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Experimental Investigation on the Mechanical Properties of Al 6063 Metal Matrix Reinforced with Nano-Sized Calcium Derived from Cattle Bone Ash

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Abstract

Agro-waste has gained increasing attention as a low-cost and environmentally sustainable resource for the development of advanced engineering materials. In this study, Al 6063 alloy was reinforced with nano-sized cattle bone ash (CBA) particles to improve its mechanical and microstructural properties. Al 6063 scraps were obtained from a scrap yard, while cattle bones collected from abattoir waste were processed into nano-sized CBA particles through calcination, ball milling, and air classification under a controlled vortex flow conditions. Composite samples containing 6 wt. %, 9 wt. %, and 12 wt. % CBA were produced using the stir-casting technique. Mechanical characterization showed that the tensile strength increased from 103 MPa for the unreinforced alloy to a maximum value of 140 MPa with increasing reinforcement content due to improved load transfer and stronger matrix–particle interfacial bonding. The hardness value also increased to 88.3 HV, indicating better resistance to plastic deformation. However, the impact energy decreased to approximately 5.5 kJ/m^2 at higher reinforcement levels, suggesting a reduction in ductility. Microstructural analysis revealed a fairly uniform distribution of the reinforcement particles and enhanced interfacial bonding within the aluminum matrix. The findings indicate that nano-sized cattle bone ash is a promising reinforcement material for the development of lightweight aluminum matrix composites suitable for engineering applications.

Keywords: Calcination; CBA; Nano-size; Sustainable; Reinforcement; Deformation; Characterization.

1 Introduction

The development of aluminum-based composites has attracted considerable research interest due to the increasing demand for lightweight materials with enhanced mechanical and metallurgical properties [2]. Among aluminum alloys, Al 6063 has gained significant attention and is widely used in structural and automotive applications because of its high strength-to-weight ratio, good formability, corrosion resistance, and moderate mechanical strength. To further improve the performance of aluminum alloys, researchers have extensively explored the incorporation of various reinforcement materials such as rice husk, sugarcane bagasse, red mud, eggshell, and cattle bone [4].

Although synthetic reinforcements such as silicon carbide, boron carbide, and molybdenum disulfide have been reported to significantly improve the mechanical and microstructural properties of aluminum matrix composites, their applications are often limited by high cost, processing challenges, and restricted availability. In contrast, agricultural waste materials have emerged as promising alternative reinforcements for the development of cost-effective and lightweight aluminum matrix composites with satisfactory mechanical performance. The abundance, renewability, and low processing cost of agro-waste materials have further stimulated research into their utilization as sustainable reinforcement sources for engineering applications [11].

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According to literatures, [5] investigated the use of aloe vera powder as reinforcement in aluminum metal matrix composites to evaluate its mechanical performance. Although fly ash has been widely employed by several researchers as a particulate reinforcement in aluminum matrices, their findings revealed that aloe vera reinforcement produced notable improvements in tensile strength, impact strength, and hardness compared to fly ash-reinforced composites. Similarly, [3] investigated Al 8011 aluminum alloy reinforced with cow horn and corncob particulates at varying weight fractions using the stir-casting technique. The fabricated composites were subjected to mechanical testing and microstructural characterization, and the results showed improvements in yield strength, ultimate tensile strength, and hardness, thereby demonstrating the potential of agro-waste materials in composite development.

The use of agricultural waste particulates as reinforcement in metal matrix composites offers benefits beyond economic advantages to manufacturing industries (SDG 3) because of their low cost and wide availability. Their utilization also promotes environmental sustainability and resource efficiency (SDG 9) through the conversion of agro-processing residues into valuable engineering materials [1], [6].

Despite several studies on agro-waste-reinforced aluminum composites, limited attention has been given to the use of nano-sized cattle bone ash as reinforcement in Al 6063 alloy. Therefore, this study investigates the effect of nano-sized cattle bone ash particles on the mechanical and microstructural properties of Al 6063 aluminum matrix composites produced through the stir-casting process.

2 Material and methods

2.1 Materials and processing

The aluminum alloy (Al 6063) used in this study was sourced from the Aluminium Village scrap yard, Dopemu, Lagos State, Nigeria. Approximately 20 kg of Al 6063 scrap ingots were cleaned, dried, and melted at about 850 °C through gradual charging into an open furnace. The molten metal was stirred to remove slag and subsequently degassed by dropping a piece of aluminium can into the molten metal before being poured into prepared molds, where it solidified into billets for further processing.

Fresh cattle bones were collected from the Agege abattoir dump site in Lagos, Nigeria, and processed to obtain cattle bone ash (CBA). Initial manual sorting was carried out to remove residual soft tissues, followed by thorough washing with distilled water to eliminate dirt, blood, and other adhered contaminants. The bones were subsequently boiled for 30–45 minutes to remove fat and marrow in accordance with the procedure reported by [10].

After drying, the bones were placed in a covered refractory crucible and insulated with refractory wool to minimize oxygen ingress during calcination. Calcination was carried out at 700 °C for 2 hours, which corresponds to the optimum conditions for the removal of organic constituents and the formation of stable bone ash, as reported by [7]. The calcined bone ash was subsequently subjected to high-energy ball milling to reduce the particle size to the nanoscale, following the procedure described by [9]. The nano-sized CBA powder was then stored in airtight containers to prevent moisture absorption and particle agglomeration prior to composite fabrication.

2.2 Composite preparation

A portion of the Al 6063 alloy billet was sectioned for further processing, preheated at 450 °C inside a crucible furnace to minimize thermal shock, and subsequently melted at 750 °C to achieve a fully molten state suitable for stirring. The molten alloy was degassed using solid hexachloroethane tablets to reduce porosity caused by hydrogen absorption. The stir-casting technique was employed to fabricate aluminum matrix composites reinforced with nano-sized cattle bone ash (Nano-CBA) at reinforcement levels of 6 wt.%, 9 wt.%, and 12 wt.%.

Magnesium was added to reduce surface tension and promote the formation of interfacial compounds that improve wetting and bonding between the matrix and reinforcement particles. Stirring was carried out inside the crucible furnace at 450 rpm for 8 minutes, while the Nano-CBA particles were gradually introduced into the vortex. The furnace lid was partially opened during stirring to maintain adequate melt temperature throughout the agitation process.

The molten composite was subsequently skimmed to remove slag and unwanted inclusions before being poured into prepared moulds for solidification. After solidification, the cast samples were removed, fettled, machined, and prepared for mechanical and microstructural characterization. An unreinforced Al 6063 sample was also prepared as the control specimen for comparison during characterization.

2.3 Mechanical testing

Mechanical tests were conducted to evaluate the tensile strength, hardness, and impact properties of the fabricated composites. Tensile testing was performed using an Instron extensometer testing machine (Model 3369) in accordance with ASTM E8/E8M–08 (2008). The specimens were subjected to axial tensile loading at a strain rate of 10^{-3} s^{-1} until fracture occurred. The tensile properties were subsequently obtained from the generated stress–strain curves. Hardness testing was carried out using a Vickers hardness testing machine (Model FH8 900-391C) in accordance with ASTM E384. Three indentations were made at different locations on each sample, and the average hardness value was recorded. Impact testing was conducted using an Avery Denison Universal Impact Testing Machine following ASTM A370 standard procedures for specimen preparation and testing. The impact test specimens were machined to dimensions of 10 mm × 10 mm × 55 mm with a V-notch angle of 45° to evaluate the impact resistance of the reinforced composites.

2.4 Microstructural and XRD characterization

The phase composition and crystallographic characteristics of the composite samples were analyzed using X-ray diffraction (XRD) operated at a voltage of 45 kV and a current of 40 mA over a selected 2θ scanning range. The microstructural characteristics of the samples were examined using a 3000 inverted metallurgical optical microscope and a JEOL JSM-5900LV Scanning Electron Microscope (SEM). Before microstructural examination, the samples were grounded, polished, and etched using Keller's reagent to reveal the microstructural features.

3 Results and discussion

The fabricated composite samples were evaluated for their mechanical properties and microstructural characteristics, and the results were compared with those of the unreinforced Al 6063 alloy.

3.1 Tensile strength

The tensile strength characteristics of the control sample of Al 6063 and the nano-sized cattle bone ash (CBA)-reinforced aluminum matrix composites were shown in figure 1. The control sample exhibited a tensile strength of 103.391 MPa and a corresponding Young's modulus of 523.73 GPa, indicating moderate stiffness and provides a baseline for evaluating the effect of CBA reinforcement. A slight decrease in tensile strength to 99.327 MPa was observed for the 6 wt.% CBA composite, while the Young's modulus increased to 553.132 GPa. This initial reduction in tensile strength may be attributed to the incorporation of reinforcement particles, which could act as stress concentration sites before achieving uniform dispersion within the matrix. The 9 wt.% CBA composite exhibited the best mechanical performance, with the highest tensile strength of 140.369 MPa and an increased Young's modulus of 600.306 GPa. This improvement suggests an optimum reinforcement level at which the CBA particles were more uniformly distributed, resulting in efficient load transfer and improved matrix–particle interfacial bonding. At 12 wt.% CBA reinforcement, the tensile strength decreased to 129.856 MPa, while the Young's modulus reduced to 530.251 GPa. Although these values remained higher than those of the control sample, the reduction compared with the 9 wt. % CBA composite may be associated with particle agglomeration and microstructural non-uniformity at higher reinforcement levels. Such agglomeration could reduce the stiffness and strength of the composite material. Overall, the results indicate that the 9 wt. % CBA composite provided the optimum balance between tensile strength and stiffness among the developed composites.

3.2 Hardness

The variation in hardness of the Al 6063 composites with increasing nano-CBA reinforcement content were shown in figure 2. The hardness increased from 85.2 HV for the unreinforced Al 6063 alloy to 88.3 HV following the addition of reinforcement particulates, indicating improved resistance to indentation relative to the base alloy. This enhancement may be attributed to effective load transfer and strengthening arising from the relatively uniform dispersion of Nano-CBA particles within the matrix. However, a further increase in Nano-CBA content resulted in a reduction in hardness to 75.2 HV. The decline in hardness at higher reinforcement loading is likely due to particle agglomeration, increased porosity, and the formation of microstructural defects, which negatively affected the mechanical integrity of the composite.

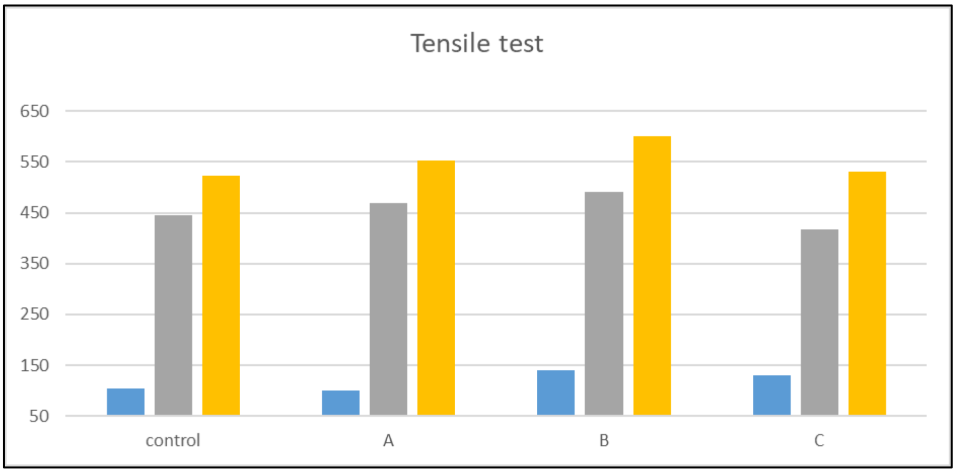


Figure 1 Tensile test on samples

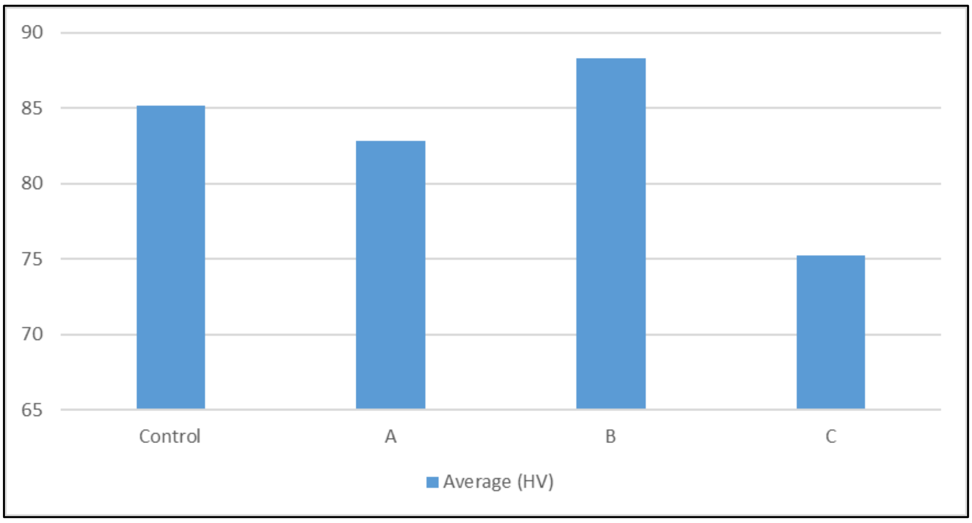


Figure 2 Vicker hardness test on samples

3.2.1 Impact Energy

Figure 3 illustrates a progressive decline in the impact energy absorption capacity of the composites with increasing CBA content. A decrease in the impact performance is primarily attributed to reduced ductility, stress concentration around the reinforcement particles, weak interfacial bonding between the matrix and reinforcement, and particle agglomeration at higher weight fractions. These factors collectively hindered effective energy dissipation and promoted crack initiation and propagation, thereby resulting in brittle fracture behavior during impact loading.

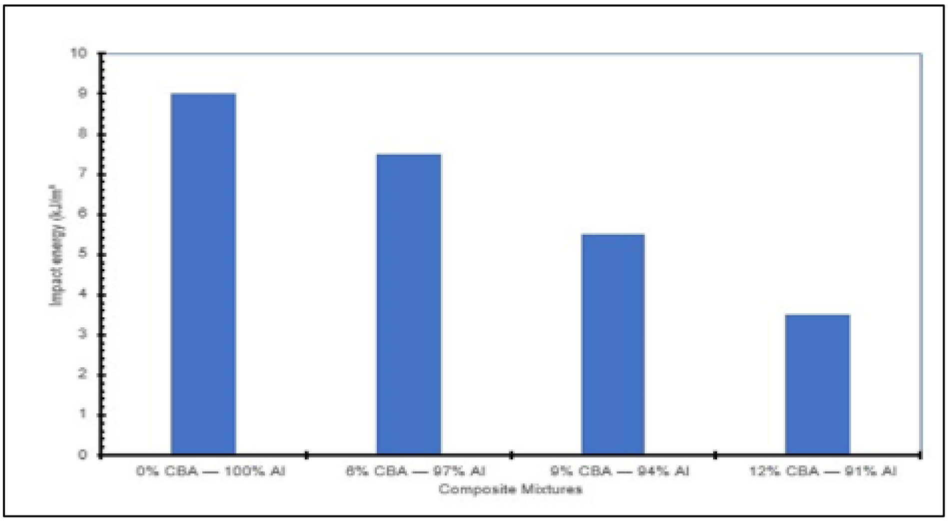


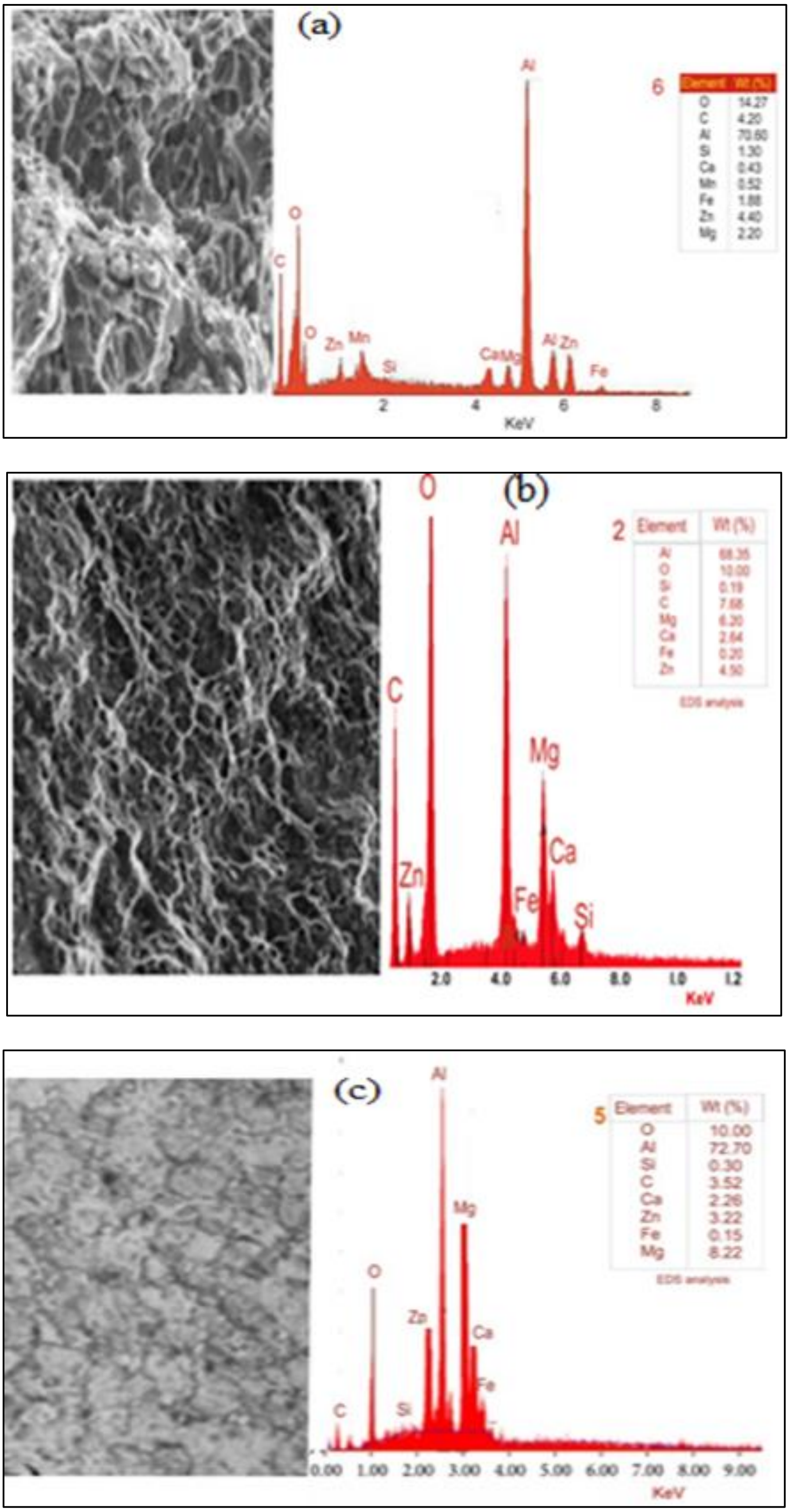
Figure 3 Impact energy test on samples

3.3 Samples' microstructure

Figure 4a presents the SEM micrograph of the control Al 6063 which exhibits a relatively rough and non-uniform surface morphology characterized by irregular ridges and shallow voids. This surface texture is typical of unreinforced aluminum alloys and reflects the inherent grain structure of the matrix in the absence of external reinforcement. Furthermore, the absence of uniformly distributed secondary phases confirms that the sample retained its intrinsic alloy composition, thereby providing a suitable baseline for comparative microstructural evaluation. The SEM micrograph of the 6 wt.% CBA–Al 6063 composite shown in Figure 4b reveals a more compact and interconnected microstructure compared to the control sample. The surface morphology appears denser, with finer and more uniformly distributed features, indicating effective dispersion of the CBA particles within the aluminum matrix. The corresponding EDS spectrum identifies aluminum (Al) as the predominant element, as evidenced by the intense Al peak. Peaks corresponding to oxygen (O) and carbon (C) were also observed, which may be attributed to surface oxidation and the carbonaceous nature of the reinforcement. Minor peaks of silicon (Si), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and calcium (Ca) were detected, consistent with the elemental composition of the Al 6063 alloy and the incorporated reinforcement. The SEM/EDS analysis therefore, confirms successful incorporation of the reinforcement while preserving the structural integrity of the matrix alloy.

The SEM micrograph of the 9 wt.% CBA–Al 6063 composite (Figure 4c) exhibits a refined, compact, and relatively homogeneous microstructure with fewer visible voids. This observation suggests improved particle dispersion, enhanced particle–matrix interaction, and stronger interfacial bonding, which collectively contributed to improved structural integrity of the composite. The EDS spectrum confirms aluminum (A l) as the dominant matrix element, while the pronounced oxygen (O) peak reflects the oxide-rich characteristics of the incorporated CBA particles. Distinct calcium (Ca) and magnesium (Mg) peaks further confirm the presence of reinforcement-derived phases. Minor peaks corresponding to silicon (Si), zinc (Zn), iron (Fe), and carbon (C) were also identified, consistent with the matrix alloy and reinforcement constituents. Overall, the SEM/EDS analysis indicates effective incorporation and relatively uniform distribution of the Nano-CBA particles within the aluminum matrix.

The SEM micrograph of the 12 wt.% CBA–Al 6063 composite shown in Figure 4d, reveals a relatively dense but partially agglomerated microstructure compared to the lower reinforcement compositions. Clusters of reinforcement particles were observed within the aluminum matrix, indicating that excessive CBA addition promoted particle agglomeration and microstructural heterogeneity. Although some degree of matrix–reinforcement bonding remained evident, the non-uniform particle distribution may have contributed to localized stress concentration and the formation of microstructural defects. Such agglomeration can adversely affect the mechanical performance of the composite by reducing effective load transfer and promoting crack initiation within the matrix. The localized clusters may introduce microstructural heterogeneities that could influence mechanical behavior, such as reduced ductility or the development of localized stress concentrations.


(a)
6
Element Wt (%)
O 14.27
C 4.20
Al 70.60
Si 1.30
Ca 0.43
Mn 0.52
Fe 1.88
Zn 4.40
Mg 2.20
KeV
(b)
2
Element Wt (%)
Al 68.35
O 10.00
Si 0.19
C 7.68
Mg 6.20
Ca 2.64
Fe 0.20
Zn 4.50
EDS analysis
KeV
(c)
5
Element Wt (%)
O 10.00
Al 72.70
Si 0.30
C 3.52
Ca 2.26
Zn 3.22
Fe 0.15
Mg 8.22
EDS analysis
KeV

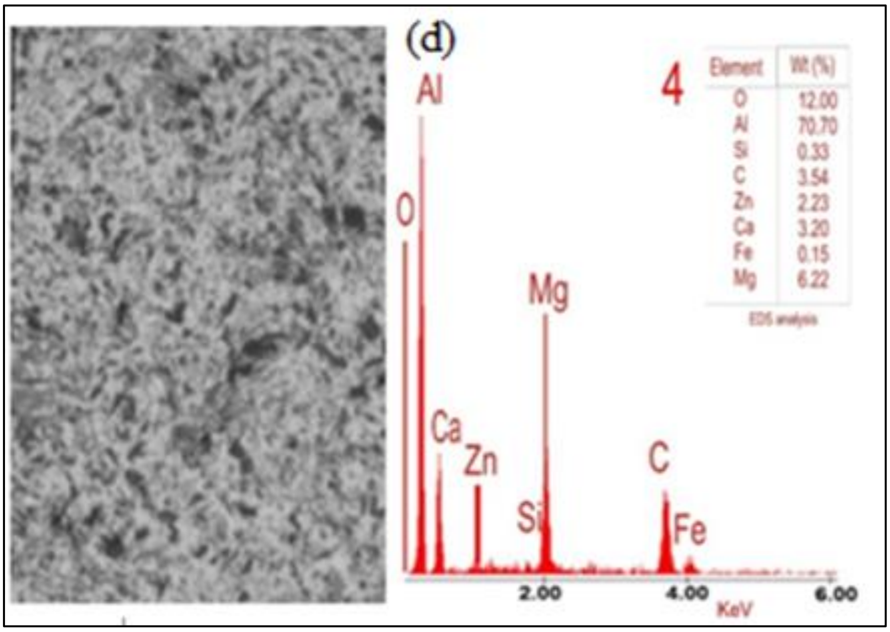


Figure 4 SEM/EDS images of (A) Control sample (B) 6% (C) 9% (D) 12% reinforcement

The EDS spectrum confirms aluminum (Al) as the predominant element, indicating the preservation of the Al 6063 matrix framework. The prominent oxygen (O) peaks are indicative of the oxide-rich nature of the cattle bone ash (CBA) reinforcement, while the detection of calcium (Ca) and magnesium (Mg) further verifies the successful integration of CBA-derived mineral phases within the composite. In addition, trace amounts of silicon (Si), zinc (Zn), iron (Fe), and carbon (C) are present, which can be attributed to contributions from both the base alloy and the biomass-derived reinforcement. Overall, the SEM/EDS analysis demonstrates effective incorporation of 12 wt.% CBA into the aluminum matrix. However, the observed particle agglomeration suggests that this reinforcement level may be approaching or exceeding the limit for uniform particle dispersion, leading to localized clustering within the matrix. Such behavior is commonly reported in particulate-reinforced aluminum matrix composites, where higher reinforcement contents can compromise microstructural homogeneity and, consequently, mechanical performance [8].

4 Conclusion

Nano-CBA is a viable, and sustainable reinforcement for Al 6063 composites, improving tensile strength and hardness, with the best performance at 9 wt.%. However, increasing reinforcement reduces impact toughness. SEM results confirmed good particle distribution and bonding, supporting the enhanced mechanical properties.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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