis of tensile and impact test specimens identified dimples, cleavage facets, river lines, intergranular cracks, and disbonding, providing critical insights into the failure mode [17]. Moreover, the degraded surfaces displayed wear mechanisms of abrasion and adhesion-delamination; the incorporation of granite particles as reinforcement in these composites led to markedly enhanced properties, establishing them as a viable alternative for future sustainable materials [17].

“A review of advancements in bulk functionally graded composite materials” was conducted by [18]. They noted that functionally graded composite materials (FGCM) are sophisticated composites characterized by a gradient in composition and microstructure along a single direction; due to their graded structure, FGCMs provide a combination of properties unattainable in monolithic materials [18]. They exhibit potential applications across several advanced domains and have thus garnered significant scientific interest [18].

“The effects of strengthening cowpat ash with aluminium composites” were examined in experimental investigations by [19]. Varun *et al.* (2022), discovered that at 6% CPA, the characteristics of the composite materials had improved. The hybrid reinforced composites (HRC) were produced with a constant 6% CPA, while the TiB₂ content was changed at 2, 4, and 6 weight percentages. Analysis revealed that at 6% CPA and 4% TiB₂, the characteristics of aluminium 7075 were improved, and the optical microstructure, SEM with EDAX, and XRD for SRC and HRC demonstrated a uniform distribution of reinforcements and their presence in the matrix, respectively. The density of both SRC and HRCs has diminished, while porosity has escalated with a rise in reinforcing percentage. The hardness has risen by 18.18% for SRC and 34.54% for HRC, while the tensile strength has grown by 14.28% for SRC and 29.67% for HRC [19]. The impact strength has diminished by 31.25% for SRC and 43.75% for HRC. The flexural strength has risen by 7.54% for SRC and 15.09% for HRC; the fracture SEM pictures revealed cracks, voids, and dimples in the tensile and impact specimens of the produced samples [19].

“The influence of using spent alumina catalyst and date palm fiber ash on the production of aluminium-based composites” was examined by [20]. They asserted that the composite can be employed in the vehicle industry, as the results demonstrate enhanced mechanical qualities and less corrosion. Verma *et al.* (2023), noted that the incorporation of 1.25% SAC and 6.25% carbonized palm fiber (CDPF) particles into scrap aluminium resulted in substantial enhancements in mechanical properties such as tensile strength, hardness, and toughness. A comparative comparison with the basic material indicates improvements of around 20.82%,

33.11%, and 22.72% in tensile strength, hardness, and toughness, respectively. Furthermore, a decrease in composite elasticity was noted by [20]. The SEM and EDX analyses reveal a homogeneous microstructure in the composite material. Corrosion investigations demonstrate that the incorporation of SAC and CDPF significantly reduces the annual corrosion rate [20].

The reinforcing elements employed in AA6061-based matrix composites typically include synthetic ceramics such as SiC, Al₂O₃, TiB₂, TiO₂, B₄C, TiC, ZrO₂, boron, and graphite to attain various characteristics. Nonetheless, synthetic ceramic reinforcements are costly and possess high density, hence constraining the utilization of AMMCs reinforced with synthetic ceramic materials in applications necessitating lightweight and high strength [21 - 23].

In aluminium-inclusive composites, substantial matrix hardening can influence the final properties, rendering the product more brittle and challenging to manipulate, which leads to work hardening and elevated tangential stresses, hence enhancing friction and wear characteristics [23]. These distinctive characteristics have unexpectedly rendered aluminium-based composites an intriguing material. Their qualities were initially examined as an aluminium alloy due to the alloying elements' significant ability to adhere to oxygen molecules on their surfaces, hence reducing crack initiation and propagation. This alloy may be produced economically through plastic deformation, and depending on its preparation, it can achieve heat-treatable combinations of enhanced tensile strength, yield strength, and fatigue resistance, along with a favorable material damping ratio [24].

In recent decades, the rising demand for lightweight and high-strength materials in engineering applications has established metal matrix composites (MMCs) as superior alternatives to conventional materials, owing to their exceptional properties, including a high strength-to-weight ratio, elevated strength and stiffness, superior thermal conductivity, and a low coefficient of thermal expansion [24].

II. Materials and Methods

A. Materials

This study utilized Al-Mg-Si alloy as the matrix material, with groundnut shell ash (GNSA), palm kernel shell ash (PKSA), avocado pear seed ash (APSA), and alumina (Al₂O₃) particulates serving as the reinforcing elements. Table 1 displays the chemical composition of the Al-Mg-Si alloy.

Table 1: Chemical composition of the Al-Mg-Si alloy matrix

Element	Ti	Mn	Zn	Cr	Cu	Fe	Si	Mg	Others	Al
%	0.02	0.08	0.11	0.19	0.25	0.35	0.6	1.0	≤ 0.15	97.25

B. Experimental Methods

1) Groundnut shell, palm kernel shell, avocado pear seed collection and preparation

Following a two-week period of washing with warm water and sun-drying, the collected groundnut shells (GNS), palm kernel shells (PKS), and avocado pear seeds (APS) were processed into a fine powder utilizing a locally constructed grain grinding machine. One thousand grams of powdered GNS, PKS, and APS were placed in batches into a muffle furnace and ashed for one hour at 500 °C for GNS and APS, and for one hour and fifteen minutes at 550 °C for PKS. The temperature and duration for the ashing process were determined through multiple trials to ensure complete ash formation and the preservation of a single-phase material. The optimal ashing conditions for GNS and APS were observed at 500 °C for one hour, while PKS was optimal at 550 °C for one hour and fifteen minutes. Ashing was conducted at temperatures of 450 °C, 500 °C, 550 °C, and 600 °C for durations of 45 minutes, one hour, one hour and fifteen minutes, and one hour and thirty minutes [24].

2) Production of composites using stir casting technique

The composites were fabricated using a two-step stir casting technique. Prior to this process, charge calculations were conducted to ascertain the quantities of GNSA, PKSA, APSA, and alumina particles needed at intervals of 2.5% from 0% to 10% for each component, with the Al-Mg-Si alloy matrix constituting the remaining weight percentage. The melting of the Al-Mg-Si alloy occurred in an electric resistance furnace at approximately 750°C, exceeding the alloy's liquidus temperature. The liquid alloy was subsequently permitted to cool to a semi-solid state at approximately 600°C. Subsequently, reinforcement particulates of GNSA, PKSA, APSA, and alumina, preheated in an oven at 250°C, were manually stirred into the melt with a steel stirring rod for 2 to 3 minutes, as per references [24, 25]. The composite slurry was superheated to 750°C ± 30°C to enhance fluidity, followed by a manual stirring cycle lasting 2 to 4 minutes. Subsequently, it was cast into permanent cylindrical molds measuring 200 mm in length and 16 mm in diameter, which had been preheated. Figures 1(a) and (b) illustrate representative cast composites and a mild steel permanent mould, respectively.



Figure 1. (a) As-cast Al-Mg-Si/GNSA composites, (b) Fabricated permanent mould [24, 26]

The temperature and holding time parameters in the stir casting of Al-Mg-Si alloy composite reinforced with GNSA, PKSA, APSA, and alumina particles were meticulously regulated to ensure the production of high-quality composite material. An optimal temperature of $750^{\circ}\text{C} \pm 30^{\circ}\text{C}$ and a holding time of 9 to 14 minutes were maintained to ensure good wettability, even distribution of GNSA, PKSA, APSA, and alumina particles, sufficient fluidity, and improved mechanical properties of the final composite, as similarly noted by [27, 28]. A suitable process temperature guarantees that the molten metal maintains adequate fluidity for effective mixing and dispersion of GNSA, PKSA, APSA, and alumina particles. Exceeding $750^{\circ}\text{C} \pm 30^{\circ}\text{C}$ may adversely affect the mechanical properties of the composite, as it can result in oxidation of the molten metal and degradation of the reinforcement particles, as noted by [27]. The holding time, defined as the duration during which the molten metal is maintained at the processing temperature prior to casting, ensures proper mixing and dispersion of GNSA, PKSA, APSA, and alumina particles, as well as a uniform distribution of reinforcement within the matrix, provided that it is sufficient. Excessive holding time may result in the reinforcement settling at the bottom of the crucible, leading to non-uniform distribution and inferior mechanical properties, as noted by [28, 29].

3) Determination of percentage porosity of the Al-Mg-Si/GNSA; Al-Mg-Si/PKSA; Al-Mg-Si/APSA; and Al-Mg-Si/ Al_2O_3 composites

The measured weight of the test samples was divided by their measured volume to ascertain the experimental density of each grade of composite generated [24, 26]. The comparison of experimental and theoretical densities for each composite composition provided the foundation for determining the % porosity, utilizing Eq (1) for the calculations [30, 31, 32].

$$\text{percentage porosity} = \left(\frac{\rho^T - \rho^{EX}}{\rho^T} \right) * \frac{100}{1} \quad \text{Eq. (1)}$$

Where ρ^T = Theoretical density and ρ^{EX} = Experimental density.

C. Mechanical analysis of the composites

The developed composite samples, together with the control sample, underwent a series of mechanical tests, including hardness, tensile strength, and fracture toughness, using various machines.

1) Hardness measurement of the produced composites

The hardness of the composites was evaluated using a hardness testing instrument applying a substantial load of 100 kgf and a 1.59mm indenter on the Rockwell B (HRB) hardness scale. Testing and sample preparation were conducted in accordance with the ASTM E18-20 standard. Smooth, plane-parallel surfaces of the samples were prepared for testing, and a direct force of 100 kgf was applied for a dwell time of ten seconds to create an indentation. Five hardness indents were measured for each sample, and the average hardness values for each composite composition were calculated from these readings, with a margin of $\pm 2\%$ [32].

2) Tensile test of the produced composites

The electromechanical-computerized model 3369K1781, a universal testing device with a capacity of 50 KN (1125 lb), was employed to evaluate the tensile properties of the manufactured composites. The composite test samples were machined to dimensions of 4 mm gauge diameter, 6 mm grip diameter, 5 mm grip length, and 30 mm gauge length. The samples were secured to the testing platform with clamps and subjected to tensile stress until they broke at a strain rate of 10^{-4} s^{-1} , in accordance with usual procedure. To guarantee the validity and consistency of the test results, three duplicate tests were conducted for each composite composition [32]. The tensile parameters assessed included ultimate tensile strength, specific strength, and strain to fracture.

3) Fracture toughness of the produced composites

Tensile tests on circumferential notch test (CNT) specimens were conducted to assess the fracture toughness values of the composites, adhering to the detailed standards outlined in [34, 35]. The composite test samples exhibited the following dimensions: notch diameter of 4.2 mm, notch angle of 60° , gauge diameter of 5 mm, grip length of 5 mm, grip diameter of 6 mm,

and gauge length of 30 mm. The notched samples were subjected to tensile testing using a universal device until they fractured in tension mode at a strain rate of 10^{-3} s^{-1} . The fracture loads (P_f) obtained from the load-extension plots of the CNT samples, according to the empirical relationship in [36], were utilized to evaluate the fracture toughness Eq. (2).

$$K_{1C} = \frac{P_f}{D^{3/2} [1.72(\frac{D}{d}) - 1.27]} \quad \text{Eq. (2)}$$

where D and d stand for the unnotched and notched diameters of the CNT samples, respectively. The following was established as the plane strain condition required for a suitable estimation of fracture toughness using the relationship in Eq. (3), [34, 37]:

$$D \geq \left(\frac{K_{1C}}{\sigma_y} \right)^2 \quad \text{Eq. (3)}$$

Furthermore, throughout the machining process, it was necessary to ensure that the length of the CNT specimens was a minimum of $4D$. Three replicate tests were conducted for each composite composition to verify the accuracy of the gathered data [34].

D. Microstructural evaluation

A JSM 7600F Jeol ultra-high resolution field emission gun scanning electron microscope (FEG-SEM) equipped with an energy dispersive spectrometer (EDS) was employed to meticulously analyse the microstructural features and qualitative elemental composition. [24]

III. Results and Discussion

The outcomes of the % porosity, mechanical properties, and SEM analysis of the fabricated composites and the Al-Mg-Si alloy are illustrated in Figures 1 through 12 and examined.

A. Percentage porosity of the produced composites

Figure 1 illustrates the percentage porosity of the fabricated composites and Al-Mg-Si alloy.

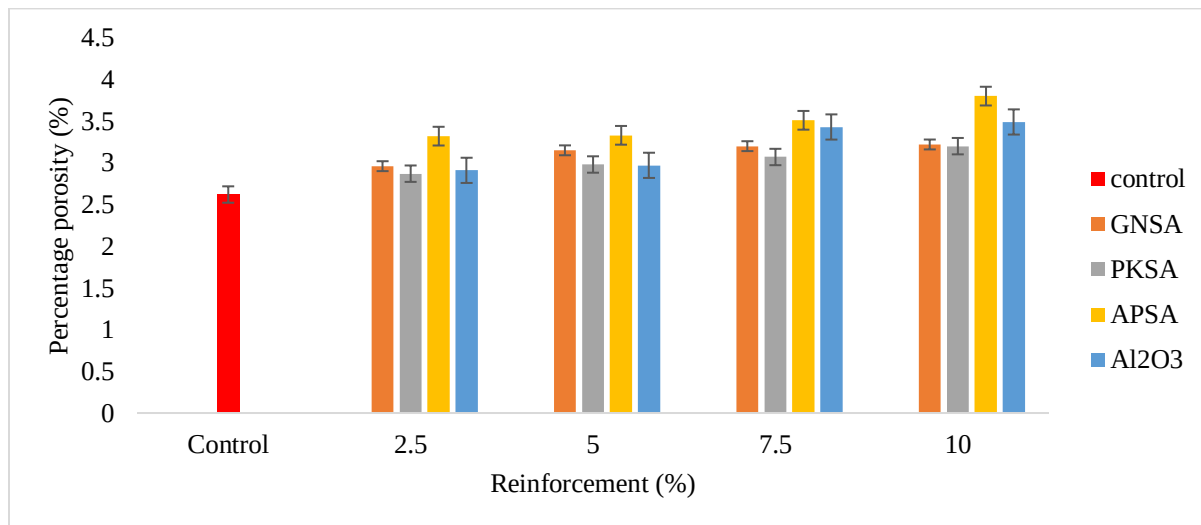


Figure 1: Percentage porosity of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al₂O₃ composites

According to Figure 1, the control exhibits the lowest porosity owing to the absence of foreign particles (reinforcement) and minimal gas trapping. In all reinforced composites, porosity escalates with a higher percentage of reinforcement, attributed to poor wettability of reinforcements, particle agglomeration at elevated weight percentages, and gas entrapment during solidification. The APSA-reinforced Al-Mg-Si alloy composite consistently exhibits the largest porosity, which increases more sharply with reinforcement. This may indicate inadequate dispersion or bonding of APSA particles, as well as a more irregular morphology. The Al₂O₃ (ceramic) reinforced Al-Mg-Si alloy composite consistently exhibits the lowest porosity among the reinforced samples, possibly attributable to enhanced particle stability, cleaner interfaces, and a more uniform particle morphology. The GNSA reinforced Al-Mg-Si alloy composite and the PKSA reinforced Al-Mg-Si alloy composite exhibit intermediate characteristics, with PKSA demonstrating marginally larger porosity than GNSA at elevated weight percentages. The implications of Figure 1 indicate that Bio-ash reinforcements (GNSA, PKSA, and APSA) generally enhance porosity to a greater extent than ceramic (Al₂O₃) reinforcement. The increase in porosity is directly related to the percentage of reinforcement, and above a threshold of 5–7.5%, dispersion may deteriorate and gas trapping may increase. For applications necessitating minimal porosity and enhanced mechanical integrity, Al₂O₃ reinforced Al-Mg-Si alloy composite is optimal. The GNSA reinforced Al-Mg-Si alloy composite represents the optimal balance for porosity when utilising bio-based ashes for sustainability or cost considerations.

B. Hardness of the produced composites

The hardness of the produced composites and Al-Mg-Si alloy is presented in Figure 2.

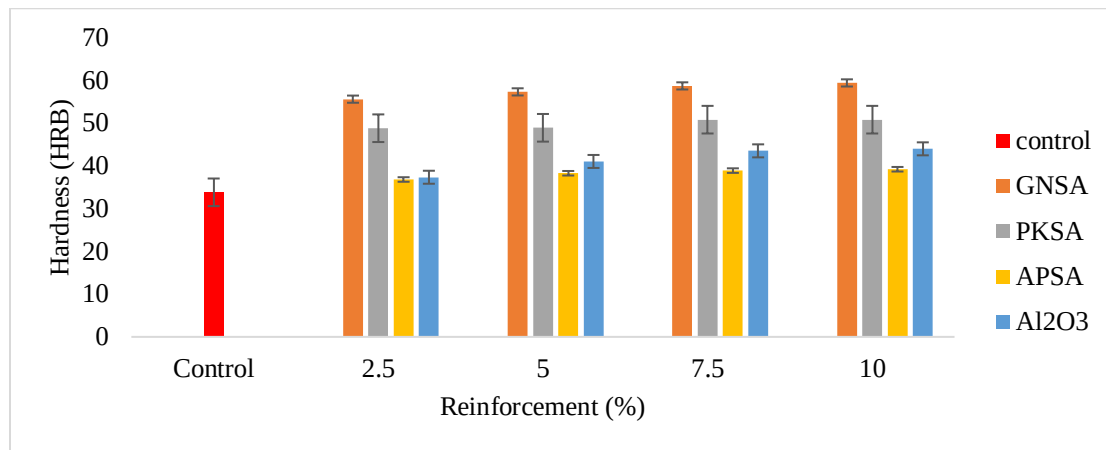


Figure 2: Hardness of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al₂O₃ composites

Figure 2 indicates that the hardness of the control is 33.81 HRB, which is anticipated for unreinforced Al-Mg-Si alloy and serves as the benchmark for assessing composite enhancements. All composites depicted in Figure 2 exhibit enhanced hardness with increased reinforcement weight percentage, attributable to the load-bearing capacity of reinforcement particles and the obstruction of dislocations. The GNSA (Groundnut Shell Ash) reinforced Al-Mg-Si alloy composite exhibits the highest hardness value among all reinforcement levels, indicating robust matrix-particle bonding and a significant hardness contribution from the ash particles, likely due to superior particle distribution compared to others. The PKSA reinforced Al-Mg-Si alloy composite exhibits the second highest hardness across all levels. It is more effective than APSA reinforced Al-Mg-Si alloy composite and Al₂O₃ reinforced Al-Mg-Si alloy composite, however marginally inferior to GNSA reinforced Al-Mg-Si alloy composite, suggesting moderate reinforcing quality and dispersion. The APSA (Avocado Pear Seed Ash) reinforced Al-Mg-Si alloy composite exhibits the lowest hardness among all reinforcements and demonstrates a little rise with weight percentage, suggesting inadequate particle-matrix adhesion and potential irregularities in particle shape. The Al₂O₃ (Alumina) reinforced Al-Mg-Si alloy composite surpasses the APSA reinforced Al-Mg-Si alloy composite; however, it is inferior to both the GNSA and PKSA reinforced Al-Mg-Si alloy composites, demonstrating a consistent improvement in hardness, attaining 43.98 HRB at 10 wt.%. This is below expectations, maybe attributable to agglomeration, particle-matrix interface complications, or insufficient dispersion or wetting [38, 39].

C. Tensile properties of the produced composites

The results of the tensile properties of the produced composites are presented in Figure 3 to Figure 5.

1) The Ultimate Tensile Strength of the produced composites

The ultimate tensile strength (UTS) of the produced composites and Al-Mg-Si alloy is presented in Figure 3.

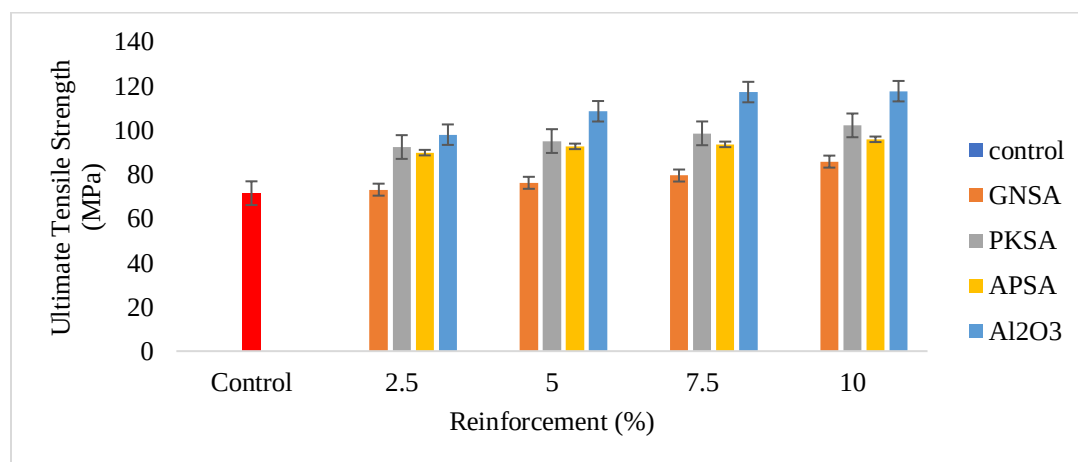


Figure 3: Ultimate tensile strength of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al₂O₃ composites

Figure 3 illustrates the ultimate tensile strength (UTS) of the composites in comparison to the control. The UTS of 71.5 MPa for unreinforced Al-Mg-Si alloy serves as a benchmark for assessing the advantages of reinforcement. The ultimate tensile strength

(UTS) rises with the percentage of reinforcement in all composites, indicating efficient load transfer from the matrix to the reinforcement. The rate of UTS enhancement differs by reinforcing type, indicating variations in reinforcement efficacy. The Al_2O_3 (Alumina) reinforced Al-Mg-Si alloy composite exhibits superior performance, characterised by high stiffness and strength of ceramic particles, robust interfacial bonding, and efficient load distribution. The PKSA (Palm Kernel Shell Ash) reinforced Al-Mg-Si alloy composite exhibits the second greatest ultimate tensile strength among all reinforcement levels, demonstrating relatively effective reinforcement. The GNSA (Groundnut Shell Ash) reinforced Al-Mg-Si alloy composite exhibits considerable enhancement; nevertheless, the increase in tensile strength is constrained, likely due to elevated porosity and suboptimal stress transfer at the interface. The APSA (Avocado Pear Seed Ash) reinforced Al-Mg-Si alloy composite consistently exhibits lower ultimate tensile strength (UTS) compared to the PKSA reinforced Al-Mg-Si alloy composite and the Al_2O_3 reinforced Al-Mg-Si alloy composite, yet it demonstrates a marginally superior performance relative to the GNSA reinforced Al-Mg-Si alloy composite, indicating a modest increase in UTS and suggesting limited interfacial bonding and reinforcement efficacy [40]. Table 1 presents a comparative analysis of ultimate tensile strength (UTS) in relation to porosity and hardness.

Table 1: Cross comparison of UTS with porosity and hardness

Reinforcement	Porosity	Hardness	UTS	Comment
GNSA	Moderate high	Very high	Low moderate	High hardness but poor UTS: Likely brittle
PKSA	Moderate	High	High	Good all round performance
APSA	High	Low	Moderate	Weakest reinforcing effect
Al_2O_3	Low	Moderate	Very high	Best structural reinforcement
Control	Low	Very low	Low	Reference

The Al_2O_3 reinforced Al-Mg-Si alloy composite is the optimal reinforcement, providing the highest tensile strength and lowest porosity. Although its hardness is not the greatest, it is the preferred choice for structural applications where mechanical strength is paramount. The PKSA reinforced Al-Mg-Si alloy composite from Bio-Ash Performance is the most promising bio-ash reinforcement due to its optimal balance of mild porosity, high ultimate tensile strength, and commendable hardness. The GNSA reinforced Al-Mg-Si alloy composite has high hardness but low ultimate tensile strength, making it appropriate for wear-resistant applications rather than load-bearing ones. The reinforced Al-Mg-Si alloy composite exhibits the lowest efficiency in terms of hardness and tensile strength. Reinforcements improve mechanical qualities; nevertheless, porosity must be regulated to prevent adverse consequences such as fracture initiation, reduced ductility, and diminished fatigue life. Nonetheless, the porosity of all reinforcements remains within acceptable limits for cast aluminium, as noted in reference [24].

2) The Specific Strength of the produced composites

The specific strength of the produced composites and Al-Mg-Si alloy is presented in Figure 4.

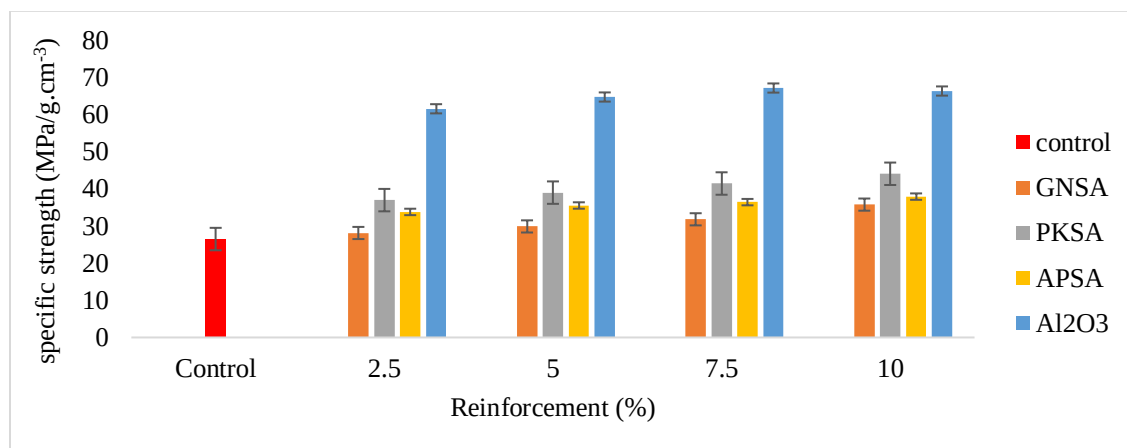


Figure 4: Specific strength of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al_2O_3 composites

Figure 4 illustrates the specific strength of the composites and the Al-Mg-Si alloy. Specific strength quantifies strength in relation to density, serving as a crucial statistic for lightweight structural applications. The baseline specific strength of the Control (Al-Mg-Si alloy) serves as the benchmark for assessing the influence of reinforcing on specific strength. The Al_2O_3 (Alumina) reinforced Al-Mg-Si alloy has the maximum specific strength across all reinforcement percentages, peaking at 7.5 wt%, followed by a modest decline at 10 wt%, perhaps attributable to agglomeration or processing constraints. The PKSA (Palm Kernel Shell Ash) strengthened Al-Mg-Si alloy ranks as the second most effective among natural ashes. It demonstrates

consistent enhancement from 2.5 wt% to 10 wt% reinforcement [38]. The PKSA reinforced Al-Mg-Si alloy surpasses both the GNSA reinforced and APSA reinforced Al-Mg-Si alloys, suggesting superior interfacial bonding or ash properties. The APSA (Avocado Pear Seed Ash) reinforced Al-Mg-Si alloy composite exhibits modest performance that remains rather uniform across varying reinforcement levels, indicating a limitation in its strengthening potential. The GNSA (Groundnut Shell Ash) reinforced Al-Mg-Si alloy composite has the lowest performance among the reinforcements, with the exception of the control group. The GNSA reinforced Al-Mg-Si alloy composite outperforms the unreinforced alloy but is less effective than the PKSA reinforced Al-Mg-Si alloy or the APSA reinforced Al-Mg-Si alloy composite. All reinforcements enhance specific strength compared to the control alloy (Al-Mg-Si alloy). The high hardness, thermal stability, and compatibility of Al_2O_3 with Al-Mg-Si alloy likely enhance the strengthening of the Al-Mg-Si alloy composite. Bio-based ashes exhibit heterogeneity in particle size, content (SiO_2 , CaO , Al_2O_3 , etc.), and compatibility, which affects their reinforcing efficacy [38].

3) The Strain to Fracture of the produced composites

The strain to fracture of the produced composites and Al-Mg-Si alloy is presented in Figure 5.

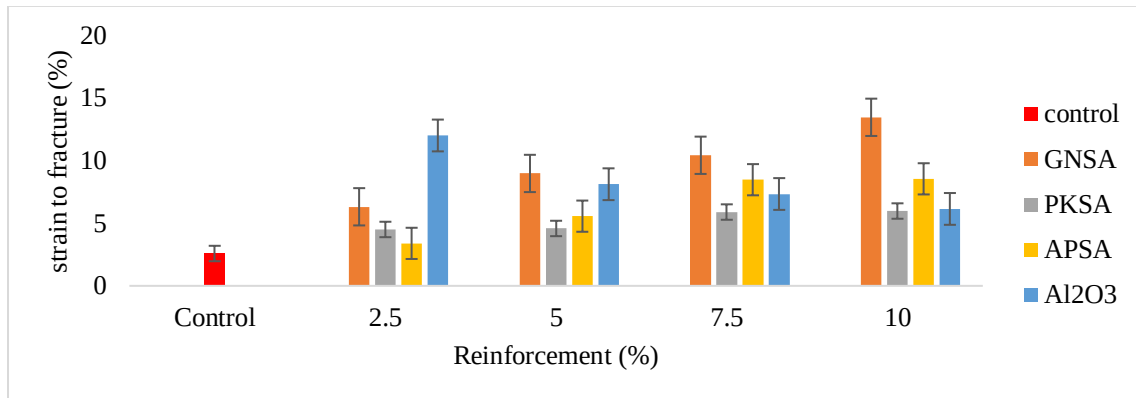


Figure 5: Strain to fracture of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al_2O_3 composites

Figure 5 illustrates the strain to fracture for various Al-Mg-Si alloy-based composites with differing reinforcements. This strain to fracture quantifies ductility, indicating the extent to which a material can undergo plastic deformation prior to failure. Elevated values signify enhanced formability and toughness. The control (Al-Mg-Si alloy) exhibits minimal strain to fracture, indicating that the base alloy is deficient in toughness within the test environment. The GNSA (Groundnut Shell Ash) reinforced Al-Mg-Si alloy exhibits the maximum strain to fracture, indicating that GNSA boosts ductility, maybe due to superior plastic deformation mechanisms or enhanced crack-bridging effects [39]. The Al_2O_3 (Alumina) reinforced Al-Mg-Si alloy composite exhibits strong ductility, which diminishes progressively with an increase in reinforcement. Alumina is generally hard and brittle; thus, the reduction indicates that beyond a certain threshold, it hinders flexibility and promotes brittleness. The APSA (Avocado Pear Seed Ash) reinforced Al-Mg-Si alloy composite demonstrates a continuous rise in strain to fracture, suggesting significant potential for enhancing the alloy's toughness. PKSA (Palm Kernel Shell Ash) reinforced Al-Mg-Si alloy composites exhibit the lowest strain to fracture among bio-based ashes, indicating that PKSA may enhance strength at the expense of ductility. All reinforcements, however, markedly enhance ductility compared to the control alloy, [38, 39].

D. Fracture toughness of the produced composites

The fracture toughness of the produced composites and Al-Mg-Si alloy is presented in Figure 6.

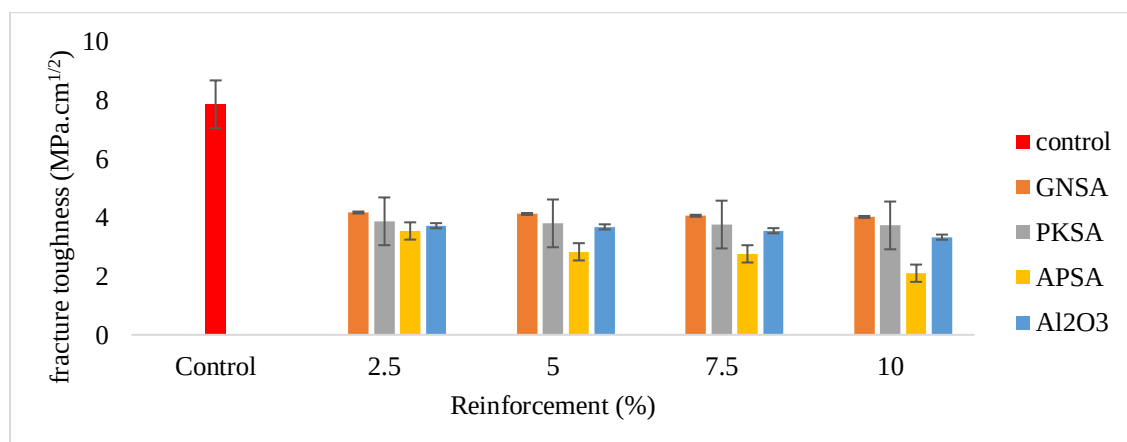


Figure 6: Fracture toughness of Al-Mg-Si alloy reinforced GNSA, PKSA, APSA and Al_2O_3 composites

Figure 6 illustrates the fracture toughness of Al-Mg-Si and its composites. This quantifies a material's resistance to crack propagation, with elevated values indicating a greater capacity to absorb energy prior to fracture, even in the presence of a fault. The control (Al-Mg-Si alloy) exhibits the maximum fracture toughness, far surpassing all reinforced composites in crack resistance. The reinforcement diminishes toughness, presumably because the additional particle-matrix contacts serve as loci for crack initiation. All reinforced composites have reduced fracture toughness relative to the control [41, 42]. The GNSA (Groundnut Shell Ash) reinforced Al-Mg-Si alloy exhibits superior overall toughness compared to other reinforcements, with a rather consistent trend from 2.5 wt% to 10 wt%, indicating that GNSA facilitates reduced crack initiation or enhances energy absorption during fracture. The PKSA (Palm Kernel Shell Ash) reinforced Al-Mg-Si alloy exhibits the second highest fracture toughness and demonstrates slightly greater variability, however outperforms APSA and Al_2O_3 at elevated reinforcement percentages. The APSA (Avocado Pear Seed Ash) reinforced Al-Mg-Si alloy has the lowest fracture toughness, suggesting that it may possess increased brittleness or a higher propensity for interfacial defects. Reinforcement is reported to diminish fracture toughness in comparison to unreinforced Al-Mg-Si alloy. Toughness typically does not enhance with increased reinforcement, potentially attributable to agglomeration at elevated percentages, diminished ductility, and an increased number of interfaces for crack initiation [42].

E. Microstructural analysis

The morphology of select stir-cast test samples is depicted in Figures 7 through 11. The samples comprise the as-cast control (Al-Mg-Si alloy), Al-Mg-Si with 5% GNSA, Al-Mg-Si with 5% PKSA, Al-Mg-Si with 5% APSA, and Al-Mg-Si with 5% Al_2O_3 .

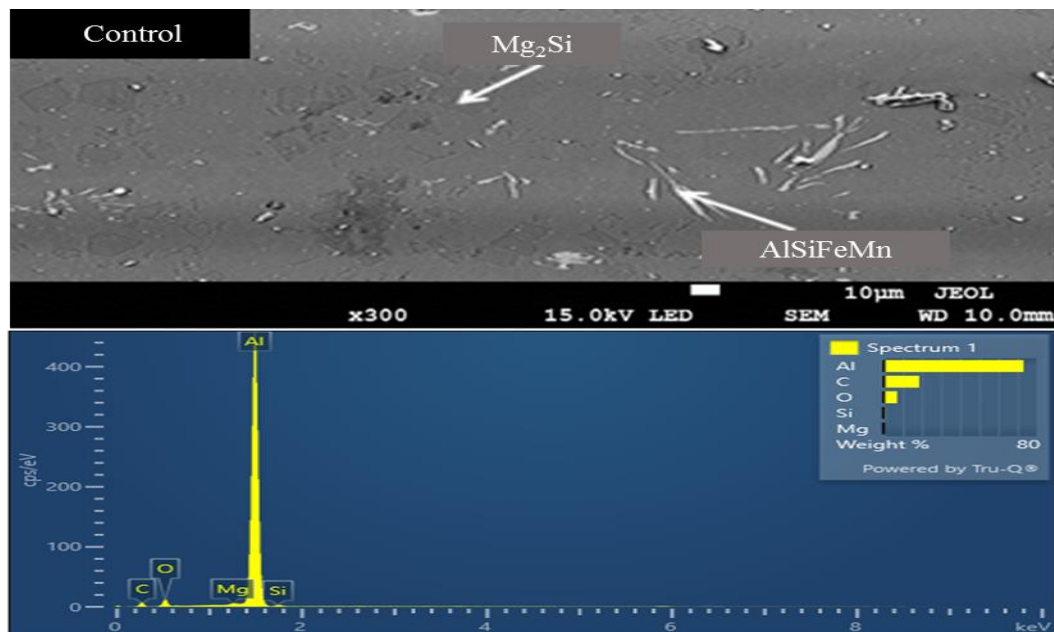


Figure 7: SEM-EDX micrograph of Al-Mg-Si alloy (as cast)

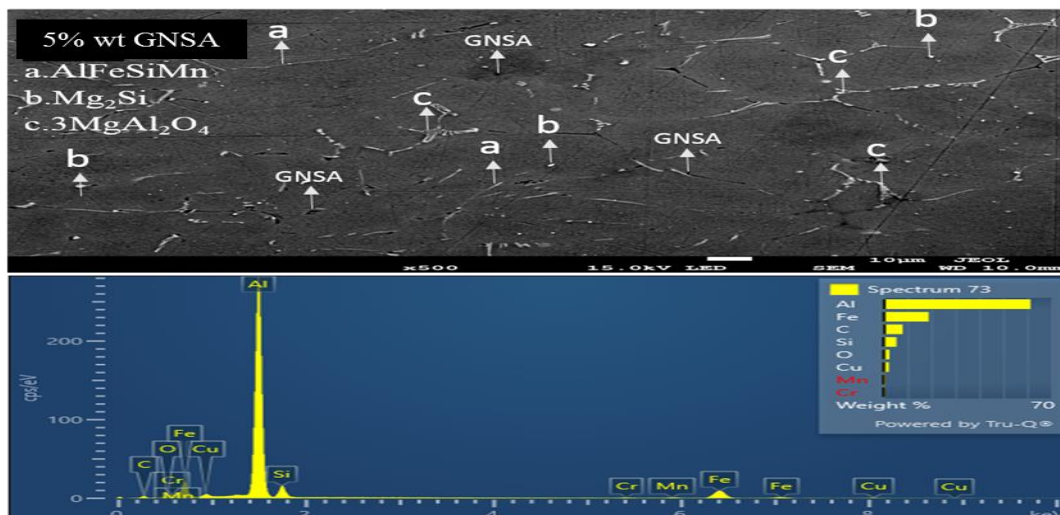


Figure 8: SEM-EDX micrograph of Al-Mg-Si + 5% GNSA

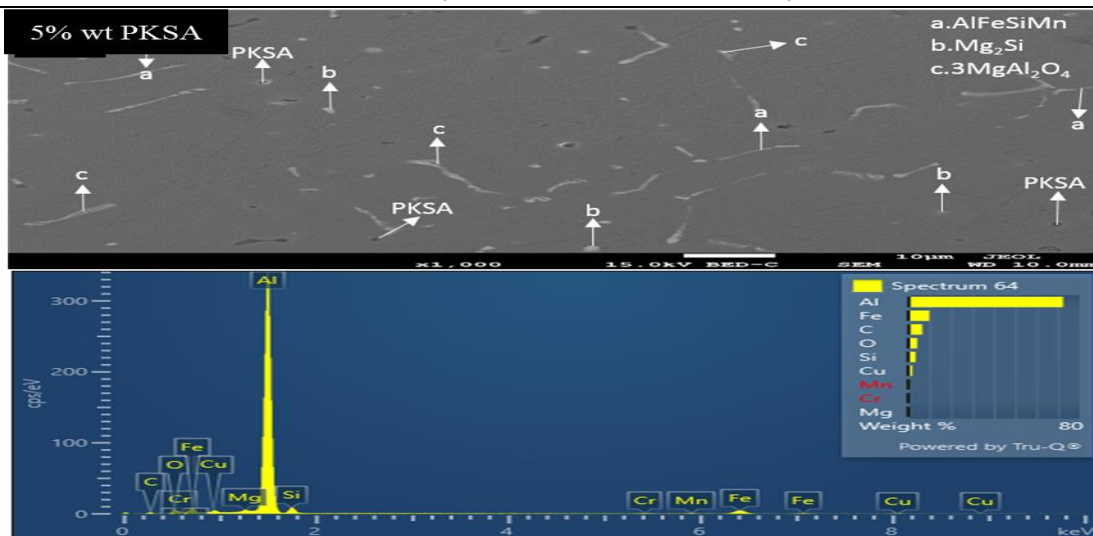


Figure 9: SEM-EDX micrograph of Al-Mg-Si + 5% PKSA

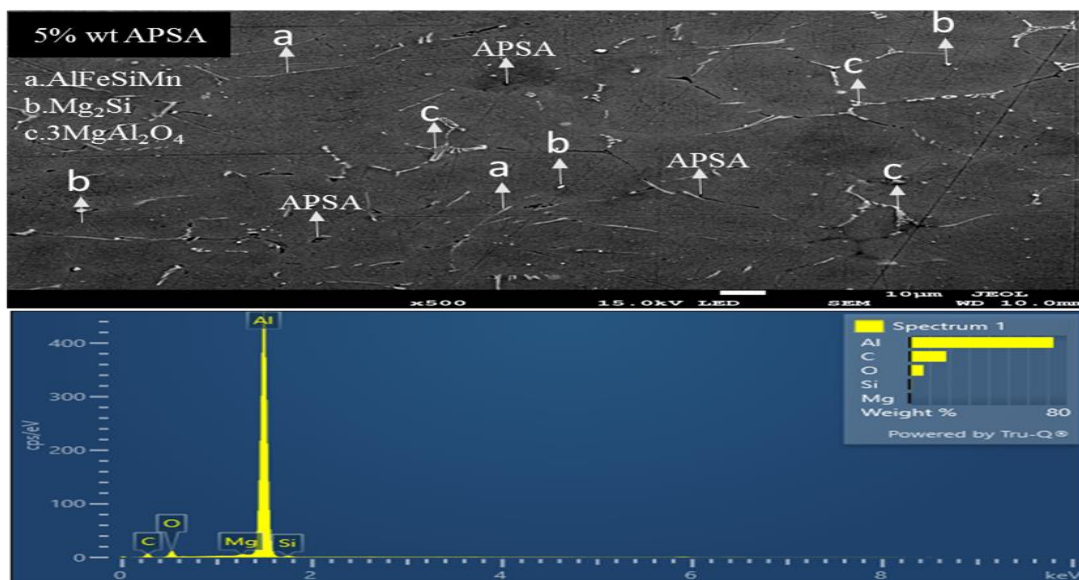


Figure 10: SEM-EDX micrograph of Al-Mg-Si + 5% APSA

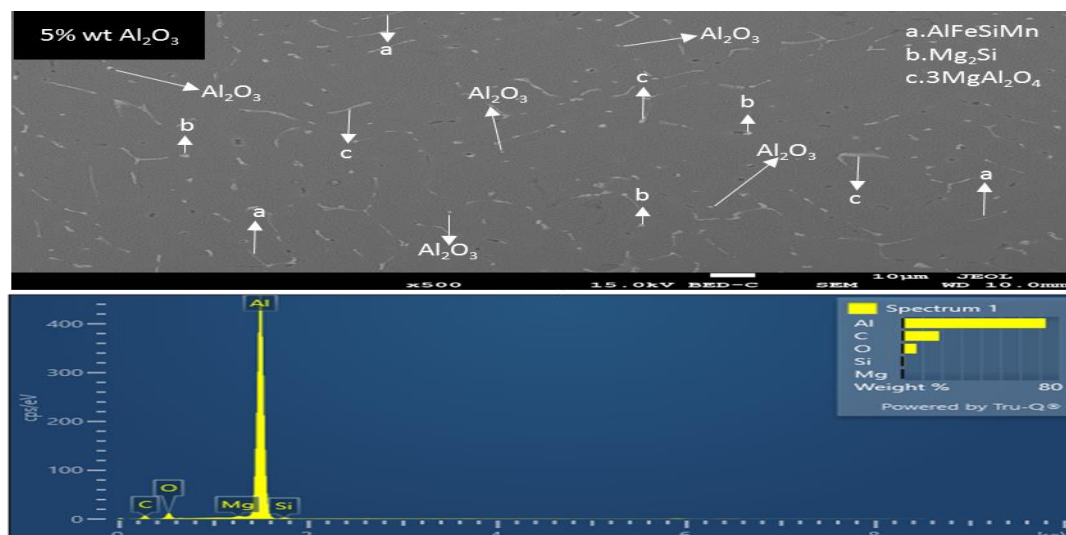


Figure 11: SEM-EDX micrograph of Al-Mg-Si + 5% Al₂O₃

Interfacial bonding plays a pivotal role, as robust bonding between reinforcement particles and the Al-Mg-Si alloy matrix enhances the composite's mechanical properties. Effective interfacial bonding arises from the uniform distribution of reinforcement particles within the matrix, which is vital for achieving consistent mechanical properties. The nature of interfacial bonding influences the composite's fracture mechanism; strong bonding may result in brittle fractures characterised by cracks and particle failures, while weak bonding leads to ductile fractures exhibiting dimples and voids. Additionally, effective bonding can affect the composite's density and strength, where the incorporation of bio-based ash reinforcement particles into the Al-Mg-Si alloy matrix can reduce the composite's density without compromising its mechanical properties, thus benefiting applications that require lightweight materials. The development of intermetallic phases in an Al-Mg-Si alloy matrix composite supplemented with bio-based ash particles entails many mechanisms. The oxides such as SiO_2 , Al_2O_3 , and CaO present in these bio-based particles (Figures 8 to 10) react with the matrix, resulting in the formation of intermetallic phases like spinel (MgAl_2O_4) and other compounds. The diffusion of magnesium from the Al-Mg-Si alloy matrix into the reinforcement particles may lead to spinel formation. Additionally, solid-state reactions between the reinforcement particles and the Al-Mg-Si alloy matrix can occur, potentially resulting in the formation of intermetallic phases. These reactions are influenced by temperature, time, and the composition of the reinforcement during the solidification process. The uniform distribution of reinforcement particles within the matrix during the stir casting process facilitates the formation of intermetallic compounds. The production of intermetallic phases or compounds can enhance the characteristics of the composite [42, 45, 46].

In Figure 11, Al_2O_3 particles are discernible as luminous white contrast regions, distributed throughout the matrix. Although the dispersion is predominantly homogeneous, some aggregation exists, potentially facilitating microvoid formation, inducing localised stress concentration, and diminishing mechanical integrity under tensile strain [47]. No substantial macro-porosity is detected; however, microporosity and microcracks may be present in areas adjacent to reinforcement/matrix interfaces, typically resulting from inadequate wetting between the Al-Mg-Si alloy matrix and ceramic particles, as well as thermal mismatch stress arising from the disparate coefficients of thermal expansion between the Al-Mg-Si alloy and Al_2O_3 [47]. The dispersion from Figure 8 to Figure 11 is generally satisfactory; however, clustering indicates possible inefficiencies in stirring or mixing during processing.

IV. Conclusion

The comparative examination of Al-Mg-Si alloy composites reinforced with GNSA, PKSA, APSA, and Al_2O_3 demonstrated notable differences in their mechanical and microstructural characteristics. All reinforcements augmented porosity to differing degrees, with APSA demonstrating the greatest level (31.1%) and PKSA the lowest (18.1%); nonetheless, the porosity levels remained within the acceptable limits for cast aluminium alloys. GNSA reinforced composites exhibited the most significant enhancement in hardness (43.1%), succeeded by PKSA (33.4%), signifying enhanced wear resistance. Al_2O_3 demonstrated the most significant enhancement in ultimate tensile strength (39.2%) and specific strength (60.1%), highlighting its reinforcing capabilities in strength-dependent applications. Natural ash reinforcements, specifically APSA and GNSA, surpassed Al_2O_3 in terms of ductility and fracture resistance, with APSA exhibiting an extraordinary 274.3% enhancement in fracture toughness and GNSA demonstrating a notable 80.8% increase in strain to fracture. Conversely, Al_2O_3 exhibited a reduction in both ductility and toughness. SEM examination verified a generally uniform distribution of reinforcement with occasional localised clumping. In summary, although Al_2O_3 demonstrates superior strength, the agro-waste reinforcements, particularly APSA and GNSA, provide a more harmonious blend of strength, ductility, and toughness, rendering them viable low-cost and sustainable alternatives for structural applications in the automotive and aerospace industries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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