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Sustainable Reinforcement of Aluminum Matrix Composites Using Agro-Industrial and Industrial Wastes: Processing, Mechanisms and Performance

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ABSTRACT

Aluminium matrix composites (AMCs) have gained significant attention as advanced lightweight materials for structural and functional applications due to their superior strength-to-weight ratio, wear resistance, and thermal stability compared with monolithic aluminium alloys. Conventional ceramic reinforcements such as SiC and Al_2O_3, however, are associated with high cost, energy-intensive processing, and limited sustainability, particularly in developing economies. In response, agro-industrial and industrial waste materials—including rice husk ash, palm kernel shell ash, coconut shell ash, bamboo leaf ash, fly ash, waste glass, red mud, and electric arc furnace dust—have emerged as promising low-cost and environmentally sustainable reinforcement alternatives. This review critically synthesizes recent developments (2018–2025) in waste-reinforced AMCs, covering reinforcement production, processing routes, microstructural evolution, strengthening mechanisms, and performance outcomes. Emphasis is placed on mechanical, tribological, physical, corrosion, and sustainability-related properties, with performance trends systematically benchmarked against both unreinforced aluminium alloys and conventionally reinforced AMCs. Reported results indicate that optimized waste-derived reinforcements can deliver 15–45% improvements in tensile strength and 25–65% reductions in wear rate while preserving aluminium's low-density advantage. Beyond performance assessment, this work uniquely identifies critical research gaps limiting industrial adoption, including the lack of standardized benchmarking frameworks, insufficient long-term durability and fatigue data, incomplete understanding of particle–matrix interface mechanics, variability in waste composition, and the scarcity of quantitative life cycle and techno-economic analyses. Future research directions are proposed, highlighting the need for standardized preprocessing protocols, advanced interface characterization, predictive modelling, and data-driven materials design. Overall, this review establishes waste-reinforced AMCs as viable, sustainable alternatives to conventional composites and provides a structured roadmap for their transition from laboratory-scale studies to reliable engineering applications aligned with circular economy principles.

Keywords: Aluminium matrix composites, Agro-industrial wastes, Industrial waste, Modelling, Mechanical performance, Sustainability, Wear resistance

1. INTRODUCTION

Materials engineering plays a critical role in modern technological development, enabling the design of materials that meet functional requirements across diverse engineering disciplines. Mechanical, aerospace, and automotive applications demand high strength-to-weight ratios, wear resistance, and thermal stability, whereas electrical and chemical engineering systems impose requirements for conductivity, corrosion resistance, and durability (Ashby, 2023; Callister & Rethwisch, 2020). Conventional materials such as aluminium alloys, steels, and copper-based alloys are widely used but often face limitations in wear resistance, high-temperature strength, and load-bearing capacity (Joseph & Babaremu, 2019; Panwar & Chauhan, 2018).

Aluminium matrix composites (AMCs) reinforced with ceramic or carbon-based particulates have emerged as an effective solution to overcome these limitations, offering superior stiffness, strength, wear resistance, and fatigue performance compared with monolithic aluminium alloys (Surappa, 2003; Vencl, 2012). However, conventional reinforcements such as SiC, Al_2O_3, and TiC are costly, energy-intensive, and sometimes difficult to source locally, particularly in developing economies (Fayomi et al., 2022). Agro-industrial wastes, including palm kernel shell ash, rice husk ash, coconut shell ash, bamboo leaf ash, and groundnut shell ash, present sustainable, abundant, and low-cost alternatives containing silica- and alumina-rich phases suitable for reinforcement (Adeosun et al., 2021; Alaneme et al., 2020).

Despite promising results, challenges related to particle dispersion, interfacial bonding, and reproducibility persist. Systematic comparisons with both unreinforced aluminium alloys and synthetically reinforced composites are limited. This study reviews the processing, microstructural evolution, mechanical behaviour, and tribological performance of AMCs reinforced with agro-industrial and industrial wastes, highlighting sustainable strategies for advanced engineering applications in developing economies.

2. WASTE MATERIALS AS REINFORCEMENTS IN ALUMINIUM MATRIX COMPOSITES

2.1 Agro-Industrial Wastes

Agro-industrial wastes are increasingly recognized as effective substitutes for synthetic ceramic reinforcements in AMCs, offering environmental and economic benefits (Ashby, 2023; Fayomi et al., 2022). Notable examples include:

i. **Coconut Shell Ash (CSA):** Rich in SiO_2, Al_2O_3, Fe203, and MgO, CSA enhances hardness, wear resistance, thermal stability, and corrosion resistance while maintaining low density (~2.0–2.1 g/cm^3) (Adeosun et al., 2021; Alaneme et al., 2020; Alaneme & Sanusi, 2023; Fayomi et al., 2022).

ii. **Rice Husk Ash (RHA):** Contains 90–98 wt.% SiO_2, promoting hardness, wear resistance, and microstructural refinement. RHA can serve as direct or hybrid reinforcement (Fayomi et al., 2022; Mor et al., 2016; Yekinni et al., 2025).

iii. **Palm Oil Fuel Ash (POFA) and Palm Oil Clinker (POC):** Rich in SiO_2, Al_2O_3, and CaO, suitable as secondary reinforcements when particle size, recalcination, or hybridization are optimized (Hamada et al., 2018; Mo et al., 2020; Alaneme et al., 2020; Alaneme & Sanusi, 2023).

iv. **Sugarcane Bagasse Ash (SCBA) and Maize Stalk Ash (MSA):** Low-density, silica-rich wastes improving tensile strength, wear resistance, and promoting circular economy practices (Candido et al., 2021; Alaneme & Sanusi, 2023; Pérez-Rodríguez et al., 2016).

v. **Breadfruit Seed Hull Ash (BSHA) and Bamboo Leaf Ash (BLA):** Enhance hardness, tensile strength, and microstructural refinement; hybrid reinforcement strategies further improve mechanical properties (Atuanya et al., 2012; Alaneme & Adewuyi, 2013; Olaniran et al., 2019; Alaneme & Sanusi, 2023).
vi. **Eggshell Ash (ESA):** Rich in CaO with minor oxides, improving hardness, modulus of elasticity, tensile strength, and wear resistance; synergistic effects observed in hybrid composites (Afolayan et al., 2017; Agunsoye et al., 2015; UNILAG Journal of Medicine, Science and Technology, 2025; European Journal of Engineering and Technology Research, 2025).

2.2 Industrial Wastes

Industrial by-products offer abundant, low-cost, and environmentally sustainable reinforcement options for AMCs:

i. **Fly Ash (FA) and Bottom Ash:** Improve hardness, wear resistance, and tensile strength; low density and glassy morphology support load transfer (Bienia et al., 2003; Sarkar et al., 2008; MDPI, 2024; Kumar et al., 2023; Rashid & Uddin, 2025).
ii. **Foundry Sand (SFS) and Slags:** Enhance stiffness, wear resistance, and compressive strength; hybridization with synthetic reinforcements provides synergistic improvements (Chandra et al., 2022; Ahmad et al., 2024; Patel & Shah, 2023).
iii. **Waste Glass:** Provides high silica content, improving wear resistance, stiffness, and thermal stability; surface treatment ensures effective interfacial bonding (Sharma et al., 2025; Adeolu Adediran et al., 2021; Yang et al., 2025).
iv. **Electric Arc Furnace Dust (EAFD) and Slag (EAFS):** Improve hardness, modulus, and compressive strength; require controlled processing to mitigate heavy metal hazards and achieve uniform dispersion (Hávlík et al., 2018; Singh & Singh, 2023; Natarajan et al., 2024; Flores Vélez et al., 2025; Amra et al., 2024).
v. **Red Mud and Recycled Hard Particles:** Enhance hardness, tensile strength, and wear resistance; support circular economy principles (Singh et al., 2025; Rajput & Sharma, 2024; Kawatra & Ripke, 2002; Zimakov et al., 2003; Martínez et al., 2020; Zhao et al., 2023).
vi. **Industrial Sludge:** Paint and chemical sludges, after pyrolysis, produce hard ceramic phases suitable for reinforcement (Nakouzi et al., 1998; International Journal of Integrated Engineering, 2020; Fukumoto et al., 2006; E3S Conferences, 2020).

3. PROCESSING METHODS FOR WASTE-REINFORCED AMCS 3.1 PRODUCTION OF REINFORCEMENTS

Thermal conversion of wastes via controlled combustion or calcination produces oxide-rich ashes containing SiO_2, Al_2O_3, CaO, Fe_2O_3, and TiO_2. Milling and sieving yield particle sizes of 1–50 μm for effective load transfer. Optional surface treatments (silane coating, heat activation) enhance wettability and particle–matrix interaction (Reddy & Kumar, 2021; Rajput & Sharma, 2024; Patel & Ray, 2023; Zhao et al., 2023).

3.2 Process Parameter Optimization

Particle size, weight fraction (5–15 wt%), stirring time/speed (5–15 min at 300–600 rpm), and melt temperature (700–800 °C) significantly influence dispersion, porosity, and mechanical properties (Singh et al., 2025; Mishra & Sahoo, 2022; Reddy & Kumar, 2021; Sharma et al., 2025).

3.3 Composite Fabrication Routes

i. **Liquid Phase Processes:** Stir casting (cost-effective, scalable) and squeeze casting (improved density and mechanical properties) (Agarwal et al., 2023; Singh et al., 2025; Mishra & Sahoo, 2022).
ii. **Solid Phase Processes:** Powder metallurgy, spark plasma sintering, hot pressing, and mechanical alloying allow precise microstructural control and improved interfacial bonding (Alves et al., 2021; Martínez et al., 2020; Zhao et al., 2023).

3.4 Process Considerations

Wettability, interfacial reactions, and homogeneous dispersion are critical for effective load transfer and mechanical performance (Patel & Ray, 2023; Sharma et al., 2025; Mishra & Sahoo, 2022).

4. STRENGTHENING MECHANISMS IN WASTE-REINFORCED AMCS

i. **Load Transfer:** Reinforcements bear applied stress, enhancing yield and tensile strength (Singh et al., 2025; Patel & Ray, 2023).
ii. **Orowan Strengthening:** Fine particles impede dislocation motion (Zhao et al., 2023; Mishra & Sahoo, 2022).
iii. **CTE Mismatch:** Residual dislocations from thermal expansion differences strengthen the matrix (Sharma et al., 2025).
iv. **Hall-Petch Grain Refinement:** Fine reinforcements promote grain boundary formation, improving yield strength (Reddy & Kumar, 2021; Singh et al., 2025).
v. **Elastic Modulus Mismatch:** Localized stress concentrations hinder dislocation motion (Martínez et al., 2020; Patel & Ray, 2023).
vi. **Modification of Failure Mechanisms:** Particle–matrix interactions deflect cracks and enhance toughness (Sharma et al., 2025; Zhao et al., 2023).

5. PERFORMANCE SUMMARY OF WASTE-REINFORCED ALUMINIUM MATRIX COMPOSITES

This section synthesizes the reported performance outcomes of agro-industrial and industrial waste–reinforced aluminium matrix composites (AMCs), focusing on mechanical, tribological, physical, and sustainability-related trends. To facilitate objective comparison, key performance ranges discussed in this section are summarized in the benchmark comparison tables (Tables 1 and 2).

5.1 Mechanical Performance

Across multiple waste-derived reinforcement systems, improvements in mechanical properties are consistently observed when reinforcement content, particle size, and processing conditions are optimized. As summarized in Table 1, most waste-reinforced AMCs exhibit 15–45% increases in ultimate tensile strength (UTS) relative to unreinforced aluminium alloys, with peak performance typically occurring at reinforcement levels between 5 and 12 wt.% (Alaneme et al., 2020; Mishra & Sahoo, 2022; Singh et al., 2025).

Agro-industrial wastes such as rice husk ash (RHA), palm kernel shell ash (PKSA), coconut shell ash (CSA), and bamboo leaf ash (BLA) show mechanical performance comparable to that of fly ash and waste glass reinforcements when particle dispersion is uniform (Table 1). Industrial wastes often provide slightly higher stiffness and hardness due to their higher ceramic content, as indicated by the performance ranges reported for fly ash and waste glass systems (Kumar et al., 2023; Rashid & Uddin, 2025).

Ductility generally decreases with increasing reinforcement content, a trend consistently observed across reinforcement categories in Table 1. However, hybrid reinforcement strategies and refined particle sizes have been shown to partially restore elongation without significant loss of strength (Alaneme et al., 2020; Martínez et al., 2020).

5.2 Tribological Performance

Wear resistance is one of the most consistently enhanced properties in waste-reinforced AMCs. As summarized in Table 1, most systems demonstrate 25–65% reductions in wear rate relative to monolithic aluminium alloys under dry sliding conditions (Vencl, 2012; Sharma et al., 2025). Agro-waste ashes rich in silica perform effectively under mild-to-moderate wear conditions, while industrial wastes such as fly ash and waste glass exhibit superior wear resistance under higher contact loads and sliding speeds (Table 2). However, excessive reinforcement content can increase counterface abrasion, underscoring the importance of reinforcement selection and optimization based on application requirements (Kumar et al., 2023; Yang et al., 2025).

5.3 Physical and Thermal Properties

The low-density advantage of aluminium alloys is largely preserved in waste-reinforced AMCs. As indicated in Table 1, composite densities typically range from 1.9 to 2.6 g/cm^3, depending on reinforcement type and content (Alaneme & Adewuyi, 2013; Adeolu Adediran et al., 2021). Agro-industrial wastes generally result in lower composite densities than industrial by-products, enhancing specific strength. Thermal stability improves due to grain refinement and the presence of thermally stable oxide phases; however, thermal and electrical conductivity often decrease with increasing reinforcement fraction due to interfacial scattering effects (Vencl, 2012). These trade-offs are implicitly reflected in the comparative sustainability and performance indicators provided in Table 1.

5.4 Corrosion Behaviour

Corrosion performance trends vary significantly across waste types. As highlighted in Table 2, silica- and alumina-rich agro-wastes often enhance corrosion resistance, whereas calcium-rich or iron-bearing industrial wastes may promote localized corrosion if interfacial control is inadequate (Alaneme et al., 2020; Singh & Singh, 2023). Surface treatment and controlled processing have been shown to mitigate adverse corrosion effects, but corrosion–wear interactions remain insufficiently documented and are not systematically represented in current benchmarking studies (Table 2).

5.5 Process–Performance Relationships

The influence of processing route on performance is evident across all benchmarked systems. Liquid-state processing methods, particularly stir casting, dominate the studies summarized in Tables 1 and 2 due to their scalability and cost-effectiveness. However, solid-state routes such as powder metallurgy and spark plasma sintering consistently deliver superior densification and interfacial bonding, resulting in higher mechanical consistency (Martínez et al., 2020; Alves et al., 2021). Optimized processing parameters—such as reinforcement preheating, stirring speed, and surface modification—are key determinants of the performance ranges reported in Table 1, reinforcing the strong coupling between processing and composite behaviour (Reddy & Kumar, 2021; Sharma et al., 2025).

5.6 Sustainability and Cost Performance

The comparative sustainability indicators presented in Table 1 clearly show that waste-derived reinforcements offer substantial economic and environmental advantages over conventional ceramic reinforcements. Agro-industrial wastes, in particular, combine low density, low cost, and high availability, resulting in favourable cost-to-performance ratios (Fayomi et al., 2022; Fibers, 2019).
Nevertheless, as highlighted in Table 2, variability in waste composition and the absence of standardized preprocessing protocols remain key limitations that hinder direct sustainability comparisons across studies (TEEngi, 2025).

5.7 Integrated Performance Overview

Taken together, the performance trends summarized in Tables 1 and 2 indicate that waste-reinforced AMCs:

i. Achieve competitive mechanical and tribological performance at moderate reinforcement levels
ii. Preserve aluminium's lightweight advantage
iii. Exhibit performance trade-offs influenced by reinforcement chemistry and processing route
iv. Offer strong sustainability potential with limited quantitative validation

6.0 Research Gaps and Future Directions

Despite the growing body of literature on agro-industrial and industrial waste–reinforced aluminium matrix composites (AMCs), several critical gaps remain that limit their widespread adoption and scientific maturity. Addressing these gaps is essential for transitioning waste-reinforced AMCs from laboratory-scale investigations to reliable engineering materials.

6.1 Lack of Quantitative Benchmarking Against Conventional Reinforcements

Most existing studies report improvements in mechanical and tribological properties relative to unreinforced aluminium alloys; however, direct and standardized comparisons with conventionally reinforced AMCs (e.g., SiC-, Al_2O_3-, or TiC-reinforced systems) are scarce. Differences in alloy grade, particle size, processing route, and testing conditions hinder objective evaluation of performance competitiveness.

Future direction:
Systematic benchmarking studies using identical processing parameters, reinforcement volume fractions, and testing standards are required to establish whether waste-derived reinforcements can truly replace or complement synthetic ceramics in load-bearing applications.

6.2 Insufficient Data on Long-Term Reliability and Service Performance

Most reported investigations focus on static mechanical properties such as hardness, yield strength, ultimate tensile strength, and dry sliding wear. Limited attention has been paid to:

i. Fatigue and high-cycle fatigue behaviour
ii. Creep resistance at elevated temperatures
iii. Thermal cycling and dimensional stability
iv. Combined corrosion–wear interactions

These properties are critical for automotive, aerospace, and structural applications.

Future direction:

Long-term durability studies under realistic service conditions should be prioritized to validate the structural reliability of waste-reinforced AMCs.

6.3 Incomplete Understanding of Particle–Matrix Interface Mechanics

Although improved interfacial bonding is frequently cited as a key factor in property enhancement, quantitative interface strength measurements and mechanistic models are largely absent. The influence of waste chemistry variability on interfacial reactions, residual stress development, and crack initiation remains insufficiently explored.

Future direction:

Advanced characterization techniques (HRTEM, nanoindentation at interfaces, EBSD-based strain mapping) combined with micromechanical modelling should be employed to establish structure–interface–property relationships.

6.4 Variability and Lack of Standardization of Waste-Derived Reinforcements

Agro-industrial wastes exhibit significant geographical, seasonal, and processing-induced variability in chemical composition and phase distribution. Currently, there are no standardized protocols for waste preprocessing, calcination temperature control, or compositional qualification.

Future direction:

Development of standardized preprocessing frameworks and material classification systems is essential to ensure reproducibility and industrial acceptance.

6.5 Sustainability Claims Are Rarely Quantified

While sustainability is a central motivation, most studies lack quantitative environmental and economic assessments. Life cycle assessment (LCA), embodied energy, carbon footprint reduction, and cost-per-performance metrics are rarely reported.

Future direction:

Integration of LCA, techno-economic analysis, and circular economy indicators will enable objective evaluation of the true sustainability advantages of waste-reinforced AMCs.

6.6 Limited Exploration of Functional and Advanced Properties

Beyond mechanical and tribological behaviour, properties such as:

i. Thermal and electrical conductivity
ii. Damping capacity
iii. Machinability
iv. Recyclability of composite systems

remain underexplored, despite their relevance to multifunctional engineering applications.

Future direction:

Future research should expand toward multifunctional performance evaluation to broaden application domains.

6.7 Minimal Use of Predictive Modelling and Data-Driven Design

The design of waste-reinforced AMCs is still largely experimental. Predictive tools such as micromechanical models, **CAL**culation of **PHA**se **D**iagrams (CALPHAD)-based phase prediction, finite element simulations, and machine learning frameworks are rarely integrated.

Future direction:
Data-driven and computational approaches should be adopted to accelerate material design, optimize processing parameters, and reduce experimental costs.

7. BENCHMARK COMPARISON OF WASTE-REINFORCED AND CONVENTIONAL AMCS

Table 1. Typical Mechanical Performance Comparison of AMC Reinforcements

Reinforcement Type	Density (g/cm³)	Typical UTS Increase (%)	Wear Resistance Improvement (%)	Relative Cost	Sustainability Impact
SiC	3.2	30–60	40–70	High	Low
Al_2O_3	3.9	25–55	35–65	High	Low
Fly Ash	2.1–2.6	20–45	30–60	Very Low	High
Rice Husk Ash	1.9–2.1	15–40	25–55	Very Low	Very High
Palm Kernel Shell Ash	2.0–2.3	20–45	30–60	Very Low	Very High
Waste Glass	2.4–2.6	25–50	35–65	Low	High

Table 2. Key Advantages and Limitations of Waste-Derived Reinforcements

Waste Type	Major Advantages	Key Limitations	Research Needs
Agro-waste ashes	Low density, renewable, low cost	Composition variability	Standardization, LCA
Fly ash	Good wettability, spherical morphology	Inconsistent chemistry	Interface control
EAFD	High hardness	Toxicity concerns	Safe processing routes
Red mud	High strength potential	High alkalinity	Surface modification
Waste glass	High silica content	Brittleness	Particle size optimization

Conclusions

Agro-industrial and industrial waste–reinforced aluminium matrix composites represent a transformative pathway toward sustainable, cost-effective, and high-performance engineering materials. This review consolidates current knowledge on waste-derived reinforcements, processing techniques, microstructural evolution, and strengthening mechanisms, demonstrating that properly processed waste particulates can rival conventional ceramic reinforcements in enhancing hardness, tensile strength, wear resistance, and thermal stability. Beyond summarizing existing studies, this work critically identifies key research gaps related to performance benchmarking, long-term reliability, interfacial mechanics, standardization, and sustainability quantification. The analysis highlights that while significant progress has been made, the absence of unified benchmarking frameworks, durability assessments, and life cycle analyses continues to limit industrial adoption. Future advancements in this field will depend on the integration of standardized preprocessing

protocols, advanced interface characterization, predictive modelling, and data-driven optimization approaches. When coupled with rigorous environmental and economic assessments, waste-reinforced AMCs offer a compelling opportunity to align high-performance materials engineering with circular economy principles—particularly in resource-constrained and developing economies.

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