RESEARCH PAPER

Experimental Investigation of Hybrid AA7075-T651 Aluminium Metal Matrix Composite Material Reinforcement with Waste Bamboo Ash and Boron Carbide

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ABSTRACT
In this work, a new idea of sustainable material development, waste bamboo ash (AWB) has been used for the reinforcement of hybrid composites. The aim of this research is to enhance the mechanical properties of AA7075-T651 alloy by adding AWB and B_4C reinforcement with stir casting process. The mechanical properties of neat AA7075-T651 were then compared to the mechanical properties of the various synthesized hybrid composite samples that were prepared containing varying amounts of B_4C (3%, 6% and 9%) and AWB (2 wt%). Microstructural analysis revealed that the 6% B4C and 9% B_4C composites contain particle agglomeration, which results in comparatively low mechanical properties due to the distribution of stress that is not regular. The 3 wt% B_4C composites exhibit a reasonable mechanical properties and material integrity, the 6 wt% B_4C composite exhibits moderate mechanical properties and material integrity and the 9% B_4C composite is more suitable for application with high wear resistance, but with a lower ductility.

Keywords: Sustainable Materials; Waste Bamboo Ash; Boron Carbide (B_4C); Hybrid Metal Matrix Composite; AA7075-T651; Stir Casting; Microstructure.
How to cite this article: Ajay T1 Karunakaran K2*. Experimental Investigation of Hybrid AA7075-T651 Aluminium Metal Matrix Composite Material Reinforcement with Waste Bamboo Ash and Boron Carbide. Int J Drug Deliv Technol. 2026;16(80s):1676-1681. DOI: 10.25258/ijddt.16.80s.207.

1. Introduction

Aluminium matrix composites (AMCs) are widely used as industrial engineering materials because of their favourable strength-to-weight ratio. However, their comparatively higher cost relative to conventional aluminium alloys continues to limit wider adoption. The present study explores bamboo leaf/stem waste as a low-cost reinforcement for aluminium-based composites in order to address this cost limitation.

Bannaravuri and Birru (2019) studied the mechanical properties of stir-cast Al-4.5%Cu alloy reinforced with SiC and bamboo leaf ash (BLA), examining the composites through SEM, optical microscopy, tensile and hardness testing. A clear interfacial boundary was observed between the matrix and the reinforcement particles. The addition of SiC increased composite density, whereas the inclusion of BLA reduced it relative to the unreinforced alloy; reinforcement particles improved the tensile strength and hardness of both the SiC-only and the SiC/BLA hybrid composites. Alaneme et al. (2020) investigated how silicon carbide and bamboo leaf ash together influenced the hot-deformation behaviour of an aluminium-based composite, performing isothermal compression tests on a Gleeble 3500 thermomechanical simulator across 300–400 °C and a strain rate of 0.01 s^{-1}. Flow stress was found to be largely insensitive to strain rate but increased as deformation temperature decreased, a trend typical of Al 6XXX-series systems.

Haile et al. (2024) reinforced pure aluminium with Bamboo Stem Ash Powder (BSAP) at concentrations from 0 to 10 wt% and reported that 7.5 wt% BSAP produced the peak hardness (239.66 HV) and compressive strength (308.32 MPa). Wang et al. (2022) developed an environmentally stable bamboo composite with a hierarchical SiO2-coated GO/bamboo structure that exceeded natural bamboo in toughness (17.5 MJ/m3), flexural strength (428.4 MPa) and tensile strength (641.6 MPa) — improvements of roughly 480%, 250% and 360% respectively — while its specific tensile strength (513.3 MPa·cm3/g) at a low density of 1.25 g/cm3 exceeded that of aluminium, steel and titanium alloys. Atuanya et al. (2018) used the stir-casting route to reinforce cast aluminium with cost-effective bamboo leaf stem ash particulates (BLSAp), obtaining a 16.93% increase in tensile strength and a 12.15% increase in hardness at 15 wt% BLSAp, alongside a 14.91% reduction in density and an 18.64% reduction in impact energy at the same loading.

Kumar and Birru (2017) reinforced an Al-4.5%Cu matrix with 2, 4 and 6 wt% bamboo leaf ash and found that hardness and tensile strength increased up to 4 wt% BLA before declining, while density decreased and porosity increased as the BLA fraction rose. Using a double stir-casting process, Alaneme et al. (2014) prepared Al-Mg-Si hybrid composites containing 10 wt% total reinforcement (alumina with 2, 3 or 4 wt% BLA); the 4 wt% BLA hybrid exhibited the highest coefficient of friction and wear rate, while the 2 and 3 wt% BLA hybrids showed wear resistance marginally better than the single-reinforced alumina composite. In an earlier study, Alaneme et al. (2013) combined SiC (10 wt% total reinforcing phase) with 0, 2, 3 and 4 wt% BLA in an Al-Mg-Si matrix; the hybrid composites showed higher fracture toughness than the single-reinforced Al/10 wt% SiC composite, and the 2–3 wt% BLA hybrids showed better corrosion resistance in 5 wt% NaCl, although the single-reinforced composite performed better in 0.3 wt% H2SO4.

Bannaravuri and Birru (2018) added 0, 2, 4 and 6 wt% BLA to an Al-4.5%Cu matrix and found that wear rate decreased with BLA addition, with the 4 wt% BLA composite showing the best anti-wear performance, attributed to increased dislocation density. Ebenezer et al. (2021) reinforced an A356.2 alloy with 2, 4 and 6 wt% BLA and subsequently electrodeposited nickel onto the composite surface; polarization testing in aerated 3.5% NaCl showed that both mechanical behaviour and corrosion resistance improved as the BLA content increased. While the studies above confirm that bamboo-derived ash is an effective, low-cost reinforcement, the great majority of this work has targeted comparatively low-strength casting alloys — Al-4.5Cu, A356.2 and commercially pure aluminium — rather than the high-strength, precipitation-hardenable AA7075 system. A separate body of work has instead examined AA7075 reinforced with boron carbide (B_4C) alone or in hybrid combination with other waste-derived fillers.

Demir et al. (2023) reinforced AA7075 with 4–12 wt% B_4C by squeeze casting and reported progressive improvements in hardness, tensile strength and wear resistance with increasing B4C content, accompanied by a reduction in ductility — a trend consistent with the agglomeration-related loss of ductility observed at high reinforcement levels in the present study. Aherwar et al. (2020) combined a fixed 4 wt% B4C with 0–16 wt% waste porcelain ceramic in an AA7075 matrix and found that micro-hardness, tensile strength and compressive strength all increased with the added ceramic phase while density decreased, demonstrating that a second low-cost waste filler can be paired with B4C without compromising its strengthening contribution. Rajpradeesh et al. (2026) combined up to 15 wt% B_4C with a fixed 3 wt% rice-husk ash in an AA7075 hybrid and measured a tensile strength of 269.3 MPa and a hardness of 169 BHN at the highest B4C loading, against 120.2 MPa and 125 BHN for the unreinforced alloy — underscoring B4C as the dominant strengthening constituent in such hybrids. The review of Sambathkumar et al. (2023) of AA7075 composites reinforced with Al2O3, SiC and B_4C similarly concluded that reinforcement type and content govern the trade-off between strength/hardness and ductility, mirroring the balance identified among the 3, 6 and 9 wt% B4C + AWB compositions evaluated in the present work. Taken together, these AA7075-specific studies corroborate the trends observed here and indicate that pairing B4C with an alternative, low-cost waste-derived filler — bamboo ash, in this case — is a viable route to further reduce material cost without sacrificing the strengthening mechanism already established for B_4C. A clear research gap therefore exists at the intersection of these two bodies of work: the combination of ash of waste bamboo (AWB) with the advanced, high-strength aluminium alloy AA7075-T651 remains minimally studied, despite the demonstrated compatibility of both AWB and B4C with other aluminium matrices individually. This study evaluates AWB's reinforcing attributes in an AA7075-T651/B_4C hybrid system to develop a sustainable material option that is both cost-effective and environmentally responsible, while filling this specific gap in the literature.

This investigation introduces hybrid composites integrating waste bamboo ash into AA7075-T651 using its sustainable, natural origin, addressing both advanced-material development and waste-management objectives simultaneously. The study characterizes how the mechanical and microstructural properties of the AA7075-T651 hybrid composite change as AWB and B4C reinforcement levels vary, with the aim of identifying compositions suited to high-performance industrial applications such as automotive and aerospace components. By reducing dependence on non-renewable ceramic reinforcement while converting an agricultural waste stream into a value-added input, AWB offers both environmental and economic benefits. The findings are intended to inform the development of hybrid composites for applications demanding lightweight, robust and environmentally responsible materials.

Objectives of the present study:

- To fabricate AA7075-T651 hybrid composites reinforced with 3, 6 and 9 wt% B_4C at a fixed 2 wt% AWB addition, using the stir casting technique.
- To characterize the resulting microstructure by optical microscopy and compare it against the neat AA7075-T651 base alloy.
- To evaluate the qualitative structure–property trends across the composition range and identify the reinforcement combination offering the best balance of strength, hardness and ductility for target applications.

2. Materials and Methods

2.1 Materials

The AA7075-T651 base metal alloy was procured in ingot form, and spectrochemical analysis was used to verify the chemical composition of the sample. Boron carbide (B_4C) particles with an average size of 50 µm were used as the primary ceramic reinforcement.

Figure 1. Synthesis of composites

Table 1. Designation and nominal composition of the samples evaluated in this study

Sample ID	AA7075-T651 (wt%)	B_4C (wt%)	AWB (wt%)
S0 — Neat alloy	100	0	0
S1	95	3	2
S2	92	6	2
S3	89	9	2

2.2 Ash Preparation

Waste bamboo chips were collected and heated in a furnace at 700 °C for three hours to produce ash. The resulting ash was sieved to below 75 µm before use as reinforcement.

2.3 Composite Fabrication by Stir Casting

Figure 1 illustrates the stir-casting route used to prepare the composites. An electric resistance furnace was used to melt 2 kg of AA7075-T651 alloy in a graphite holding crucible, held at 750 °C for 30 minutes to achieve uniform melting conditions. The molten alloy was degassed using solid hexachloroethane (C_2Cl_6) to remove trapped gases. B_4C particles and bamboo ash were separately pre-heated in a muffle furnace at 450 °C for one hour to remove moisture and improve wettability with the molten alloy. A mechanical stirrer fitted with a zirconia-coated impeller was used to create a vortex in the melt, with stirring maintained at 500 rpm for ten minutes to ensure uniform particle distribution. B4C particles were added stepwise into the vortex, followed by the bamboo ash; the reinforcement mixture (for example, 3% B_4C with 2 wt% AWB) was stirred for an initial two minutes to minimise agglomeration before the full stirring cycle was completed. The molten composite was poured at 730 °C into a graphite-coated, 150 mm × 150 mm × 10 mm mild-steel mould pre-heated to 250 °C. The mould was left at room temperature for two hours to allow solidification before the casting was extracted and allowed to cool further to room temperature.

Figure 2. The prepared composite samples

2.4 Heat Treatment (T6)

After solidification, each composite was subjected to a T6 heat treatment to enhance mechanical properties. Samples were solution-treated at 480 °C for two hours in a muffle furnace, followed by water quenching. This was followed by an artificial ageing step at 120 °C for 24 hours, after which the samples were allowed to cool naturally. The heat-treated material was machined to remove surface defects prior to testing.

2.5 Metallographic Sample Preparation and Microstructural Examination

Samples for metallographic analysis were sectioned using an abrasive cutter and mounted in bakelite for handling during polishing. A mirror-like finish was achieved by sequentially polishing with silicon carbide papers from 240 to 1200 grit, followed by finishing with an alumina suspension. Keller's reagent — a mixture of distilled water with 5 mL nitric acid (HNO3), 3 mL hydrochloric acid (HCl) and 2 mL hydrofluoric acid (HF) — was used to etch the polished samples for 10–30 seconds to reveal grain boundaries and second-phase particles. Samples were rinsed in distilled water immediately after etching and dried with hot air. Microstructural imaging was performed using an optical microscope with a 10× objective and 10× eyepiece (100× total magnification) fitted with a digital camera. Up to 100 fields of view were captured per sample to characterise grain structure and reinforcement distribution.

3. Results and Discussion

3.1 Microstructural Analysis

The microstructure of neat AA7075-T651 (Photo 1, Figure 3) shows a uniformly distributed, fine equiaxed grain structure typical of heat-treated aluminium alloys, with well-defined grain boundaries and no second-phase particles. This homogeneous grain structure reflects the alloy's inherent strength and toughness but does not benefit from the additional strengthening contribution of ceramic reinforcement. The addition of 3% B_4C with 2% AWB (Photo 2, Figure 3) produces a clearly refined microstructure, with bamboo ash dispersed through the matrix alongside fine B_4C particles. The B4C particles act as pinning sites at the grain boundaries, promoting grain refinement beyond that of the base alloy and improving hardness and wear resistance through dispersion strengthening; the contribution of the bamboo ash to these mechanical effects appears comparatively minor, though its distribution throughout the matrix remains even.

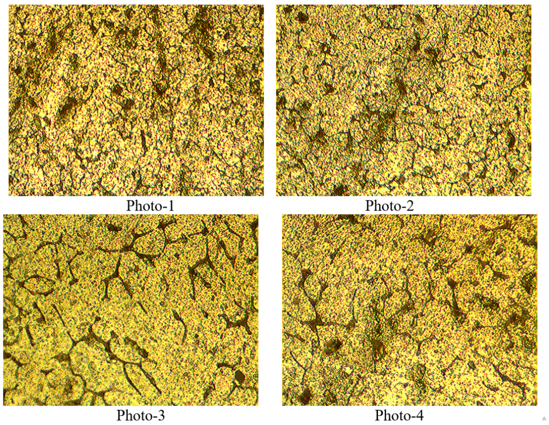

Figure 3. Microstructure of the base alloy and composites

The photo – 1 shows the Neat AA7075-T651; photo – 2 shows AA7075-T651 + 3% B_4C + 2% AWB; photo – 3 shows AA7075-T651 + 6% B_4C + 2% AWB; photo – 4 shows AA7075-T651 + 9% B_4C + 2% AWB. At 6% B_4C (Photo 3, Figure 3), the density of second-phase B_4C particles increases noticeably, and finer grains confirm that additional B_4C enhances grain-boundary pinning and refinement. However, the higher reinforcement level also produces visible agglomeration and clustering, which can locally disrupt uniform dispersion; the retained bamboo ash content helps preserve some structural integrity. While localised stress concentration may develop at these B_4C clusters, the 3% B_4C composite continues to show superior overall strength and hardness relative to the base alloy at this stage of comparison.

At 9% B4C (Photo 4, Figure 3), B_4C particles are distributed at higher density throughout the matrix, but with more pronounced clustering and segregation in localised regions. This stronger aggregation behaviour is likely to produce inconsistent mechanical properties across the sample. Because B_4C is a non-ductile ceramic, high reinforcement fractions increase overall material brittleness even as they produce the greatest grain refinement observed in this study; the resulting stress risers at agglomerated regions are expected to promote crack initiation under mechanical loading. Bamboo ash continues to contribute modestly to grain refinement relative to B_4C at this composition.

3.2 Comparative Discussion

Across the composition range studied, the 6% and 9% B_4C composites show visible particle agglomeration, which is expected to produce uneven internal stress distribution and correspondingly variable mechanical performance. The neat AA7075-T651 alloy offers high baseline strength and toughness but no enhancement in hardness or wear resistance. The 3% B_4C + 2% AWB composite offers the best balance of ductility, hardness and strength with minimal particle clustering; the 6% B_4C + 2% AWB composite offers improved wear resistance and hardness at a modest risk of localised clustering effects on ductility; and the 9% B_4C + 2% AWB composite offers the highest hardness and wear resistance but the greatest ductility penalty and stress-concentration risk from particle clustering.

Table 2. Qualitative comparison of microstructural and mechanical trends across compositions (synthesised from the microstructural findings above)

Composition	**Grain refinement**	**Particle distribution**	**Relative hardness / strength**	**Ductility**	**Best-suited application**
S0 — Neat AA7075-T651	None (coarse baseline grains)	No reinforcement	Baseline	Highest	General structural use
S1 — 3% B4C + 2% AWB	Moderate	Uniform, minimal clustering	Good	Good	Balanced strength–ductility applications
S2 — 6% B4C + 2% AWB	Higher	Some clustering	Higher	Reduced vs. S1	Wear-resistant components tolerating some

Composition	Grain refinement	Particle distribution	Relative hardness / strength	Ductility	Best-suited application
					ductility loss
S3 — 9% B4C + 2% AWB	Highest	Noticeable agglomeration / segregation	Highest	Lowest	Extreme wear-resistance applications

4. Conclusions

The reinforcement level of B_4C directly affects grain refinement and improves the mechanical properties of AA7075-T651 by strengthening and hardening the matrix. The B_4C content level above 6wt% reduces the ductility and increases the tendency for particle agglomeration. The mechanical reinforcement contribution of B_4C is more than that of bamboo ash, which is only used as a microstructure-refining agent. The 9% B4C composite is more wear resistant, but less ductile, whereas the 3% and 6% B_4C compositions have a more desirable wear-resistance/ductility balance. The 9% B_4C + 2% AWB (balance AA7075-T651) composite showed the greatest grain refinement and reinforcement density when compared to the other composites examined on a microstructural basis and is therefore recommended for use in wear critical applications where some compromise of the ductility properties is acceptable; the 3% and 6% B_4C compositions are still recommended for use where a more balanced property set is required.

5. Future Scope

- Quantitative mechanical characterization (hardness, tensile strength, wear rate, impact toughness) of all four compositions, with appropriate test standards and statistical replication, to substantiate the qualitative microstructural findings reported here.
- SEM/EDS and XRD analysis to confirm interfacial bonding, phase formation and reinforcement distribution beyond the resolution of optical microscopy.
- Optimisation of AWB content (fixed at 2 wt% in this study) alongside B4C content using a statistical design-of-experiments approach (e.g., Taguchi or response surface methodology) to identify a global optimum composition.
- Corrosion and thermal-stability evaluation, given the automotive and aerospace application space targeted for this material.
- A life-cycle and cost analysis to quantify the sustainability and economic benefit of substituting AWB for a portion of conventional ceramic reinforcement.

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