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Physico-mechanical Properties, Tribological Behaviour and Metallurgical Characteristics of Aluminium Metal Matrix Composites Reinforced with Agricultural Residues: A Review

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ABSTRACT

Aluminium Metal Matrix Composites (AMMCs) that are reinforced with agricultural residues (such as rice husk ash, coconut shell ash, sugarcane bagasse ash, maize/corn-cob ash, palm kernel and shell ash) have garnered increasing attention as environmentally friendly, low-cost, and lightweight alternatives to traditional ceramic reinforcements. This review gathers recent findings on (1) physico-mechanical properties (tensile strength, hardness, ductility, density), (2) tribological behaviour (wear rate, friction coefficient, wear mechanisms), and (3) metallurgical characteristics (microstructure, interfacial bonding, phase formation, porosity) of agro-reinforced AMMCs. The review describes common synthesis methods (stir casting and powder metallurgy), emphasises critical microstructure–property correlations, pinpoints persistent challenges (particle agglomeration, inadequate wettability, porosity, variable pre-treatment) and optimisation process. Key fabrication techniques are briefly outlined, and future research directions encompassing hybridisation techniques and surface modifications are provided.

INTRODUCTION

A metal matrix composite (MMC) is a material composed of two or more distinct constituents, including metals (Senapati *et al.,* 2016). These composites are usually formed by embedding discontinuous/continuous fibres, whiskers or particles into molten metals, resulting in a combination of high specific modulus and strength. Over the past few decades, MMCs have gained significant attention in various industrial applications due to their excellent properties, including a high strength-to-weight ratio and cost-effectiveness (Subrahmanyam et al., 2015). Typically, MMCs are metallic alloys reinforced with ceramic materials. The most commonly used metallic alloys are those of lightweight metals such as aluminium (Al), magnesium (Mg), and titanium (Ti), zinc (Zn), copper (Cu), and stainless steel, among others (Bodunrin *et al.,* 2015). Aluminium is the most widely used metal as a matrix material in the development of metal matrix composites (MMCs) (Das *et al.,* 2014). However, the high cost and limited availability of conventional ceramic reinforcing materials, particularly in developing countries, pose significant challenges in the production of discontinuously reinforced aluminium matrix composites (DRAMCs) (Bodunrin *et al*., 2015). Aluminium metal matrix composites (AlMMCs) have become increasingly important across various industries such as automotive, aerospace, sports, and mineral processing due to their lightweight and exceptional thermal conductivity (Atuanya *et al.,* 2012; Saikrupa *et al.,* 2021). Aluminium alloys (Al-alloys) are preferred as matrix materials because of their excellent casting properties, high corrosion resistance, and low density (Senapati *et al*., 2016; Kolawole *et al.,* 2020). They are recognised for their ability to provide tailored property combinations that meet the demands of a wide range of engineering applications (Daramola *et al*., 2018; Seikh *et al.,* 2022). When reinforced with ceramic particles, Aluminium composites exhibit superior performance in high-temperature applications (Saikrupa *et al.,* 2021). Owing to their low density and outstanding mechanical properties, they are widely used to manufacture lightweight components for diverse market needs (Alaneme *et al.,* 2016). These composites offer strength and wear resistance comparable to cast iron (CI), but with 67% lower density and three times higher thermal conductivity (Seikh *et al.,* 2022). Over the past three decades, numerous studies have explored the use of reinforcing particles such as alumina (Al_2O_3), titanium carbide (TiC), aluminium nitride (AlN), titanium diboride (TiB_2), boron carbide (B_4C), silicon carbide (SiC), molybdenum disulfide (MoS_2), graphite, and mica as reinforcement in AlMMCs at various sizes (Daramola *et al*., 2018). These reinforcements have been shown to enhance properties such as wear resistance, hardness, elastic modulus, and tensile strength (Gireesh *et al*., 2018). However, while the incorporation of ceramic particles into aluminium alloys improves hardness, stiffness, specific strength, and wear resistance, it also introduces certain limitations (Prasad and Krishna, 2011). One of such limitations is the increase in density of the resulting composites. Aluminium matrices typically have a lower density (2.7–2.8 g/cm³) compared to ceramic reinforcements like SiC (3.22 g/cm³) and Al_2O_3 (3.9 g/cm³). Additionally, the elastic modulus of ceramic particles (approximately 400 GPa) is significantly higher than that of aluminium alloys (around 70 GPa). This disparity leads to increased brittleness, reduced machinability, and lower fracture toughness in AlMMCs (Kanthavel *et al*., 2016). Furthermore, the presence of ceramic reinforcements in AlMMCs tends to diminish impact strength by reducing strain energy and creating stress concentration zones (Seikh *et al*., 2022; Osunmakinde *et al*., 2024). Another critical factor limiting the widespread application of AlMMCs is their high cost (Marin *et al*., 2012). Despite their enhanced mechanical properties, these composites remain economically challenging to produce, restricting their use in various industries.

Under these circumstances, the development of agro-waste-reinforced AlMMCs presents a highly advantageous solution. Agricultural waste materials can be utilised to produce low-cost, lightweight composites with excellent mechanical and tribological properties (Kolawole *et al*., 2020; Seikh *et al*., 2022). Agro-waste, a significant source of silica (SiO_2), when reinforced with aluminium alloys, offers a promising approach to addressing the challenges associated with conventional reinforcements. Researchers have highlighted the potential of agro-waste-based reinforcements due to their economic feasibility, abundance, and sustainability (Seikh *et al.,* 2022). In recent years, there has been growing interest in the production of AlMMCs reinforced with agricultural waste derivatives such as rice husk ash (RHA), coconut shell ash (CSA), palm oil fuel ash (POFA), bamboo leaf ash (BLA), bagasse ash (BA), corn cob ash (CCA), and other similar materials (Yadav *et al.,* 2018; Parveez *et al.,* 2021). These agricultural wastes, rich in oxide content, serve as cost-effective and readily available alternative reinforcing materials, offering physical and mechanical properties comparable to conventional particulates (Hasibul *et al.,* 2016).

This article aims to review the studies conducted on different combinations of agro-waste reinforcing particulates used in the development of hybrid AlMMCs fabricated through stir casting techniques, with a focus on how these reinforcements influence the overall performance of the composites.

Agricultural Residue as Reinforcement Materials

Nearly all agricultural residues, when converted into ash, are promising reinforcing materials in Al matrix composites development because they possess silica, alumina, ferric oxide and other essential reinforcing oxides such as CaO and MgO, among others. Rice husk ash, coconut shell ash, corn cob ash, and bagasse ash are considered to be rich in silica (quartz). However, breadfruit seed ash, bamboo leaf ash, POFA, groundnut shell ash, and POC are considered to be moderate. Their chemical composition varies extensively due to varying sources, ecological factors and soil content (Osunmakinde *et al.,* 2024; Vaisanen *et al.,* 2016). Some of them are extensively reviewed in this publication.

Rice husk ash

Rice Husk Ash (RHA) has emerged as a highly economical and sustainable reinforcement material for MMCs compared to conventional ceramic reinforcements. As an agricultural byproduct, RHA is abundantly available worldwide, particularly in regions with significant rice production (Akbar *et al*., 2020). Rice husk, the outer layer of rice grains, is generated in large volumes by rice processing industries. Historically, rice husk was often used as a fuel for electric power generation, but this practice contributed to greenhouse gas emissions, exacerbating environmental concerns. Additionally, the disposal of rice husk ash posed significant environmental and health challenges, including air pollution and landfill issues (Gladston *et al.,* 2017). RHA contains valuable ceramic particles such as silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), making it a suitable candidate for reinforcing metal matrix composites. It contains up to 95% silica, which is a key component for enhancing the properties of composites. Recognising its potential, researchers have increasingly utilised RHA as a reinforcement material in high-performance AMCs. It offers lower density (0.3–1.9 g/cm^3) compared to traditional ceramic reinforcements, ease of availability, and cost-effectiveness (Parveez *et al.,* 2021). The ash is produced as a burning residue when rice husk is incinerated, and its unique chemical composition makes it an attractive alternative to conventional materials (Gladston *et al.,* 2017).

The chemical compositions of RHA, along with other agricultural waste derivatives such as coconut shell ash (CSA) and cassava peel ash (CPA), among others, are presented in Table 1. These materials share similar characteristics, including high silica content and low density, making them viable options for reinforcing composites. RHA has the highest SiO_2 content (91.73%), making it highly silica-rich. CSA contains significant amounts of Al_2O_3 (15.65%), Fe_2O_3 (12.73%), and MgO (15.81%). CPA is notable for its high K_2O (18.68%), while Sugarcane Bagasse Ash (SBA) has very high Al_2O_3 (6.7%) and SiO_2 (73%). Palm Oil Fuel Ash (POFA) and Groundnut Shell Ash (GSA) also show high silica contents and moderate levels of other oxides. The chemical compositions of bean pod ash (BPA), bread fruit ash (BFA) and palm oil clinker ash (POC) are presented in Table 1 and described in subsequent sub-sections. Overall, these ashes vary widely in oxide composition, suggesting different properties and suitability for composite applications. Repurposing agricultural waste into valuable reinforcement materials allows researchers not only to address environmental concerns but also to develop cost-effective and sustainable solutions for advanced material applications.

Table 1: Chemical composition of Selected Agro-wate particles

Constituents (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	C
RHA	91.73	1.56	0.16	1.16	0.47	0.023	0.73	-	-	1.13
CPA	36.75	7.71	2.60	8.29	2.9	1.34	18.68	1.58	-	-
SBA	73	6.7	6.3	2.8	3.2	1.1	2.4	-	-	-
BPA	12.5	1.1	1.2	17.3	5.1	1.8	32.5	1.9	7.4	-
GSA	75.9	4.13	4.13	7.47	1.85	-	5.62	-	-	-
CSA	45.46	15.65	12.73	0.75	15.81	0.42	-	-	0.02	-
BFA	15.45	35.80	30.34	-	1.20	0.45	0.52	-	-	-
POFA	52.35	6.27	13.36	11.72	-	-	15.52	-	-	-
POC	81.8	3.5	1.9	6.0	1.7	0.26	3.05	3.3	0.9	0.5

Source: (Asafa *et al*., 2024, Seikh *et al.,* 2022, Lancaster *et al*., 2013)

This approach aligns with the growing emphasis on eco-friendly and resource-efficient manufacturing practices in the field of materials science.

Bean pod

Beans are an essential and widely consumed food crop, known for their large seeds that belong to several genera of the *Fabaceae* family, also known as *Leguminosae* (Aigbodion, 2019). They serve as a vital source of protein and nutrients for humans and are also used in animal feed globally. However, during the processing of legumes, a significant amount of agricultural residue is generated in the form of bean pods. These pods, often considered waste, constitute approximately 39% of the total weight of the harvested fruit, leading to a substantial accumulation of agricultural by-products worldwide. Despite being perceived as waste, bean pods possess significant industrial potential. When burned to ash, bean pod residues transform into a valuable raw material with various applications. In traditional practices, the ash derived from bean pods has been utilised in the production of soap and as a natural dye for the garment industry (Akbar *et al*., 2020). This highlights the versatile utility of bean pod ash beyond its agricultural origin.

Chemical analysis of Bean Pod Ash (BPA) reveals its rich composition of oxide compounds, including about 12.5% SiO_2, 17.3% Cao, 32.5% K_2O, sodium aluminium silicate ($NaAlSi_3O_2$), calcium carbonate ($CaCO_3$), and aluminium carbide oxide (Al_4O_4C), among others (see Table 1). These compounds impart unique physical and chemical properties to the ash, making it suitable for various industrial applications. Aigbodion (2019) studied aluminium matrix reinforced with nanoparticles derived from BPA and showed that the addition of BPA significantly enhanced the hardness of the composite material. Specifically, increasing the BPA content from 0% to 4% by weight resulted in a marked improvement in composite hardness, with values rising from 46.7 HRB to 67.3 HRB. This improvement underscores the potential of bean pod ash as a cost-effective and sustainable reinforcing agent in composite materials.

Furthermore, the use of agro-waste materials like BPA contributes to environmental sustainability by reducing industrial reliance on synthetic reinforcements and minimising agricultural waste. Table 2 presents a comparative summary of the density of various agro-waste-based reinforcing materials, highlighting the efficiency and economic viability of BPA in advanced material development. According to the table, alumina (3.90 g/cm^3) and silicon carbide (3.20 g/cm^3) are the densest. In contrast, cassava peel ash (1.70 g/cm^3), breadfruit hull ash (1.98 g/cm³), coconut shell ash (2.05 g/cm³), and sugar bagasse ash (1.95 g/cm³) exhibit lower densities. RHA (0.3–1.9 g/cm³) and BPA (0.4 - 0.9 g/cm³) have the widest density range, indicating variability in processing and composition. These lower-density agro-waste ashes offer potential for lightweight, sustainable composites.

Table 2: Density of Reinforcing Materials in AMCs

Reinforcing material	Density (g/cm³)	Reference
Alumina (Al_2O_3)	3.90	Daramola *et* al. (2018)
Silicon carbide (SiC)	3.20	Daramola *et* al. (2018)
Coconut shell ash (CSA)	2.05	Madakson *et al*. (2012)
Breadfruit hull ash (BFA)	1.98	Atuanya *et al*. (2012)
Sugar bagasse ash (BA)	1.95	Kandpal (2021)
Cassava peel ash (CPA)	1.70	Osunmakinde *et al*. (2023)
Bean pod ash (BPA)	0.4-0.9	Atuanya and Aigbodon (2014)
Rice husk ash (RHA)	0.3–1.9	Parveez *et al*. (2021)

Groundnut shell ash

Groundnut Shell Ash (GSA) is a byproduct derived from groundnut/peanut processing. Despite the abundance of peanut shell waste, its potential remains largely untapped. With global peanut production exceeding 16 million tons annually, peanut shell waste is readily available (Akbar *et al*., 2020). Chemical analysis of GSA reveals the presence of oxide compounds, including aluminium oxide, iron oxide, and silicon oxide, as detailed in Table 1. These properties make GSA a suitable candidate for use as a reinforcement material in metal matrix composites. Previous studies have explored the production of metal matrix composites using hybrid reinforcements of GSA and silicon carbide (SiC) (Alaneme *et al*., 2016). Studies have also shown that reinforcement fractions of 6% wt and 10% wt, with GSA-to-SiC ratios of 0:1, 1:3, 3:1, and 1:0, lead to significant improvements in hardness and tensile strength compared to pure aluminium alloy.

Sugar bagasse ash

Sugarcane is a highly sustainable, renewable, and carbon-neutral crop, renowned for its exceptional energy conversion efficiency. During the processing of sugarcane, one of the primary byproducts generated is bagasse, a yellowish, fibrous residue left after the extraction of juice from the cane. Bagasse is composed mainly of water, cellulose fibres, and a variety of minerals, including methane, which contribute to its potential for various industrial applications (Akbar *et al.,* 2020). Further analysis of Sugar Bagasse Ash (SBA), which is derived from the combustion of bagasse, reveals its unique chemical composition. Energy-dispersive X-ray spectroscopy (EDS) studies indicate that SBA is particularly rich in silicon, with silicon content ranging between 62% and 71% by weight. X-ray diffraction (XRD) investigations further identify the presence of several oxide compounds in SBA, including silicon dioxide (SiO_2), calcium oxide (CaO), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), and magnetite (Fe_3O_4) (Imran and Khan, 2018) (Table 1). These compounds contribute to the thermal and mechanical properties of ash, making it a valuable material for high-temperature applications.

SBA exhibits remarkable thermal stability, withstanding temperatures of up to 1600°C, and possesses a relatively low density of 1.95 g/cm³, which enhances its suitability for lightweight applications (Kandpal *et al.,* 2021). These characteristics make SBA an attractive candidate for use in advanced materials, particularly in the development of metal matrix composites. A study conducted by Chandla *et al*. (2020) explored the potential of SBA as a reinforcing agent in aluminium-based composites. Using a stir casting technique, they reinforced Al6061 alloy, already containing 5% by weight of aluminium oxide (Al_2O_3), with varying amounts of bagasse ash. The study found that increasing the content of bagasse ash in the composite led to significant improvements in both hardness and tensile strength. This suggests that SBA not only enhances the mechanical properties of the composite but also offers a sustainable and cost-effective alternative to traditional reinforcement materials.

Breadfruit seed husk ash

The breadfruit seed husk is abundantly available as a byproduct from the breadfruit processing industries, which are predominantly located in regions such as Nigeria, western India, Ghana, and Jamaica. The disposal of this agricultural waste poses significant challenges to both public health and the environment, as its accumulation can lead to pollution and other ecological issues. Consequently, there is a growing emphasis on research aimed at identifying eco-friendly and sustainable applications for this waste material. One promising avenue is the utilisation of Breadfruit Seed Husk Ash (BSHA) in the production of composite materials. BSHA is particularly attractive for this purpose due to its relatively low density of 1.98 g/cm^3, which is significantly lower than that of conventional reinforcement materials such as aluminium oxide (Al_2O_3) and silicon carbide (SiC) (Kandpal *et al*., 2021). This lightweight property, combined with its availability and low cost, makes BSHA a viable alternative for use in composite manufacturing.

Research conducted by Atuanya *et al*. (2012) demonstrated the successful incorporation of BSHA particles into an aluminium-based matrix. Using the stir casting technique, they reinforced an Al–Si–Fe alloy with BSHA particles and observed notable improvements in the mechanical properties of the composites, including increased strength and hardness. This highlights the potential of BSHA as an effective reinforcement material in metal matrix composites. The chemical composition of breadfruit husk ash, as detailed in Table 1, further underscores its suitability for such applications. The ash is composed of various oxides, including silicon dioxide (SiO_2) at 15.45%, aluminium oxide (Al_2O_3) at 35.80%, iron oxide (Fe_2O_3) at 30.34%, and smaller amounts of other compounds such as chromium oxide (5.06% Cr_2O_3), magnesium oxide (1.20% MgO), sodium oxide (0.45% Na_2O), potassium oxide (0.52% K_2O), manganese oxide (MnO), and zinc oxide (ZnO). These components contribute to the observed properties, making it a valuable material for composite production.

Coconut shell ash

Coconut shells are an abundant agricultural waste material, particularly in tropical regions where coconut cultivation is widespread. However, the improper disposal or burning of coconut shells contributes to environmental pollution, releasing harmful gases such as carbon dioxide (CO_2) and methane (CH_4), which negatively impact air quality and human health. To address this issue, researchers are exploring sustainable and eco-friendly applications for Cassava shell Ash (CSA), particularly in the field of advanced materials for reinforcement of material in MMCs. The ash derived from coconut shells contains a significant proportion of hard phases, including 45.46% SiO_2, 15.65% Al_2O_3 and 12.73% Fe_2O_3 as the top three phases identified through X-ray fluorescence (XRF) analysis (Osunmakinde *et al*., 2023). These compounds, as detailed in Table 1, make CSA a suitable candidate for enhancing the mechanical properties of composites. Additionally, CSA exhibits excellent thermal stability, withstanding temperatures of up to 1500°C, and has a relatively low density of 2.05 g/cm³, which is significantly lower than that of synthetic reinforcement materials like silicon carbide (SiC) or aluminium oxide (Al_2O_3) (Kandpal *et al.,* 2021). This combination of properties makes CSA an attractive and cost-effective alternative for composite manufacturing.

Research has demonstrated the effectiveness of CSA in improving the mechanical and wear properties of hybrid composites. For instance, studies have shown that the addition of 8% by weight of CSA to hybrid composites results in increased hardness and tensile strength (Satheesh and Pugazhvadivu, 2019). Furthermore, the compressive strength of composites has been found to improve with the incorporation of 6% by weight of CSA. In terms of wear resistance, the addition of CSA to Al6061-SiC composites has been shown to enhance their durability and performance under abrasive conditions.

Palm oil fuel ash

Palm Oil Fuel Ash (POFA) is a widely available agricultural solid waste derived from the palm oil industry. It is generated through the combustion of oil palm biomass, including oil palm fibres, shells, empty fruit bunches, and mesocarp, which are used as boiler fuel to produce steam for palm oil mill operations (Ahmadi *et al*., 2016). Despite being a byproduct, POFA is rich in siliceous materials, making it a valuable resource for various industrial applications, particularly as a reinforcing material in composite production (Hashimah and Mohamad, 2019). The primary component of POFA is silica, which constitutes up to 40% of its composition. In addition to silica, POFA contains other significant chemical compounds, including K_2O, MgO, CaO, Al_2O_3, and Fe_2O_3 (Parveez *et al*., 2021). These oxides contribute to the mechanical and thermal properties of the material, making POFA a suitable candidate for enhancing the performance of composites.

Studies have shown that the addition of POFA leads to increased hardness and tensile strength in the resulting composites. Furthermore, POFA enhances wear resistance and reduces the coefficient of friction, making the composites more durable and efficient in applications involving friction and abrasion (Hashimah and Mohamad, 2019). These improvements highlight the potential of POFA as a cost-effective and sustainable alternative to conventional reinforcement materials. The utilisation of POFA not only addresses the environmental challenges associated with agricultural waste disposal but also provides a practical solution for enhancing the performance of composite materials. Continuous research and development in this field could further optimise the use of POFA and unlock new possibilities for its application in advanced materials and engineering solutions.

Palm oil clinker

Palm Oil Clinker (POC) is a byproduct generated during the processing of palm oil in industrial settings. It is formed when oil palm shells, a residue from palm oil production, are combusted in boilers to generate energy. Despite being a waste material, POC has traditionally been considered of little economic value, prompting researchers to explore innovative and sustainable applications for its utilisation. Currently, POC is being investigated and used in industries such as concrete production and MMC manufacturing, where its unique properties can be harnessed effectively (Kandpal *et al*., 2021). The chemical composition of POC, as presented in Table 1, reveals that it is primarily composed of SiO_2, which makes up approximately 81.8% of its content. Other significant components include Al_2O_3 at 3.5%, (Fe_2O_3 at 5.18%, K_2O at 4.66%, CaO at 2.3%, MgO at 1.24%, and P_2O_5 at

0.76% (Lancaster *et al*., 2013). This composition makes POC a suitable material for various industrial applications, particularly as a reinforcing agent or filler in composites and construction materials.

In the construction industry, POC has been utilised as a lightweight aggregate in concrete production. Its low density and high silica content contribute to the development of lightweight and durable concrete, which is particularly beneficial for reducing the overall weight of structures while maintaining strength and stability (Kandpal *et al*., 2021). Additionally, the use of POC in concrete helps reduce the environmental impact of construction by repurposing industrial waste and decreasing the reliance on natural resources. In the field of metal matrix composites, POC has shown promise as a reinforcement material. Its high silica content and other oxides enhance the mechanical properties of composites, such as hardness, tensile strength, and wear resistance. Incorporating POC into MMCs will help manufacturers produce materials that are not only cost-effective but also environmentally friendly, as they reduce the need for synthetic reinforcements and contribute to waste management.

Bamboo leaf ash

Bamboo trees are widely distributed across various regions of the world, particularly in tropical and subtropical areas. These trees shed their leaves abundantly, contributing to organic waste in these regions. However, Bamboo Leaf Ash (BLA), derived from the combustion of these leaves, has emerged as a valuable resource with significant economic potential. BLA is primarily composed of ceramic oxides such as SiO_2, Al_2O_3, CaO, K_2O, and Fe_2O_3, as detailed in Table 1. This unique chemical composition makes BLA a suitable candidate for use as a reinforcement material in AMCs (Bannaravuri and Birru, 2019; Shridhara *et al.,* 2015). The incorporation of BLA into aluminium alloys has been shown to enhance the mechanical and tribological properties of the resulting composites. For instance, Aleneme *et al.* (2014b) conducted studies in which BLA was reinforced with aluminium alloy and results revealed a significant improvement in the wear resistance of the composites, making them more durable and suitable for applications involving friction and abrasion. This improvement is attributed to the hard ceramic oxides present in BLA, which contribute to the hardness and strength of the composite. In addition to its mechanical benefits, the use of BLA in composites offers environmental and economic advantages. The potential applications of BLA extend beyond wear-resistant composites. Its lightweight nature and high silica content make it a promising material for use in construction, ceramics, and other industries.

Summary of Agro-residue Ash Reinforced Al Composites

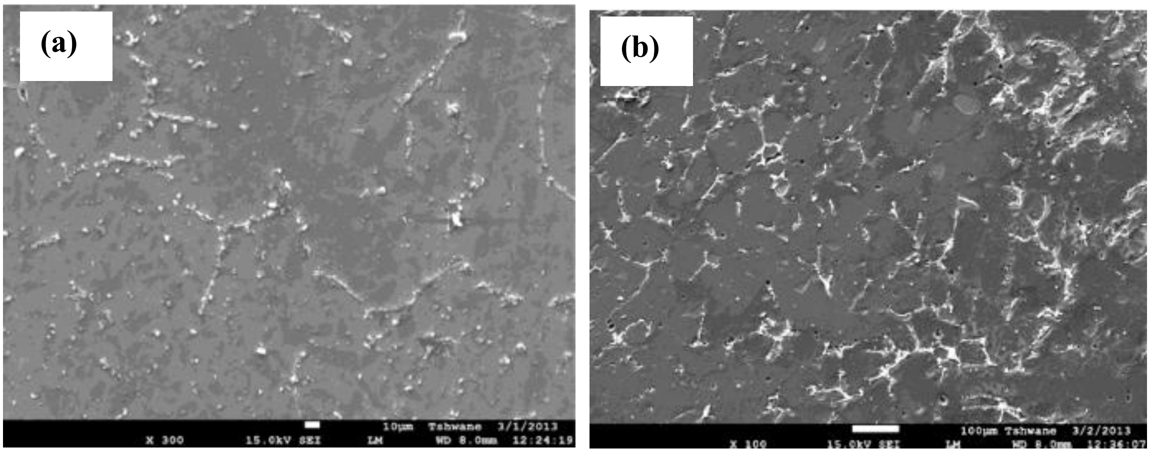
Table 3 provides an overview of various composite materials, focusing on reinforcing materials, matrix compositions, characterisation techniques, fabrication methods and key characteristics. The reinforcing materials are incorporated into aluminium-based matrices (e.g., AA6061, AlSi10Mg, A356, and Al-Mg-Si alloys) to enhance mechanical, physical, microstructural, and tribological properties. The characterisation techniques commonly employed help in assessing the microstructural homogeneity, phase distribution, mechanical properties (tensile strength, hardness), tribological behaviour (wear resistance), and physical properties (density, porosity) of the composites. Fabrication techniques primarily involve stir casting and its variants, such as double stir casting and compo-casting, indicating the prevalence of liquid-state processing for these composites. This is discussed in more detail in section 4.0. Stir casting is favoured due to its simplicity, cost-effectiveness, and ability to achieve uniform dispersion of reinforcements. However, double stir casting is employed in cases requiring improved particle distribution, particularly for hybrid composites like RHA/FA or CSA/SiC.

Table 3: Summary of Agro-residue ash-based reinforced AMCs

Reinforcing materials	Matrix	Characterisation	Fabrication Techniques	Characteristics	References
RHA	Al alloy	SEM, EDX, XRD, Porosity	Stir casting	Microstructural, mechanical, physical	Yekinni *et al.* (2019)
RHA/Fly Ash (FA)	A356	SEM, wear rate, XRF	Double stir casting	Microstructural, tribological	Vinod *et al.* (2018)
RHA/FA	AlSi10Mg alloy	SEM, EDS, XRD, UTS	Stir casting	Microstructural, tribological, mechanical	Subrahmanyam *et al.* (2015)
RHA	AA6061	EBSD, SEM, EDS	Compo casting	Microstructural	Gladston *et al.* (2017)
RHA/CPA/ CSA	Al powder	XRD, SEM, EDX, Density, Porosity	Double stir casting	Microstructural, mechanical, physical	Asafa *et al.* (2024)
RHA	Al	XRD, SEM, EDX, Density	Stir casting	Microstructural, physical.	Ahamed *et al.* (2016)
GSA/SiC	Al–Mg–Si alloy	SEM, XRD, UTS Wear	Double stir casting	Microstructural, mechanical, tribological	Alaneme *et al.* (2016)
CSA	Al6061	SEM, XRD, tensile	Stir casting	Microstructural, mechanical	Nithyanandhan *et al.* (2017)
RHA /Graphite /alumina	Al-Mg-Si alloy (AA6063)	SEM, EDS, wear rate	Double stir casting	Microstructural, tribological	Alaneme and Sanusi (2015)
RHA/ alumina	Al-Mg-Si	Density, SEM, XRD, UTS	Double stir casting	Microstructural, mechanical, physical	Alaneme and Olubambi (2013)
CSA		EDS, SEM, tensile	Stir casting	Microstructural, mechanical	Madakson *et al.* (2012)
BA/GSA/RHA/ CSA	Al matric	Density, SEM, XRD, UTS	Stir casting	Microstructural, mechanical, physical	Butola *et al.* (2019)
CSA/ZrO_2	Al6082	XRD, SEM, UTS	Stir casting	Microstructural, mechanical	Kumar *et al.* (2018)
CSA/SiC	Al6061	XRD, EDS, SEM, wear rate	Double-stage stir casting	Microstructural, mechanical, Tribological.	Satheesh and Pugazhvadivu (2019)
CSA	Al1100	SEM, XRD, tensile	Stir casting	Microstructural, mechanical	Kumar *et al.* (2016)

Preparation, physical, metallurgical and Mechanical properties of Agro-Waste Reinforced Composites

This section provides more details on over decade-long studies on AMCs reinforced with agro-waste derivatives and synthetic ceramic particulates. Alaneme and Adewale (2013) investigated the effect of RHA and SiC weight ratios on the mechanical properties of Al-Mg-Si alloy-based hybrid composites. The study employed RHA and SiC in varying weight ratios (0:1, 1:3, 1:1, 3:1, and 1:0) to produce composites with 5, 7.5, and 10 wt% reinforcement using a two-step stir casting method. Scanning electron microscopy (SEM) analysis revealed a uniform dispersion of RHA and SiC particles within the Al alloy matrix, with minimal clustering (Figure 1). The results demonstrated that increasing the reinforcement content (RHA + SiC) enhanced tensile strength, yield strength, and specific strength, while fracture toughness exhibited a declining trend.



SEM images of Al-Mg-Si reinforced with (a) 5 wt% SiC and (b) 10 wt% RHA (Alaneme and Adewale, 2013)

Dinaharan *et* al. (2017) explored the effect of rice husk ash particles on the microstructure and tensile behaviour of AA6061 aluminium matrix composites produced using friction stir processing (FSP). AA6061/18wt% RHA AMC was produced using FSP. RHA particles were homogeneously dispersed in the aluminium matrix during stirring which improved the tensile strength of the composite from 220 MPa for the aluminium matrix to 285 MPa for 18 vol %RHA composites. In another study, Atuanya *et al.* (2012) examined the effect of breadfruit seed hull ash (BSHA) on the microstructures and properties of Al–Si–Fe alloy, by varying BSHA from 2 to 12 wt% using a double stir casting process. Macrostructural observations revealed a reasonably uniform distribution of BSHA particles in the aluminium alloy. The BSHA particles were influenced by the good wettability of the molten metal and good interfacial bonding between BSHA particles and the matrix material, as shown in Figure 2. An increase in wt% of BSHA was also reported to decrease the density of the composite material. Figure 3 presents the XRD patterns of the aluminium alloy and the alloy reinforced with 8 wt% BSHA composites. The presence of α-Al, FeSi, SiO_2, Al_2O_3 and Fe_3C in the matrix aluminium alloy are evidence of the breadfruit seed hull ash particles in the composite.

Prasad *et al*. (2014) conducted a study on stir-cast aluminium hybrid composites reinforced with equal proportions of RHA and SiC, varying the reinforcement content from 2% to 8% by weight.

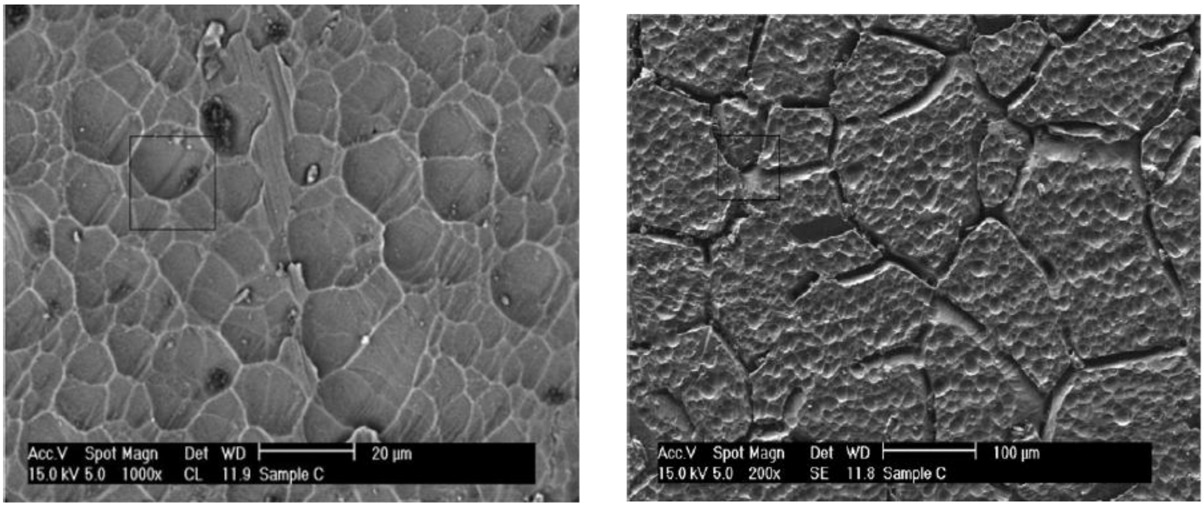


Figure 2: Micrograph of Al–Si–Fe alloy (a) without reinforcement (b) reinforced with 12 wt% BSHA

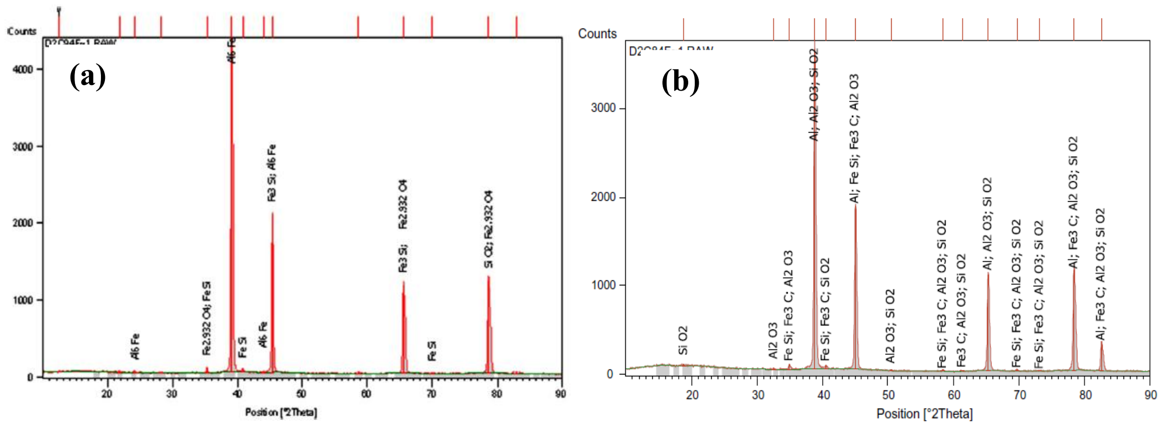


Figure 3: XRD pattern of the Al alloy (a) without reinforcement (b) reinforced with 8 wt% BSHA (Atuanya *et al.,* 2012)

Microstructural analysis (Figure 4) confirmed a homogeneous distribution of the reinforcing particles within the aluminium matrix. The mechanical characterization revealed a direct correlation between reinforcement content and key strength properties - hardness, yield strength, and ultimate tensile strength all increased with higher reinforcement loading. Conversely, ductility (measured by percentage elongation) and thermal expansion coefficient exhibited an inverse relationship, decreasing as reinforcement levels rose. This behaviour was attributed to the restrictive effect of ceramic particulates on dislocation movement and thermal deformation. In a related study, Alaneme *et al.* (2013a) explored the feasibility of producing cost-effective, high-performance aluminium matrix composites using hybrid reinforcements of Al_2O_3 and RHA. Employing a two-step stir casting technique, they achieved optimal particle dispersion in composites containing 4 wt.% RHA, as evidenced by optical micrographs. The uniform distribution of RHA and Al_2O_3 contributed to enhanced mechanical properties while maintaining economic viability due to the use of agro-waste-derived RHA.

Further expanding the scope of agro-waste reinforcements, Kumar *et al.* (2016) investigated

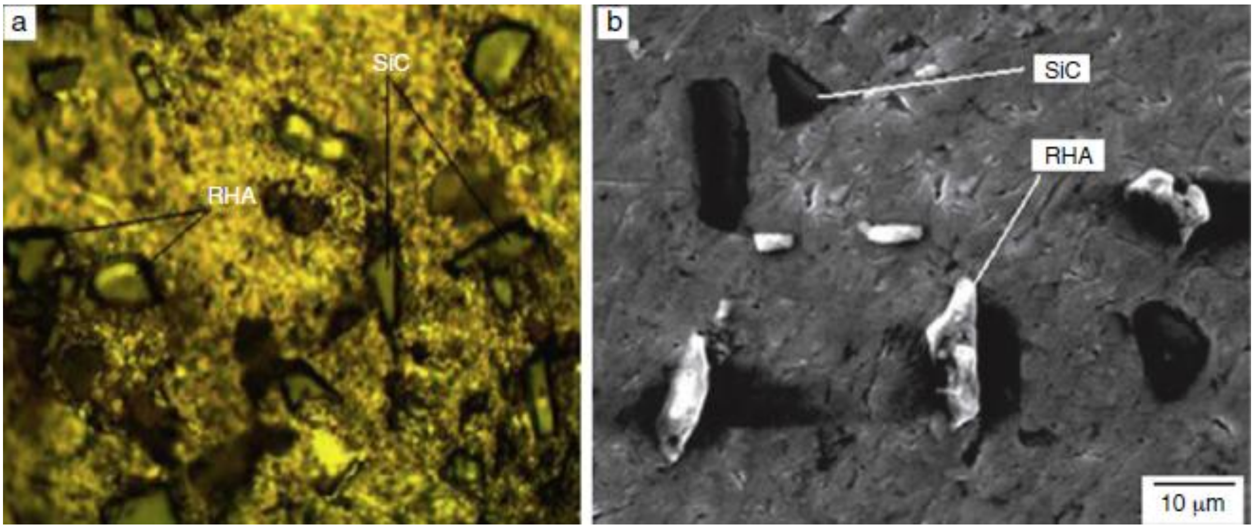


Figure 4: SEM of Al 356 reinforced with 2% RHA/SiC (a) coloured image (b) black-white image (Prasad *et al.,* 2014).

AMCs reinforced with 15 wt.% CSA particulates, fabricated via casting. The composite demonstrated significantly higher hardness compared to pure Al-1100, which the authors attributed to the presence of SiO_2 and MgO in CSA, the hard ceramic phases that impede plastic deformation. The study also evaluated the machinability of the composite to provide critical insights into the performance of the composite under secondary processing conditions.

Asafa *et al.* (2024) investigated the synergistic effects of RHA, CSA, and CPA as hybrid reinforcements in an aluminium matrix composite. Using a two-step stir casting method, the study incorporated a total reinforcement content of 15 wt.%, varying the combinations of RHA, CSA, and CPA. The results demonstrated a notable improvement in tensile strength compared to unreinforced aluminium, attributed to the dispersion-strengthening effect of the agro-waste particulates. Additionally, the study found that wear resistance significantly increased when all three reinforcement particles were used at 5 wt.% each, suggesting that multi-component reinforcements provide better load distribution and resistance to abrasive wear. Furthermore, the elastic modulus of the composites was enhanced substantially, as illustrated in Figure 5, indicating improved stiffness due to the reinforcing phases of different compositions as indicated by alpha-numerical sample codes. In a previous study, Osunmakinde *et al.* (2023) examined aluminium composites reinforced with RHA, CSA, and CPA. XRD analysis confirmed the presence of reinforcing phases such as SiO_2, MgO, iron silicide (Fe_3Si), and iron aluminide (Al_6Fe), which contribute to the enhanced mechanical properties of the composite. These ceramic and intermetallic phases improve hardness, strength, and thermal stability. SEM micrographs (Figure 6) revealed a homogeneous dispersion of reinforcement particles within the aluminium matrix, with a clean and well-bonded interface between the matrix and reinforcements. This uniform distribution minimizes stress concentrations and enhances load transfer efficiency, leading to improved mechanical performance.

Hossain *et al.* (2017) conducted a study on the fabrication of hybrid composites using aluminium alloy A356 reinforced with RHA at varying weight percentages of 2%, 4%, and 6%.

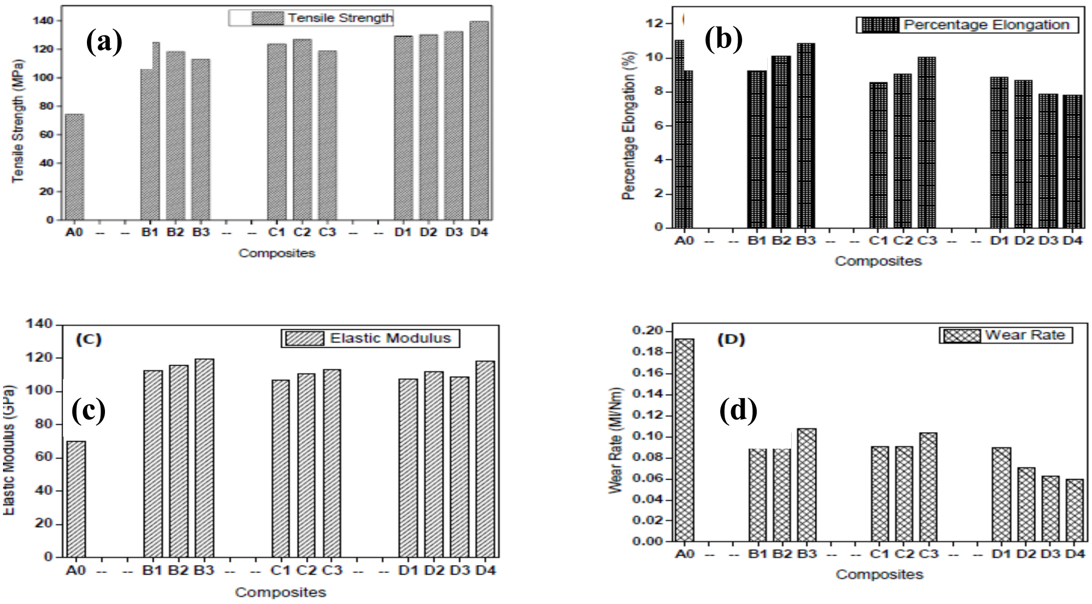


Figure 5: (a) Tensile strength, (b) Percentage elongation, (c) Elastic modulus, (d) wear rate of Aluminium matrix reinforced with RHA, CSA, and CPA (Asafa *et al.,* 2024). Different composites are indicated by the alpha-numeric combinations.

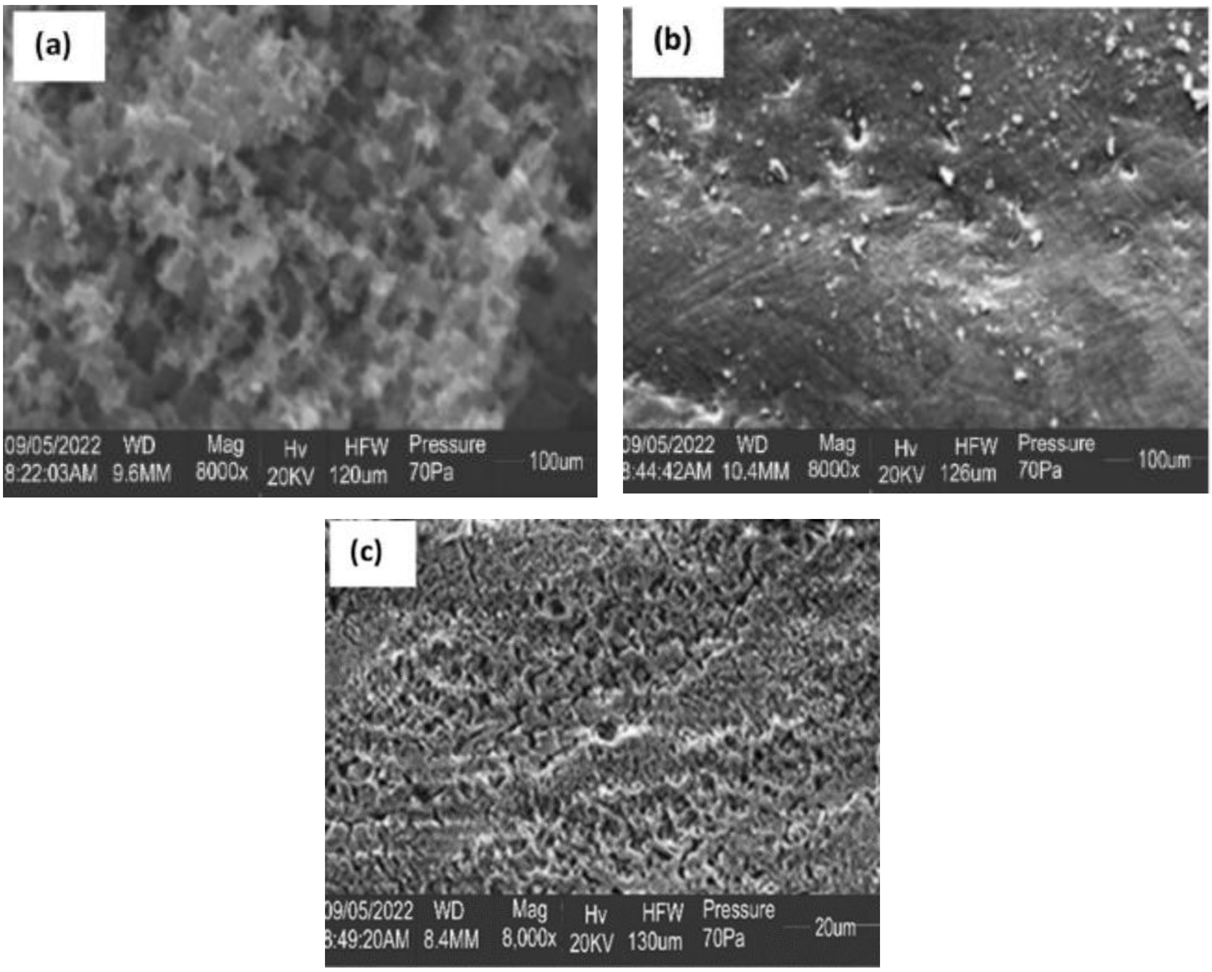


Figure 6: SEM images of (a) Pure Al-alloy (b) Al-alloy + 15%wt of CSA (c) Al-alloy + 5%wt CSA + 5%wt RHA + 5%wt CPA (Osunmakinde *et al.,* 2023)

The composites were produced using the stir-casting method. The experimental results revealed that with an increase in the weight percentage of RHA, there was a notable enhancement in mechanical properties such as tensile strength, compressive strength, impact strength, and hardness. However, a reduction in the percentage area of reduction was observed with increasing RHA content, indicating decreased ductility. These improvements in mechanical performance suggest the potential application of such composites in structural components like door and window frames, and roof elements such as beams and columns, as well as in automotive and other construction-related sectors, as illustrated in Figure 7.

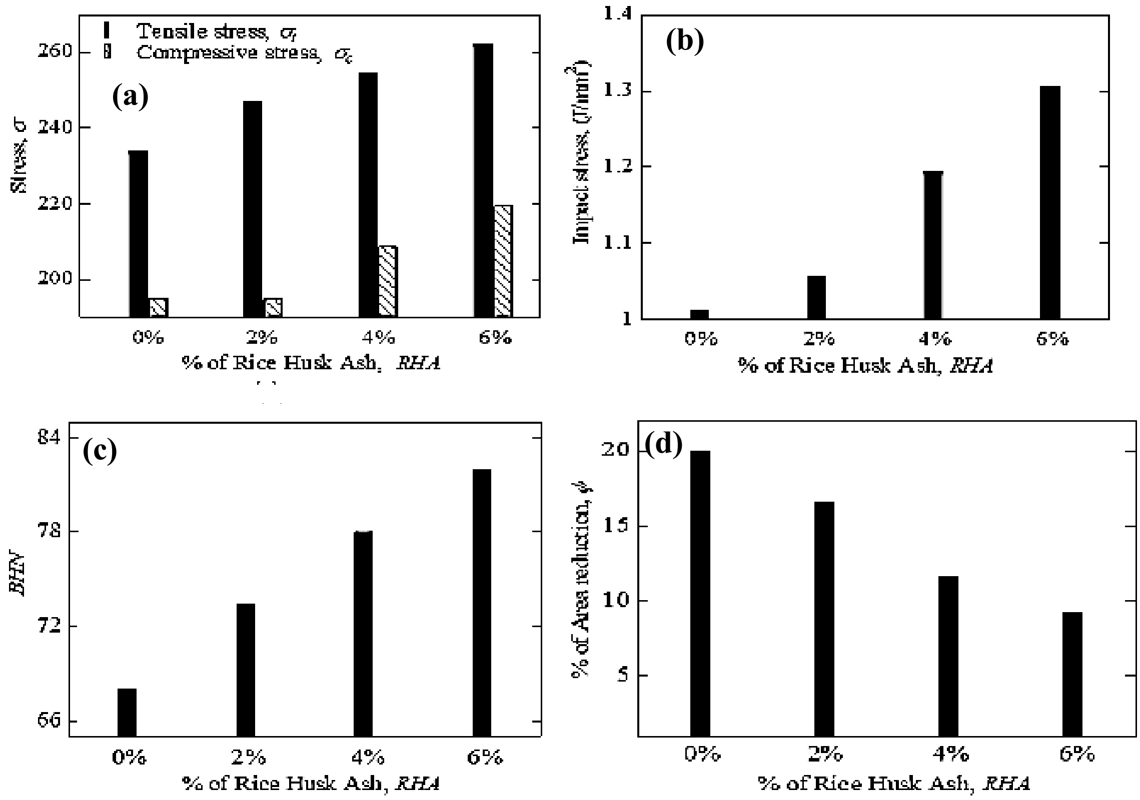


Figure 7: Mechanical properties of hybrid aluminium alloy A356 reinforced with RHA (a) tensile and compressive test, (b) impact test, (c) hardness test and (d) area reduction test. (Hossain *et al.*, 2017)

Similarly, Saravanan and Kumar (2013) explored the development of metal matrix composites using aluminium alloy AlSi10Mg reinforced with RHA particles at 3, 6, 9 and 12 wt% through the liquid metallurgy route. The study focused on evaluating surface morphology and mechanical properties, including tensile strength, compressive strength, hardness, and percentage elongation. The microstructural analysis demonstrated a uniform distribution of RHA particles within the matrix, with no visible voids or discontinuities, and strong interfacial bonding between the matrix and reinforcement, as shown in Figure 8. The mechanical testing further confirmed that ultimate tensile strength, compressive strength, and hardness increased with higher RHA content of particle size of 50-75 μm. However, a decreasing trend in elongation was observed with increased reinforcement, indicating a compromise in ductility, as illustrated in Figure 9.

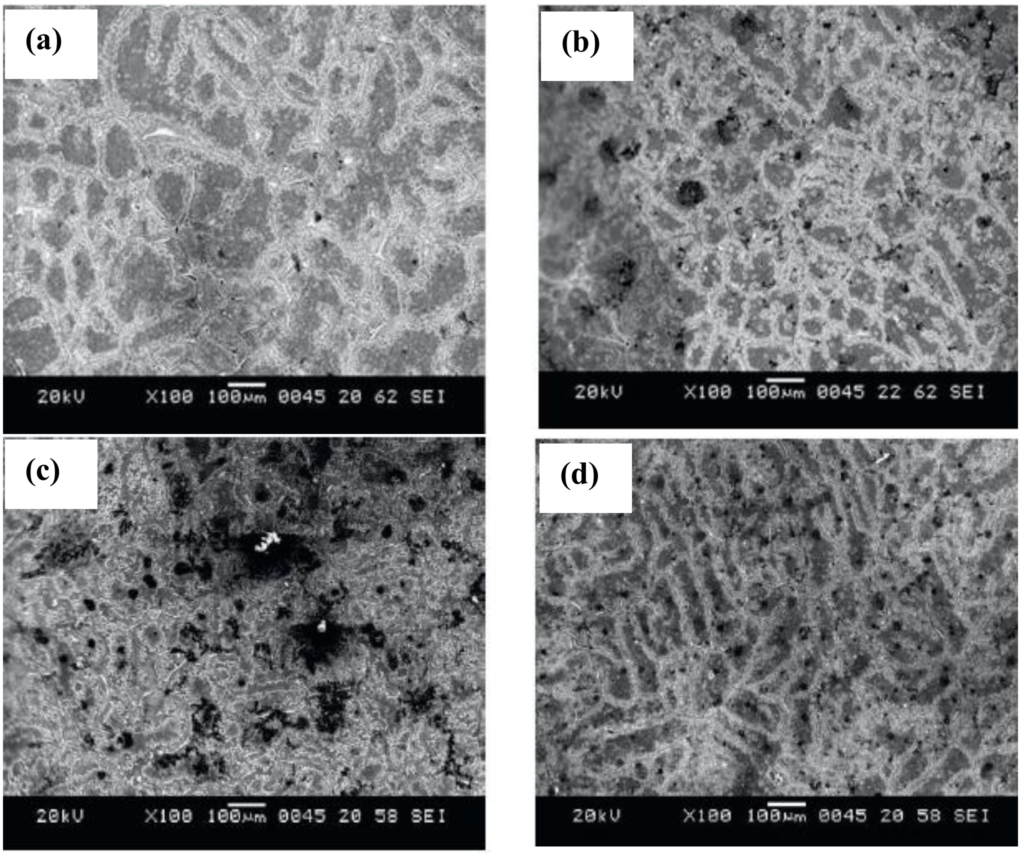


Figure 8: SEM images of AlSi10Mg alloy (a) unreinforced (b) reinforced with 6 % RHA (c) reinforced with 9 % RHA and (d) reinforced with 12 % RHA. (Saravanan and Kumar, 2013)

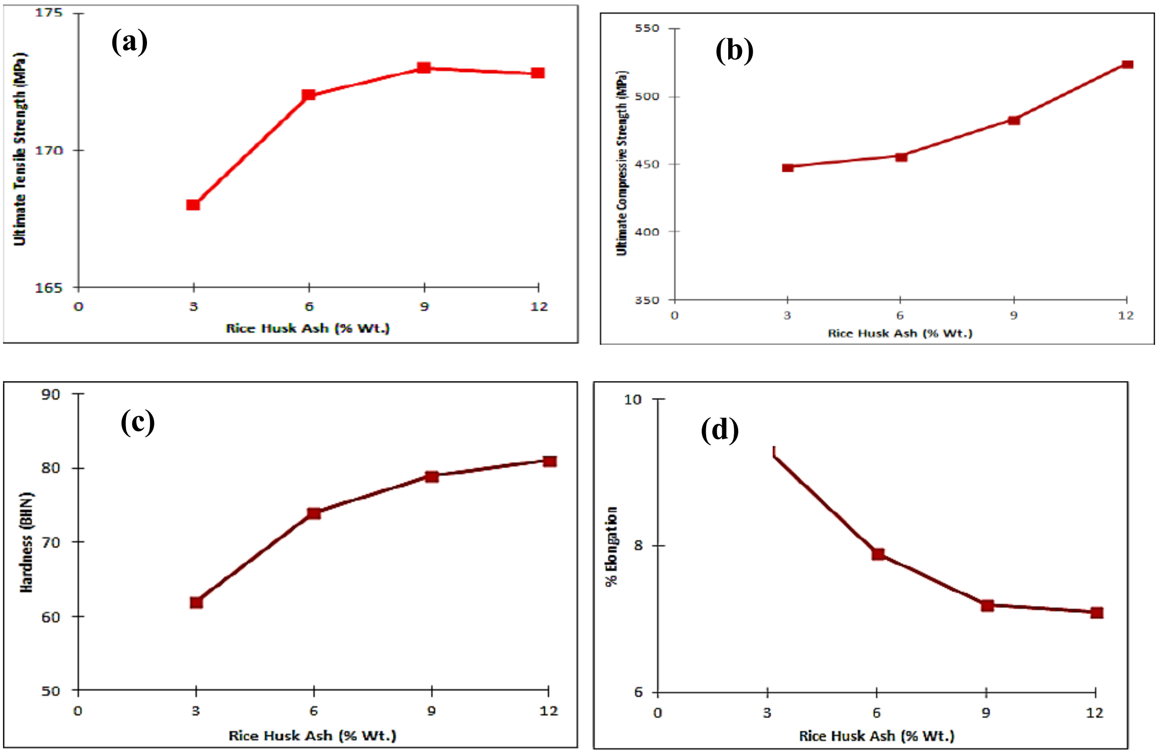


Figure 9: Variation of mechanical properties: (a) ultimate tensile strength (b) compressive strength (c) hardness (d) % elongation with the weight fraction of RHA (Saravanan and Kumar, 2013)

Ahamed *et al.* (2016) performed a systematic investigation on the development of aluminium matrix composites reinforced with RHA at varying weight percentages (3, 6 and 9 wt%). Using the stir casting fabrication method, the microstructural characteristics and mechanical properties of pure aluminium alloy and reinforced composites were examined. SEM analysis revealed an optimal dispersion of RHA particles within the aluminium matrix at lower reinforcement levels (3 and 6 wt%), while the 9 wt% RHA composite showed less satisfactory particle distribution, likely due to increased particle clustering at higher concentrations. The study reported an inverse relationship between composite density and RHA content, with density decreasing progressively as the RHA percentage increased. However, this reduction in density was accompanied by significant improvements in mechanical properties, as both tensile strength and hardness demonstrated a proportional increase with higher RHA content. These findings suggest that RHA can serve as an effective reinforcement for aluminium matrices, particularly at moderate loading levels where optimal particle distribution can be achieved.

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Mishra *et al.* (2018) investigated the influence of RHA as a reinforcement material and artificial ageing treatment on the mechanical properties of aluminium alloy LM6-based composites. In the study, 6% by weight of RHA was incorporated into the LM6 alloy, and the composite was subjected to artificial ageing at temperatures of 135°C, 175°C, and 225°C. The mechanical properties analysed included hardness and wear resistance. The results revealed that the hardness of both the base alloy and the RHA-reinforced composite increased with ageing temperature, reaching a peak at 175°C. However, further ageing at 225°C led to a decline in hardness, indicating over-ageing. Additionally, the composite consistently exhibited lower weight loss compared to the unreinforced alloy across all ageing temperatures and sand concentrations, due to the enhanced wear resistance provided by the hard RHA particles.

In a related study exploring alternative agro-waste reinforcements, Aigbodion (2019) investigated aluminium MMCs using Al-A2009 (Al-Cu-Mg) as the base alloy reinforced with BPA particles at concentrations ranging from 0 to 4 wt%. The research evaluated the effects of BPA reinforcement on mechanical properties, microstructural evolution, and tribological behaviour. SEM micrographs (Figure 10) indicated uniform particle distribution in both unreinforced and 4 wt.% BPA composites, with no observable porosity, indicating excellent wettability and interfacial bonding between the aluminium matrix and BPA reinforcement. The mechanical testing results demonstrated remarkable improvements, with BPA reinforcement increasing tensile strength and hardness by 35% and 44.1%, respectively at the maximum 4 wt.% loading. The tribological analysis revealed a complex relationship between reinforcement content and wear behaviour. While the wear rate decreased with increasing BPA content, the friction coefficient showed an opposite trend of gradual increase (Figure 11). This study highlights the potential of BPA particles as a sustainable reinforcement for aluminium alloys, particularly in applications requiring enhanced strength and wear resistance, though the increased friction coefficient at higher reinforcement levels may require careful consideration in specific engineering applications.

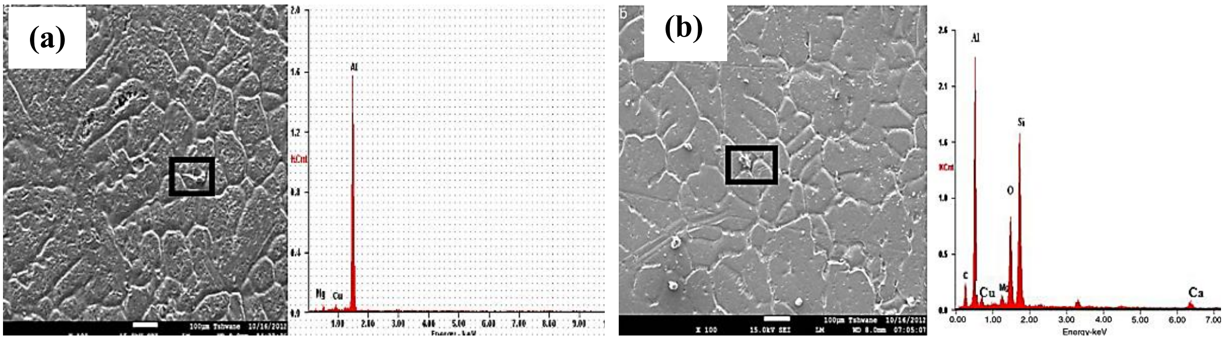

Figure 10: SEM/EDS spectrum of aluminium alloy (a) unreinforced (b) reinforced with 4 wt% BPA nanoparticles (Aigbodion, 2019)

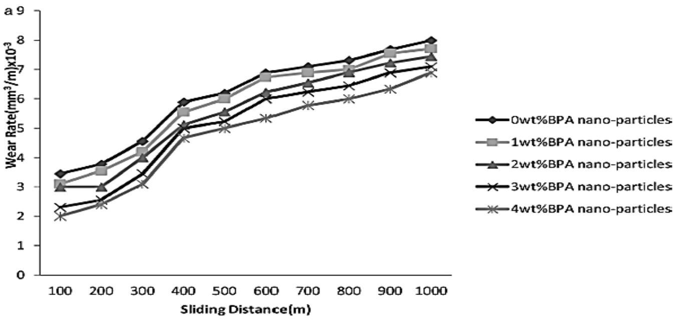

Figure 11: Variation of wear rate with sliding distance for aluminium alloy reinforced with 4 wt% BPA particles **(**Aigbodion, 2019).

In another study, Gireesh *et al.* (2018) conducted a comparative analysis of aluminium matrix composites reinforced with fly ash (FA) and aloe vera ash (VA), fabricated via the stir casting method. The composite was prepared using 10 wt%FA and 3 wt%VA by weight of the base aluminium metal. The investigation demonstrated that VA particles were well dispersed within the aluminium matrix, which significantly improved both the hardness and tensile properties of the material. The Brinell hardness number (BHN) of the aloe vera-reinforced composite (AMC-AV) was found to be 33.8 BHN, which was higher than that of both pure aluminium (19.0) and the fly ash-reinforced composite (AMC-FA) at 28.2 BHN. In terms of tensile strength, the incorporation of FA resulted in a 31.44% increase, while aloe vera ash contributed to a more substantial enhancement of 55.62%. These findings underscore the superior reinforcing capability of VA for high-strength applications. Shaikh *et al.* (2019) examined the wear behaviour of aluminium composites reinforced with SiC and RHA, using the powder metallurgy process. Aluminium was reinforced with SiC at a fixed 10 wt.% along with varying RHA content of 0%, 5%, 10%, and 15%. Among the different compositions, the composite containing 10% SiC and 10% RHA exhibited the best wear resistance, with a 33% improvement over unreinforced aluminium. Furthermore, it was observed that the coefficient of friction decreased progressively with an increase in the total reinforcement content, indicating better tribological performance with higher filler loading.

Alaneme and Sanusi (2015) conducted a study on Al-Mg-Si alloy (AA 6063) composites reinforced with a hybrid mixture of RHA, alumina, and graphite at varying compositions using a two-step stir casting technique. SEM analysis of the microstructure showed that the reinforcement particles were fairly well dispersed within the aluminium matrix. Hardness is found to decrease with increasing weight ratios of RHA and graphite, though when RHA content exceeds 50%, the influence of graphite on hardness becomes negligible (Figure 12). In terms of tensile behaviour, composites containing 0.5 wt% graphite along with up to 50% RHA demonstrate higher tensile strength compared to graphite-free composites, while also exhibiting superior toughness across all tested compositions. Interestingly, elongation remains consistent within a narrow range of 10–13% regardless of RHA or graphite content, indicating stable ductility. Regarding wear performance, graphite-free composites display greater wear susceptibility, while the addition of graphite initially improves wear resistance, though this benefit diminishes when graphite content increases beyond 0.5 wt%, with resistance declining at higher concentrations (1.5 wt%). These findings suggest that an optimal balance of mechanical and tribological properties can be achieved by maintaining RHA content below 50% and graphite at approximately 0.5 wt%.

Alaneme and Olubambi (2013) conducted a study to assess the corrosion and wear behaviour of hybrid aluminium matrix composites based on Al-Mg-Si alloy reinforced with rice husk ash (RHA) and alumina. The composites were developed with a total reinforcement content of 10 wt.%, comprising different ratios of RHA to alumina: 0:10, 2:8, 3:7, and 4:6. The objective was to understand how varying the proportion of RHA influences the mechanical and corrosion performance of the composites. The findings, summarised in Table 7, revealed that corrosion resistance decreased as the RHA content increased. Among the tested samples, the composite reinforced solely with 10 wt.% alumina exhibited the highest corrosion resistance when exposed to a 3.5% NaCl solution, while those with higher RHA proportions showed elevated

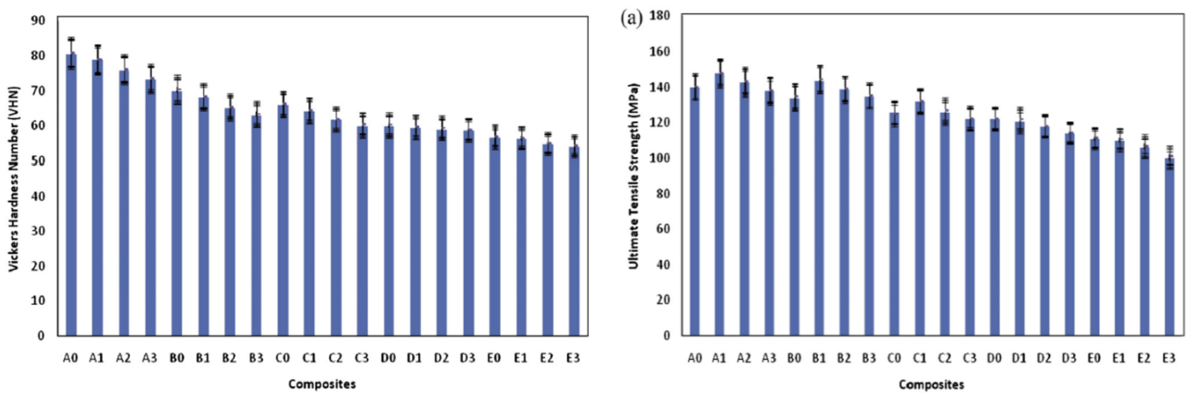

Figure 12: Variation of (a) hardness (b) tensile strength of Al-Mg-Si alloy reinforced with RHA, alumina, and graphite (Alaneme and Sanusi, 2015).

Table 7: Corrosion potentials, corrosion current densities, porosity and hardness of the produced composites.

Sample designation	Wt% (RHA:Alumina)	E_{corr} (mV)	I_{corr} ($\mu A/cm^2$)	% Porosity	Hardness (HVN)
A	0:10	816.752	2.379	1.028	78.6±1.12
B	2:8	798.422	4.209	2.292	75±0.64
C	3:7	763.623	6.823	1.917	72.2±0.35
D	4:6	836.234	7.614	1.942	70±0.55

Source: Alaneme and Olubambi, 2013.

corrosion rates. In terms of hardness, a slight decline was observed with increasing RHA content in the hybrid composites. This trend was attributed to the chemical composition of RHA, which is predominantly made up of silica (SiO_2), a material with lower hardness compared to alumina. As the proportion of RHA increased in place of alumina, the overall hardness of the composite decreased accordingly. Furthermore, tribological study indicated that both the coefficient of friction and the wear rate of the composites rose with higher RHA content. These results suggest that although RHA can be used as a cost-effective and sustainable reinforcement, its increasing presence may compromise certain mechanical and corrosion-resistant properties when compared to alumina-dominant compositions.

Islam *et al.* (2021) successfully incorporated ESA and RHA as reinforcements into aluminium Al 3105 alloy using stir casting technique. The study focused on analysing both the microstructural features and mechanical properties of the resulting metal matrix composites. As shown in Figure 13, the SEM images of the composite containing 5% ESA and 5% RHA by weight reveal a uniform distribution of reinforcement particles throughout the aluminium matrix. This uniformity is attributed to the strong intermolecular forces and good interfacial bonding between the reinforcing particles and the aluminium alloy, indicating high wettability and efficient particle-matrix integration. The mechanical characterisation further confirmed that the composite with 5% ESA and 5% RHA exhibited the highest tensile strength and hardness among the tested compositions. These enhancements demonstrate the synergistic effect of combining ESA and RHA as reinforcements. Based on these findings, the researchers concluded that both ESA and RHA are viable, sustainable materials that can be effectively used in the development of high-performance aluminium-based composites.

Kumar *et al*. (2018) investigated the mechanical properties and microstructural characteristics of hybrid aluminium matrix composites based on Al 6082, reinforced with zirconium oxide (ZrO_2) and CSA. Findings revealed that the incorporation of ceramic particles significantly enhanced the hardness of the composites; however, an increase in CSA content led to a gradual decrease in hardness values. Additionally, the inclusion of both ZrO_2 and CSA resulted in a reduction in the impact strength of the composites, indicating a trade-off between hardness and toughness when using these reinforcements. Alaneme *et al*. (2016) carried out a study on the mechanical performance of Al-Mg-Si alloy composites reinforced with GSA and SiC.

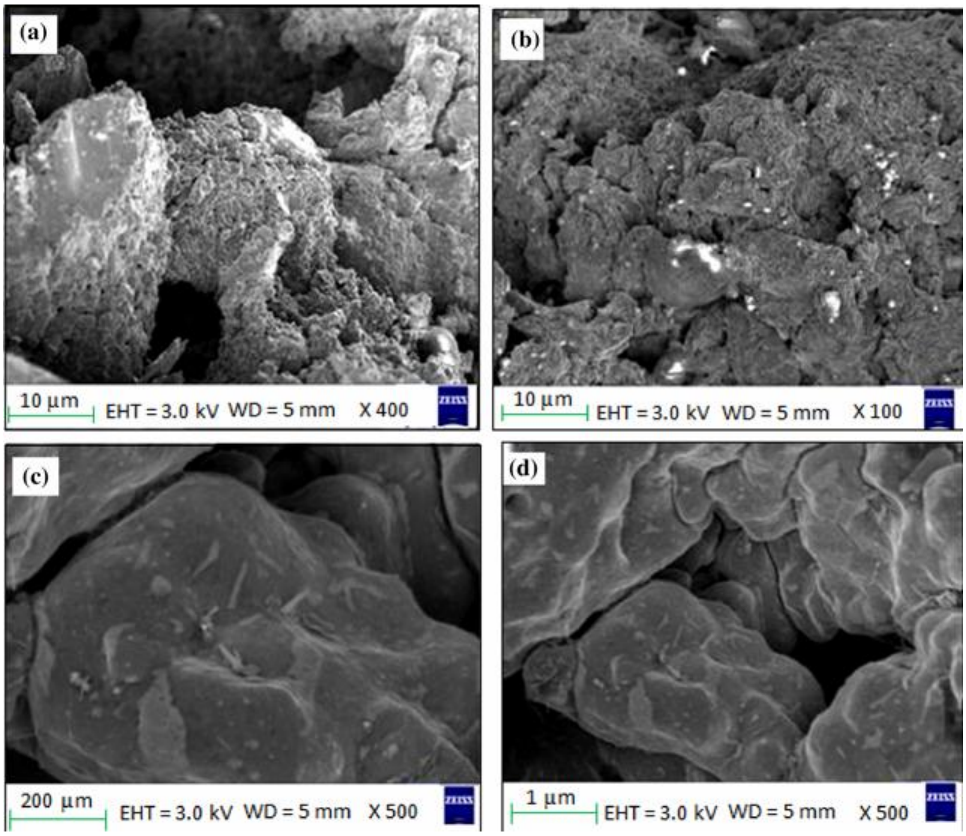

Figure 13: SEM images of Al 3105 aluminium alloy reinforced with 5% ESA and 5% RHA at different magnifications (Islam *et al.,* 2021)

A range of mechanical tests, including tensile strength, fracture toughness, and hardness assessments, was performed. The results indicated that both hardness and tensile strength increased with the overall reinforcement content. However, a slight decrease in these properties was noted as the proportion of GSA increased, likely due to its relatively lower hardness compared to SiC. Interestingly, the percentage elongation showed a marginal improvement with rising GSA content, suggesting that GSA contributed to enhancing ductility.

Satheesh and Pugazhvadivu (2019) explored the physical and mechanical properties of Al6061-SiC/CSA hybrid composites. The study demonstrated a uniform dispersion of reinforcement particles within the aluminium matrix. Mechanical characterisation revealed that hardness and tensile strength improved with the addition of CSA up to 8 wt.%, while compressive strength peaked at 6 wt.% CSA. Furthermore, wear behaviour analysis, as illustrated in Figure 14, showed that wear resistance of the composite significantly increased with CSA addition, reinforcing its potential for applications where wear resistance is critical. Gladston *et al.* (2017) studied the dry sliding wear behaviour of AA6061 reinforced with varying RHA content (0, 2, 4, 6, and 8 wt.%) using the compo casting method. Wear tests were conducted at room temperature using a pin-on-disc apparatus. The study revealed that RHA reinforcement effectively enhanced the wear resistance of the composites. Improvements were attributed to a combination of factors, including increased hardness, the formation of strain fields, uniform particle dispersion, the spherical morphology of RHA particles, and the reduction in effective contact area during sliding, as depicted in Figure 15. Additionally, the presence of RHA was found to minimise plastic deformation on the worn surfaces and reduce the size of wear debris, further validating its role in improving tribological performance.

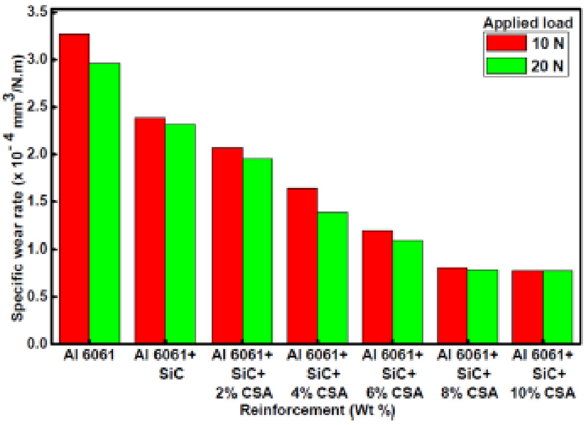

Figure 14: Specific wear rate of Al6061 and its composites (Satheesh and Pugazhvadivu, 2019).

Alaneme *et al.* (2013b) investigated the microstructure, mechanical properties, and corrosion behaviour of Al-Mg-Si alloy matrix composites reinforced with varying weight percentages of BLA and SiC in ratios of 0:10, 2:8, 3:7, and 4:6, respectively. The experimental results demonstrated that as the BLA content increased, both the hardness and ultimate tensile strength (UTS) of the composites improved, while the percentage elongation decreased. Notably, the fracture toughness of the BLA-containing hybrid composites was higher than that of the single-reinforced Al-10 wt.% SiC composite, indicating enhanced resistance to crack propagation. Furthermore, corrosion studies using gravimetric analysis revealed that the addition of BLA enhanced the corrosion resistance of the hybrid composites in a 3.5% NaCl solution. However, in a 0.3 M H_2SO_4 environment, the single-reinforced SiC composite showed superior corrosion resistance. This trend of reduced corrosion performance with agro-waste ash reinforcements was consistent with previous findings, such as Alaneme *et al.* (2014a), who observed similar corrosion susceptibility in Al-Mg-Si/SiC-RHA composites exposed to a 3.5 wt.% NaCl medium. Moreover, for hybrid AMCs reinforced with RHA/Al_2O_3 and BLA/Al_2O_3 combinations, studies by Alaneme and Olubambi (2013) and Alaneme *et al*. (2014b) confirmed a decrease in corrosion resistance with the inclusion of agro-waste ashes.

The findings indicated that increasing CPA content improved the hardness and tensile strength of the composite. However, it adversely affected fracture toughness and impact energy, reflecting a compromise between strength and toughness. Joseph and Babaremu (2019) also explored the reinforcement of AlSi10Mg with RHA in different proportions (3%, 6%, 9%, and 12% by weight) through a liquid metallurgy route. SEM analysis confirmed uniform dispersion of RHA particles within the aluminium matrix. The mechanical results showed a significant improvement in both tensile strength and hardness, attributed to the enhanced interface between RHA particles and the MMC components with excellent thermal resistance.

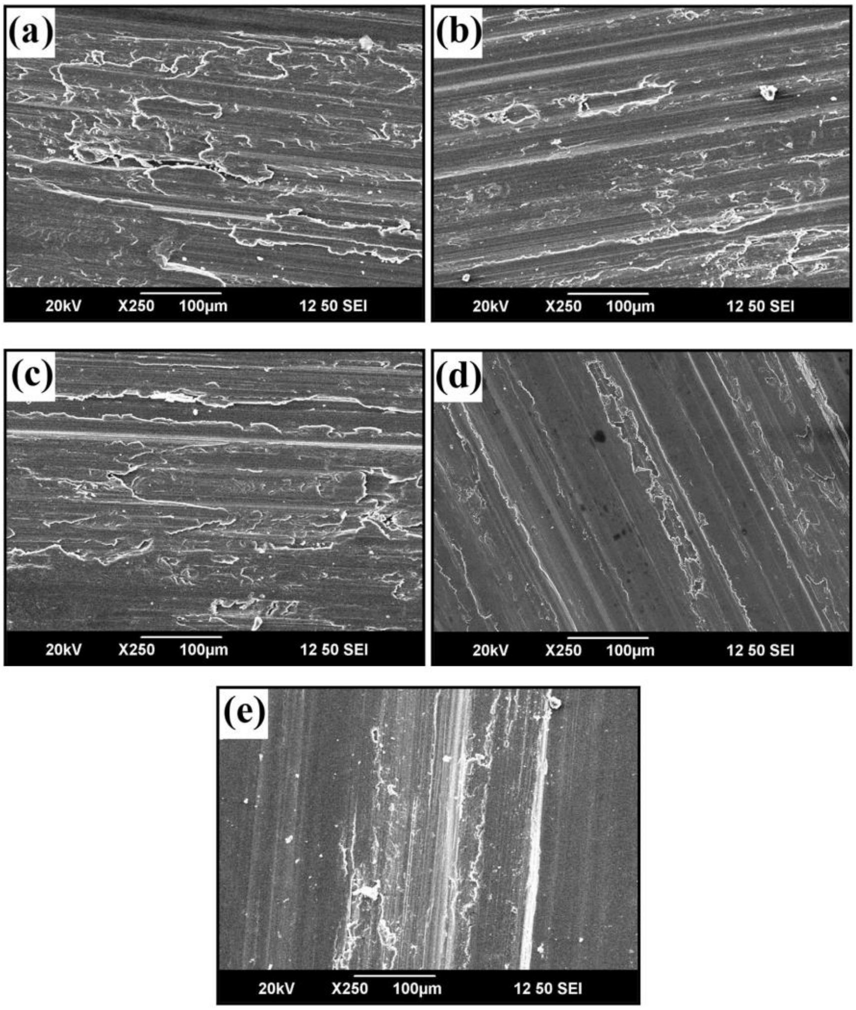

Figure 15: SEM micrographs of the worn surface of AA6061/RHA AMCs containing RHA; (a) 0 wt.%, (b) 2 wt.%, (c) 4 wt.%, (d) 6 wt.% and (e) 8 wt.% at applied load 30 N (Gladston *et al.,* 2017).

Mechanical Property of Selected Agro-Waste Reinforced Aluminium Composites

Table 8 offers a comprehensive comparison of aluminium matrix composites (AMCs) reinforced with various agro-waste ashes and ceramic particles. These reinforcements significantly influence the mechanical properties, such as tensile strength, hardness, impact strength, and density, depending on their type and concentration. According to Gireesh et al. (2018), composites reinforced with aloe vera ash (AMC-aloe vera) demonstrated superior mechanical performance compared to those reinforced with fly ash and the unreinforced aluminium matrix. With a low density of 2.21 g/cm³, the AMC-aloe vera composite had the highest ultimate tensile strength (119.83 MPa), hardness (33.8 BHN), and impact strength (1.80 J/mm²), making it an excellent candidate for lightweight structural applications. In comparison, AMC-fly ash displayed moderate improvements, and the base aluminium matrix had the lowest values across all mechanical properties. Singh et al. (2015) explored the effect of GSA on Al 6063 alloy. Their findings revealed a steady increase in hardness from 58 to 68 VHN with increasing GSA content. Compressive strength also improved with reinforcement, suggesting that GSA is an effective and sustainable additive for enhancing strength without significantly increasing weight. Nithyanandhan et al. (2017) showed that the combination of B_4C and CSA significantly improved the tensile strength of Al 6061 composite

Table 8: Physical and Mechanical Properties of selected AMCs reinforced with Agro-Wastes

Composites	Density (g/cm^3)	UTS (MPa)	UTS (MPa)	Impact Strength (J/mm^2)	Hardness (BHN)	References
Al matrix	2.70	77.0	10	0.1	19	Gireesh *et al.*,2018
AMC-fly ash	2.60	104.21	53.36	1.77	28.2	
AMC-aloe vera	2.21	119.83	62.97	1.80	33.8	
Al 6063 alloy	Tensile strength (MPa)		Compressive strength (MPa)		VHN	Singh *et al.*, 2015
	135		154		58	
Al6063+3%GSA	138		188		60	
Al6063+6%GSA	152		200		65	
Al6063+9%GSA	156		212		67	
Al6063+12%GSA	147		240		68	
94%Al 6061+5% B_4C+1%CSA	Tensile strength (N/mm^2)			Hardness (RHN)		Nithyanandhan *et al.*,2017
	5.153			61		
100%Al 6061	45.216			62		
90%Al 6061+8% B_4C+2%CSA	8.013			56		
Al					BHN	Kumar *et al.*, 2016
					34	
Al +15%wt CSA					46	
Al 6061		UTS(MPa)	YS(MPa)	% elongation	VHN	Butola *et al.*,2019
		94.3	57.8	24.2	41	
Al 6061 + banana ash		115.4	76.4	21	56	
Al 6061 + Coconut ash		109.3	71.2	20	55	
Al 6061 + sugar ash		94.1	63.7	22.2	51	
Al	2.66	UTS(MPa)	YS(MPa)		BHN	Ahamad *et al.*,2016
		90.81	47.5		22.54	
Al+3%RHA	2.52	95.7	52		24.68	
Al+6%RHA	2.50	112.97	58		29.77	
Al+9%RHA	2.47	115.32	61		33.60	
Al 356.2						Hasibul *et al.*, 2016.
Al 356.2+2%RHA		Tensile stress (MPa)	Compressive stress (MPa)	% elongation	76.78	
		174.6	232.64	3.37		

356.2+4%RHA	239.36	261	2.33	82.45	
356.2+8%RHA	277.66	267.9	2.01	84.44	
AlSi10mg	350		2.0	62.58	Narasaraju and Raju, 2015
AlSi10mg+15%FA+5 %RHA	392		2.9	65.05	
AlSi10mg+10%FA+1 0%RHA	410		3.2	69.02	
AlSi10mg+5%FA+15 %RHA	386		2.7	66.02	

from 45.216 N/mm² to 100.153 N/mm², while the hardness also increased from 56 to 61 RHN. This demonstrates a synergistic effect when combining ceramic and agro-waste reinforcements for improved mechanical performance. Butola *et al.* (2019) investigated the impact of different agro-waste ashes such as banana, coconut, and sugarcane on Al 6061. Banana ash led to the highest improvements, with tensile strength reaching 115.4 MPa and hardness at 56 VHN. All types of ash showed enhancements over pure aluminium, though with a slight decrease in ductility, indicating increased brittleness as reinforcement content rises. Ahamed *et al.* (2016) studied Al composites reinforced with rice husk ash (RHA) at different weight percentages. Results showed a consistent improvement in tensile strength (from 90.81 MPa to 115.32 MPa) and hardness (from 22.54 to 33.60 BHN), with a corresponding decrease in density (from 2.66 to 2.47 g/cm³). These findings confirm that RHA is effective in producing lightweight composites with improved mechanical strength.

Hasibul *et al.* (2016) examined Al 356.2 reinforced with RHA, and found significant gains in tensile and compressive strengths with increasing RHA content. For instance, tensile stress rose from 174.6 MPa to 277.66 MPa and compressive stress from 232.64 MPa to 267.9 MPa as RHA increased from 2% to 8%. However, elongation dropped from 3.37% to 2.01%, again reflecting a trade-off between strength and ductility. Narasaraju and Raju (2015) investigated hybrid composites of AlSi10Mg reinforced with combinations of fly ash (FA) and RHA. The highest tensile strength (410 MPa) and hardness (69.02 BHN) were observed in the composite with 10% FA and 10% RHA. This hybrid reinforcement also improved impact strength, indicating that optimal combinations of waste-based reinforcements can maximise mechanical performance.

Fabrication Techniques for Agro Waste-Based Metal Matrix Composites

AMCs can be manufactured using two primary processing routes: liquid-state processing and solid-state processing (Bodunrin *et al.,* 2015). Liquid state processing includes methods such as stir casting, squeeze casting, and semi-solid processing, while powder metallurgy is a widely recognised technique under solid state processing (Kandpal *et al.,* 2021). Among these methods, stir casting has emerged as the most commonly adopted method due to its simplicity, cost-effectiveness, and suitability for large-scale production (Alaneme and Adewale, 2013; Awasthi *et al*., 2018). This makes it particularly attractive for industrial applications where both performance and production efficiency are crucial.

Liquid-State Processing

Liquid-state processing has emerged as a dominant manufacturing route for MMCs, particularly for aluminium and magnesium-based systems reinforced with ceramic particles, carbon fibres, or agro-industrial waste materials (Hashim *et al*., 1999). This approach involves melting the metallic matrix prior to the incorporation of reinforcements. Stir casting remains the most widely adopted liquid-state technique, where mechanical stirring of molten metal creates a vortex for reinforcement introduction. Studies by Yadav *et al*. (2018) demonstrated that double stir casting of A356 aluminium alloy with RHA and fly ash reinforcements significantly enhanced wear resistance while maintaining cost competitiveness. However, this method faces challenges, including particle agglomeration and gas porosity, particularly with nano-scale reinforcements (Hashim *et al*., 1999). Figure 15 presents a schematic representation of the stir-casting setup. In this method, the aluminium matrix is initially heated beyond its red-hot temperature to achieve complete melting in a high-temperature-resistant graphite crucible. The crucible is surrounded by heating coils, which generate the necessary heat to melt the matrix material through induction or resistance heating. The molten aluminium is then partially cooled to reach a semi-solid state. At this critical stage, preheated reinforcement particles are introduced into the molten pool and thoroughly mixed with a mechanical stirrer inserted into the molten metal to create a vortex to ensure uniform dispersion of reinforcement particles into the melt. The mixture is subsequently reheated to ensure a fully liquid phase and further homogenised (Saikrupa *et al*., 2021).

This stepwise processing strategy enhances particle integration by breaking the gas barrier around the reinforcement particles, thereby promoting better wettability and bonding between the matrix and the reinforcement (Gowri *et al.,* 2013; Rajesh *et al.,* 2013). The combination of effective particle dispersion and improved interface bonding contributes significantly to the mechanical and structural integrity of the resulting composites. Once thoroughly mixed, the molten composite is poured into moulds for solidification. Several critical parameters influence the effectiveness and quality of the stir-casting process used in the fabrication of AMCs. One such factor is rotation speed, which plays a vital role in shaping the casting and ensuring uniformity during fabrication. According to Kandpal *et al.* (2017), increasing the rotation speed during the addition of reinforcement into the matrix leads to better refinement, whereas a slower speed can cause instability in the molten metal, resulting in non-uniform distribution. Another key factor is the stirring speed, which directly affects the wettability and the bonding quality between the matrix and the reinforcement particles.

As noted by Saikrupa *et al.* (2021), the stirring speed is influenced by the flow pattern of the molten metal, and optimal bonding typically occurs when the speed is maintained within the range of 300 to 600 rpm, as observed in numerous studies (Rajesh *et al.,* 2013). The stirring temperature is equally important in determining the viscosity of the molten metal and the uniform distribution of the reinforcement particles. A rise in stirring temperature leads to a decrease in molten viscosity, allowing better particle dispersion. Saikrupa *et al*. (2021) highlighted that many fabrication processes maintain a stirring temperature of around 630°C for Al 6061 in its semi-solid state, which ensures ideal conditions for mixing and particle integration. Additionally, the pre-heating temperature of the reinforcement materials significantly affects the final composite quality. Preheating reinforcements to around 250°C for three hours is a common practice aimed at removing moisture and enhancing particle-matrix wettability during melting (Asafa *et al*., 2024). This step also helps eliminate surrounding gases and impurities that may hinder proper bonding (Pradeep *et al*., 201). Together, these parameters form the backbone of an effective and high-quality stir-casting process. Another variant of stir casting is squeeze casting, which has gained prominence for high-performance applications, combining permanent mould casting with high pressure (100-150 MPa) to force molten metal into reinforcement preforms.

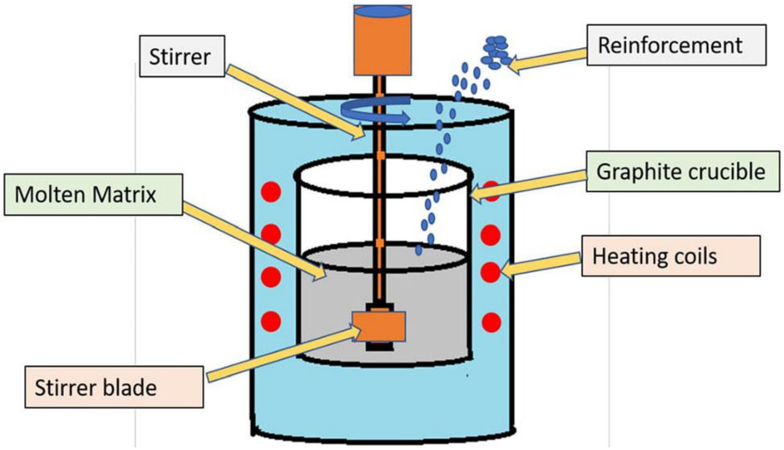

Figure 15: Schematic diagram of stir casting method (Parveez *et al*., 2021)

This technique has been successfully implemented in automotive brake disc production using Al-SiC composites, achieving near-net-shape components with porosity levels below 2%. The enhanced particle-matrix bonding achieved through squeeze casting contributes to improved mechanical properties, although at higher equipment costs (Yue and Chadwick, 1996). Compo-casting, operating in the semi-solid temperature range, offers a compromise between fully liquid and solid-state processes (Flemings, 1991). Research by Gladston *et al.* (2017) on AA6061-RHA composites revealed that maintaining 30-50% solid fraction during processing resulted in refined microstructures with reduced shrinkage defects. This technique requires precise temperature control but demonstrates superior particle distribution compared to conventional stir casting (Flemings, 1991). Infiltration techniques, including pressureless and pressure-assisted variants, have shown particular promise for fabricating composites with complex reinforcement architectures (Mortensen & Cornie, 1987).

Solid State Processing Technique

Solid-state processing techniques, particularly powder metallurgy (PM), have emerged as a promising approach for fabricating AMCs reinforced with agro-waste materials. Unlike conventional liquid-state methods such as stir casting, solid-state processing avoids common issues like particle segregation, interfacial reactions, and excessive porosity. This makes it particularly suitable for producing high-performance composites with agro-waste reinforcements. The PM process typically involves three main steps: blending, compaction, and sintering. Blending involves mechanical alloying in which high-energy ball milling ensures uniform dispersion of agro-waste particles within the aluminium matrix. Cold compaction using uni-axial or isostatic pressing then consolidates the powder mixture into green compacts, followed by sintering at temperatures below the melting point of aluminium (typically 500-600°C) to enhance diffusion bonding. Yadav *et al.* (2018) successfully fabricated Al6082/CSA composites through PM and achieved enhanced hardness (85 HV) and wear resistance due to the homogeneous distribution of CSA particles.

Other advanced solid-state techniques like friction stir processing (FSP) and spark plasma sintering (SPS) have also shown promise. FSP, a derivative of friction stir welding, embeds reinforcement particles into aluminium substrates through severe plastic deformation, as demonstrated by Satheesh and Pugazhvadivu (2019), who improved tribological properties by 30% in Al6061/CSA/SiC composites compared to stir-cast versions. SPS is an advanced sintering process that applies uniaxial pressure and pulsed direct current simultaneously to the powder compact, leading to rapid heating rates and localised joule heating at particle contacts. This enables the sintering of materials at lower temperatures and shorter times compared to conventional sintering, resulting in finer microstructures and enhanced mechanical properties (Singh *et al*., 2023). SPS offers superior control over densification kinetics and grain growth, making it ideal for sintering nanostructured and complex materials. However, the setup is expensive and maintenance cost is relatively higher than others.

The advantages of solid-state processing for agro-waste-reinforced aluminium composites are numerous. Most significantly, these methods minimize porosity issues commonly encountered in casting processes. Mechanical alloying ensures much more uniform reinforcement distribution throughout the matrix compared to liquid-state methods. The resulting composites typically exhibit enhanced mechanical properties, including higher hardness, improved wear resistance, and greater tensile strength, as reported by Butola *et al*. (2019). Additionally, solid-state processes like sintering generally require less energy than melting processes, making them more energy-efficient, according to Madakson *et al.* (2012). These benefits make solid-state processing particularly attractive for producing high-performance composites from sustainable agro-waste materials.

Despite these advantages, several challenges must be addressed when using solid-state processing for agro-waste-reinforced aluminium composites. Poor interfacial bonding between the aluminium matrix and agro-waste particles remains a significant issue, though pre-treatment methods such as alkali or acid washing of the particles can help mitigate this problem (Subrahmanyam *et al*., 2015). Another challenge is the agglomeration of fine reinforcement particles, which can be controlled through careful process optimisation during ball milling (Gladston *et al.,* 2017). Additionally, these composites sometimes exhibit limited ductility, which can be improved by using hybrid reinforcement systems combining agro-waste materials with synthetic reinforcements.

CONCLUSION

Aluminium matrix composites reinforced with agricultural residues provide a potential, sustainable category of materials capable of providing significant enhancements in hardness and wear resistance, as well as competitive specific strength when appropriately processed. The performance is fundamentally contingent upon particle pretreatment, dispersion, interfacial chemistry, and the quality of casting and sintering. The community must unify on standardized processing and testing protocols while addressing interfacial engineering and long-term durability, to get from laboratory demonstrations to reliable industrial materials.

FUTURE DIRECTIONS

The study has opened several avenues for future research in the field of AMCs reinforced with agro-waste materials. The ongoing interest in hybridisation and data-driven process optimisation is expected to expedite adoption in lightweight and tribological applications. Additionally, there is a significant need for improved manufacturing techniques to strengthen the surface modification and interface engineering for proper wettability, uniform particle dispersion, and strong matrix–reinforcement interfacial bonding. This will reduce defects such as porosity or clustering, refine the grain structure during solidification, and thereby enhance tensile strength, hardness and wear resistance. Moreover, while stir casting is widely used, other alternative fabrication methods like spray atomization, microwave field-assisted sintering, and squeeze casting deserve more research attention. Investigating these techniques along with varying process parameters could provide better control over the microstructure and mechanical properties of AMCs. Another underexplored area is the corrosion behaviour of agro-based reinforced AMCs. Limited studies are available on this subject, and deeper investigation is necessary to understand their performance in different corrosive environments, especially for applications where durability is crucial. In addition, future research should focus on particle size optimization of agro-waste reinforcements. Reducing the particle size from the micron to the nanoscale could significantly enhance the fracture toughness and ductility of AMCs without compromising their strength. The use of nano-sized particulates offers a promising route for producing composites with superior mechanical and functional properties. Lastly, future research should focus on developing hybrid reinforcement systems combining agro-waste materials with advanced reinforcements like graphene and carbon nanotubes among others.

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