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Investigation of Mechanical and Thermal Properties of Silicon Carbide and Rice Husk Ash Reinforced Aluminum Matrix Composite Produced by Stir Casting Method

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Abstract

Aluminum matrix composites reinforced with agricultural waste-derived materials offer opportunities to enhance material performance while promoting sustainable waste utilization. However, selecting appropriate reinforcement compositions requires balancing mechanical strength, deformation capacity, and thermal stability. This study investigated the mechanical and thermal properties of aluminum matrix composites reinforced with 2% silicon carbide (SiC) and varying rice husk ash (RHA) contents of 2%, 4%, and 6%, fabricated using the stir casting method. Tensile and compression tests were conducted to evaluate mechanical behavior, while thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC) were employed to characterize thermal properties. Each composition was tested once, and the resulting data were analyzed descriptively. Increasing the RHA content from 2% to 6% increased the ultimate tensile strength from 184.63 to 211.47 MPa, while the tensile strain at fracture decreased from 7.18% to 4.73%. The composite containing 4% RHA exhibited the highest compressive flow stress, approximately 370 MPa at 20% compressive strain. Mass retention at 800 °C increased from approximately 99.34% to 99.68% with increasing RHA content, whereas the DSC melting peaks remained near 664–665 °C. These findings suggest that increasing RHA content enhanced tensile strength and high-temperature mass retention but reduced tensile deformability. The 4% RHA composition demonstrated the most favorable compressive resistance among the tested formulations, whereas the 6% RHA composition achieved the highest tensile strength. Therefore, reinforcement selection should consider specific loading conditions, deformation requirements, and thermal operating limits associated with the melting behavior of the aluminum matrix. Further investigations involving replicated experiments and statistical validation are recommended to confirm the observed trends and establish the reproducibility of the results.

INTRODUCTION

Aluminum matrix composites (AMCs) represent an important approach to materials development, combining a lightweight metallic matrix with reinforcing particles to achieve mechanical and thermal properties suitable for specific engineering applications. Silicon carbide (SiC) is widely employed as a reinforcement material; however, its effectiveness depends on interfacial characteristics, reinforcement volume fraction, particle distribution, and fabrication techniques. (Lin et al., 2024) demonstrated that modifying the aluminum–SiC interface through post-oxidation treatment could

enhance the thermal conductivity of the resulting composites. These findings highlight the importance of considering not only reinforcement composition but also processing conditions that govern particle–matrix interactions and influence the overall performance of aluminum matrix composites.

In the development of alternative reinforcement materials, rice husk ash (RHA) presents opportunities to utilize silica-rich agricultural residues as a sustainable reinforcement source. Umeda and Kondoh (2010) demonstrated that appropriate pretreatment and controlled combustion of rice husks could produce silica-rich residues with low impurity and residual carbon contents. These findings indicate that preparation conditions significantly influence the characteristics and potential effectiveness of RHA as a reinforcing material. In hybrid aluminum–SiC–RHA composites, an important research consideration is how variations in RHA content affect the balance among mechanical strength, deformation capacity, and thermal behavior when the SiC reinforcement content remains constant.

Previous studies have demonstrated that incorporating RHA into aluminum matrix composites can produce different trends in mechanical properties, depending on reinforcement concentration and processing conditions (Joseph et al., 2023a; Chakravarthy & Rao, 2022). Abolusoro et al. (2024) fabricated RHA-reinforced recycled aluminum composites using the stir casting method and reported a maximum tensile strength of 121.6 MPa at an RHA content of 10 wt.%. Tensile strength decreased at higher reinforcement concentrations, whereas hardness continued to increase. Meanwhile, (Lin et al., 2024) investigated aluminum–SiC composites and emphasized the importance of interfacial characteristics in determining thermal transport properties. Collectively, these findings suggest that reinforcement selection should be guided by specific performance requirements rather than assuming that increasing reinforcement content consistently improves all material properties.

Although previous investigations have established the potential contributions of RHA and SiC reinforcement, differences in matrix compositions, reinforcement concentrations, and fabrication procedures limit the direct applicability of their findings to the composite formulations examined in this study (Saini et al., 2020). The contrasting trends in tensile strength and hardness reported by (Abolusoro et al., 2024a) demonstrate that improvements in a single mechanical property are insufficient to identify an optimal reinforcement composition. Accordingly, the research gap addressed in this study concerns the need for an integrated evaluation of tensile behavior, compressive response, thermogravimetric mass changes, and thermal transitions in stir-cast aluminum matrix composites containing a fixed SiC content of 2% and varying RHA contents of 2%, 4%, and 6%.

(Udoye et al., 2021) The theoretical foundation of this study centers on the interactions among the aluminum matrix, reinforcing particles, and particle–matrix interfaces in determining composite material behavior. Reinforcing particles can contribute to load transfer and restrict localized plastic deformation; however, their effectiveness depends on particle dispersion, interfacial bonding, and interactions with

the surrounding matrix. (Abolusoro et al., 2024a) identified particle agglomeration at higher RHA concentrations, while (Lin et al., 2024) demonstrated that interfacial characteristics significantly influenced heat transfer in aluminum–SiC composites. These findings support the combined assessment of mechanical strength and deformation capacity while emphasizing that reinforcement mechanisms, particle agglomeration, and microstructural heterogeneity require direct microstructural characterization for confirmation (Dixit & Suhane, 2022).

The novelty of this study lies in its integrated evaluation of the effects of varying RHA content at a fixed SiC concentration through tensile testing, compression testing, thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC). This approach was designed to identify trade-offs among mechanical strengthening, deformation capacity, high-temperature mass retention, and melting behavior within the investigated composition range. The relevance of evaluating melting behavior is supported by (Villada et al., 2023a), who investigated the thermophysical properties of recycled aluminum alloys for phase-change thermal energy storage applications. In the present study, thermal transition characteristics were examined to assess the melting-related limitations of the aluminum matrix, while mechanical testing provided comparative evidence of composite behavior under tensile and compressive loading.

The significance of this investigation is associated with the need to select reinforcement compositions according to the mechanical loading conditions, deformation requirements, and thermal operating limits of engineering components. (Abolusoro et al., 2024a) demonstrated that increasing RHA content did not necessarily improve all mechanical properties simultaneously, highlighting the importance of evaluating performance trade-offs. Thermal characterization is equally important because the melting behavior of aluminum-based materials influences their suitability for elevated-temperature applications, as demonstrated by (Villada et al., 2023a). Accordingly, mass retention during heating must be distinguished from the ability of the aluminum matrix to maintain its solid state and mechanical load-bearing capacity. Evaluating these characteristics together is essential to avoid selecting reinforcement compositions solely on the basis of tensile strength or minimal thermogravimetric mass loss.

Based on these considerations, this study aimed to investigate the effects of varying RHA contents of 2%, 4%, and 6% on the mechanical and thermal properties of aluminum matrix composites reinforced with a fixed SiC content of 2% and fabricated using the stir casting method. The evaluation included ultimate tensile strength, tensile stress at fracture, compressive flow stress, thermogravimetric mass changes, and calorimetric responses. The selection of these parameters was informed by previous findings concerning the dependence of mechanical properties on RHA concentration and the importance of characterizing phase transitions in aluminum-based materials (Abolusoro et al., 2024a; Villada et al., 2023a). This study was expected to contribute to a more comprehensive understanding of the relationships among reinforcement composition, mechanical performance, and thermal behavior in hybrid aluminum–SiC–

RHA composites. Furthermore, the findings were intended to provide a basis for selecting suitable reinforcement formulations according to specific loading requirements, deformation tolerances, and the thermal limitations of the aluminum matrix.

METHOD

Materials and composite fabrication

Aluminum, silicon carbide (SiC), and rice husk ash (RHA) were combined at nominal compositions of 96/2/2, 94/2/4, and 92/2/6 wt.% for Samples 1, 2, and 3, respectively. RHA was prepared through washing, drying, preliminary combustion, and subsequent furnace treatment at 600 °C for 10 h, followed by sieving through a 38 μm mesh, following the procedure described by Abolusoro et al. (2024). The composites were fabricated using the stir casting method. Aluminum was melted in a graphite crucible at 800 °C, while the reinforcement particles were preheated at 600 °C for 3 h. The preheated reinforcements were incorporated into the molten aluminum and mechanically stirred at 700 rpm for 15 min to promote particle dispersion. The resulting composite melt was poured into a permanent mold preheated to 500 °C and allowed to solidify before machining into test specimens. The casting parameters were adapted from (Hatti et al., 2026a). The nominal compositions of the composite samples are presented in Table 1.

Table 1. Composition of Composites

Sample	Al (%)	SiC (%)	RHA (%)
Sample 1	96	2	2
Sample 2	94	2	4
Sample 3	92	2	6

Mechanical characterization

The selected mechanical testing setup used an Instron universal testing machine at room temperature. Tensile specimens had a gauge length of 50 mm and a gauge diameter of 12 mm, whereas compression specimens measured 12 mm in diameter and 18 mm in height. Specimen preparation and testing were based on ASTM E8 and ASTM E9 procedures, respectively, following Hatti et al. (2026). A crosshead speed of 2 mm min^{-1} was selected following Alnaser, (2024) . Tensile strength and fracture strain were extracted from the tensile response; compressive flow stress was compared at 20% strain. Each test was performed once per composition. Results were reported as individual measurements and evaluated descriptively.

Thermal characterization and data reporting

A NETZSCH STA 449 F3 was selected for TGA and DSC, based on the instrumentation reported by Wang et al. (2021). The provisional thermal conditions used approximately 10 mg of material in an alumina crucible under air at 20 °C min^{-1}, adapted from Zewide et al. (2025). The evaluation range was 50-800 °C, with DSC melting peaks examined within 650-700 °C. DTG was defined as dW/dT and expressed in % $°C^{-1}$; DSC heat flow was normalized by sample mass. Each test was performed once per composition. Results were reported as individual measurements and evaluated descriptively.

RESULTS AND DISCUSSION

Mechanical Strength and Deformation Behaviour Analysis

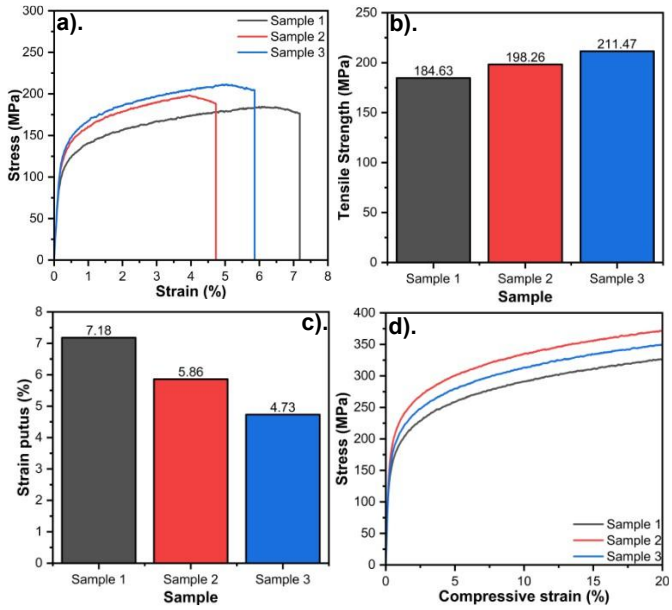


Figure 1. Tensile and compressive properties of Al-SiC-RHA composites. a, Tensile stress-strain curves. b, Tensile strength. c, Strain at fracture. d, Compressive stres-strain curves

The mechanical response of the Al-SiC-RHA composites reveals a composition-dependent balance between tensile strength, ductility and resistance to compressive deformation. With the SiC content fixed at 2%, the tensile-strength values in Fig. 1b increase from 184.63 MPa for Sample 1 to 198.26 MPa for Sample 2 and 211.47 MPa for Sample 3 as the RHA content increases from 2% to 6%. These values represent improvements of 7.38% and 14.54% relative to Sample 1, respectively. Within the investigated composition range, increasing the RHA fraction is therefore associated with a greater capacity to sustain tensile stress before reaching the maximum load.

The tensile curves in Fig. 1a exhibit a steep initial stress increase followed by more gradual stress development and a shallow maximum before fracture. This response is consistent with initial loading followed by plastic deformation and strain hardening. Sample 3 sustains the highest peak stress, while the abrupt terminal drops indicate the loss of load-bearing continuity upon fracture. The strengthening may involve load sharing with the reinforcing particles and constraints on local plastic flow within the aluminum matrix. Such mechanisms remain interpretations of the mechanical response. Nevertheless, they agree with the increased resistance to localized deformation reported by Abolusoro et al. (2024) for stir-cast aluminum composites containing moderate RHA additions.

The fracture-strain summary in Fig. 1c indicates that the strength improvement is accompanied by reduced tensile deformability. Fracture strain decreases from 7.18% for

Sample 1 to 5.86% for Sample 2 and 4.73% for Sample 3, corresponding to a 34.12% reduction between the lowest and highest RHA contents. Increasing the particulate fraction may restrict plastic accommodation within the matrix and introduce additional sites for local stress concentration and damage initiation. A related trade-off between strengthening and damage tolerance was observed by Joseph et al. (2023), who reported enhanced tensile strength at moderate RHA loading alongside declining impact resistance with increasing reinforcement content. Their findings support the need to assess strength together with deformation capacity when selecting the composite formulation.

The compressive curves in Fig. 1d show sustained stress increases up to 20% strain, consistent with continued strain hardening. At this strain, the stresses read approximately 325, 370 and 350 MPa for Samples 1-3, respectively. Sample 2 thus exhibits the greatest compressive resistance, indicating a non-monotonic response to RHA addition. The reduction from 4% to 6% RHA could reflect competing effects of particle reinforcement and processing-related heterogeneity. Particle clustering and imperfect interfacial contact are plausible explanations, consistent with strength losses reported at elevated RHA contents by Abolusoro et al. (2024); their occurrence in the present samples requires microstructural evidence. The plotted curves establish compressive flow stress within the tested strain range, while the ultimate compressive strength remains unresolved because no failure peak is shown. Sample 2 combines the highest compressive flow stress with intermediate tensile strength and fracture strain.

Thermal Stability and Melting Behaviour Analysis

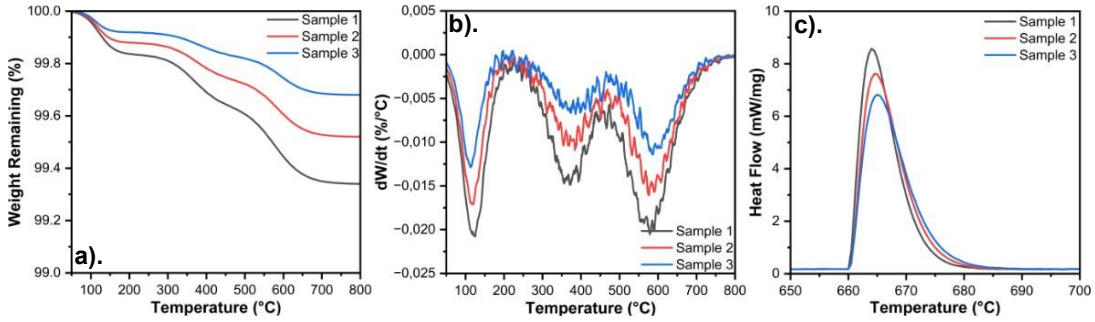


Figure 2. Thermal characterization of Al-SiC-RHA composites. A, Thermogravimetric profiles showing mass retention during heating. B, Derivative thermogravimetric profiles. C, Differential scanning calorimetry profiles around the aluminum

The thermogravimetric profiles in Fig. 2a show limited net mass loss throughout the investigated temperature range. At 800 °C, the remaining masses are approximately 99.34%, 99.52% and 99.68% for Samples 1-3, respectively, corresponding to total losses of approximately 0.66%, 0.48% and 0.32%. Increasing the RHA content from 2% to 6%, with SiC maintained at 2%, is therefore associated with higher apparent mass retention. Nevertheless, the differences remain small in absolute terms, and all compositions retain more than 99.3% of their initial mass. These results indicate limited net volatilization

under the applied heating conditions, without establishing the chemical origin of the observed losses.

The DTG profiles in Fig. 2b resolve three principal negative excursions near 110, 370 and 590 °C. Sample 1 exhibits the deepest minima, whereas the excursions become progressively less pronounced for Samples 2 and 3, qualitatively agreeing with their smaller cumulative mass losses. The lowest-temperature event is compatible with the removal of trace adsorbed moisture. The subsequent events may involve minor residual volatile or carbonaceous constituents, although their identities cannot be established from these curves alone. Zewide et al. (2025) demonstrated that thermal treatment removes organic constituents from rice-derived feedstocks and leaves a predominantly inorganic, silica-rich residue. Consequently, biomass-specific decomposition stages should not be assigned directly to the cast composites without evidence of residual organic matter.

The DSC profiles in Fig. 3c exhibit a pronounced thermal event with maxima around 664-665 °C. This temperature range is consistent with melting of the aluminum matrix. Wang et al. (2021) Clikewise identified an aluminum melting event near 660 °C during TG-DSC analysis. The closely grouped peak positions in the present composites suggest that the principal transition remains controlled by the metallic matrix, with only a small apparent displacement as the RHA content increases. Peak heat flow decreases from approximately 8.6 mW mg^{-1} for Sample 1 to 7.6 mW mg^{-1} for Sample 2 and 6.8 mW mg^{-1} for Sample 3. The reduced aluminum fraction may contribute to this decrease, while differences in peak width and thermal lag can also influence the maximum heat-flow response.

Quantitative comparison of fusion enthalpy requires integration of the baseline-corrected DSC peaks with the heating rate accounted for. Melting temperature and heat of fusion were similarly evaluated as distinct thermophysical properties by Villada et al. (2023) for aluminum-based phase-change materials. The present profiles associate increasing RHA content with reduced net mass loss and lower DSC peak intensity, while showing limited changes in the matrix melting temperature. For structural applications, this melting transition remains critical despite the high mass retention recorded by TGA.

CONCLUSION

Rice husk ash (RHA) content plays an important role in tailoring the mechanical performance of stir-cast aluminum–silicon carbide (Al–SiC) matrix composites to specific loading requirements (Yadav et al., 2018; Ranjan et al., 2022). At a fixed SiC content of 2 wt.%, the composite containing 4 wt.% RHA demonstrated the most favorable resistance to compressive deformation among the investigated formulations, whereas the composite containing 6 wt.% RHA exhibited the highest tensile strength. However, the reduction in tensile deformability with increasing RHA content highlighted the importance of considering deformation tolerance when selecting an appropriate reinforcement concentration (Zewide et al., 2025b). Consequently, the optimal composition depends on the applied stress state, mechanical loading conditions, and strain requirements of the intended application (Sarkar et al., 2018). Thermal characterization

revealed additional constraints on material selection. Increasing RHA content was associated with greater apparent mass retention during thermogravimetric analysis (TGA), while the closely clustered melting peaks observed through differential scanning calorimetry (DSC) indicated that the melting behavior remained predominantly governed by the aluminum matrix. These findings emphasized the distinction between resistance to net mass loss during heating and the ability of the composite to retain a solid, load-bearing matrix at elevated temperatures. The study therefore provided a comparative basis for selecting reinforcement concentrations according to mechanical performance requirements while accounting for the thermal limitations associated with phase transitions in the aluminum matrix. Among the investigated compositions, the intermediate RHA concentration of 4 wt.% showed potential for applications involving predominantly compressive loading, whereas the higher concentration of 6 wt.% was more favorable when tensile strength was the primary consideration. Nevertheless, the suitability of these composites for elevated-temperature applications requires further investigation through mechanical testing under representative service temperatures and loading conditions to establish their high-temperature strength, deformation behavior, and operational reliability (Patil et al., 2020).

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CONFLICT OF INTEREST

The author states that there is no conflict of interest in the preparation of this article.

AUTHOR CONTRIBUTIONS

All authors contributed to conceptualization, search and synthesis of literature, interpretation of results, manuscript preparation, and critical review of manuscripts. All authors have read and approved the final version of the manuscript.

GENERATIVE AI STATEMENT

The authors declare that Generative Artificial Intelligence (Generative AI) was used solely to assist with language refinement, grammatical correction, and improvement of manuscript readability. All scientific concepts, interpretations, literature synthesis, analyses, and conclusions were developed by the authors. All AI-assisted content was carefully reviewed, verified, and revised by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript.

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