A Review on utilization of agricultural wastes as reinforcement for aluminium matrix composites: A Circular Economy Approach

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Abstract

Global warming presents significant challenges that demand immediate attention. A number of issues are known to be infamously contributing to this worldwide issue, including industrial operations, the disposal of plastics, electrical devices, and agricultural waste. As world leaders gather to pass rules and regulations to safeguard our planet, researchers have suggested green manufacturing and agro-based alternatives to address this threat. This study challenges synthetic materials like carbon fiber and asbestos, which are known kingpins that can increase landfills worldwide and have detrimental health effects, by demonstrating the feasibility of turning agricultural waste into valuable engineering materials as an alternative manufacturing material. With an emphasis on aluminum matrix, which is a crucial component in manufacturing because of its exceptional qualities, including cheap cost and density, high strength to weight ratio, and resistance to corrosion, among others. According to a review of the literature, fly ash, bottom ash, rice husk ash, and bean pod ash are only a few of the elements that have been used as reinforcement in metal matrix composites. Publicly available research indicates that incorporating agricultural waste particles into a metal matrix in a specific ratio produces a number of desired characteristics, such as decreased greenhouse gas emissions, increased energy efficiency, and improved mechanical performance.The features and applications in several areas were studied in the article. It has been determined that aluminum matrix composites supplemented with agricultural wastes are a viable option for mitigating climate change by lowering CO2 emissions and promoting sustainable production and consumption.

Keywords: *Climate Change Mitigation, Agricultural Waste, Composites, sustainable consumption and production*

1. Introduction

The state of our natural environment has a significant impact on our quality of life and general well-being. Land, water, and air are the fundamental components of this ecosystem, which has a direct effect on the planet's equilibrium (Kabir et al., 2023). Growing carbon emissions from garbage and other human activities are seriously harming our world. According to Gupta and Verma (2021) and Mohanty et al. (2024), industrial operations and the disposal of materials after use owing to urbanization have become major difficulties with high energy consumption, health concerns, and accelerated climate change. Approximately 33% of the 2.01 billion tonnes of municipal trash produced annually worldwide is not managed in an environmentally safe way. Figure 1 shows that 44% of this is organic (food and green), and by 2050, it is predicted that global waste production will reach 3.4 billion tonnes, more than twice the rate of population growth during that time. This poses a serious threat to the environment, economy, and health of many nations, particularly developing nations (Gupta & Verma, 2021; Valavanidis & Valavanidis, 2023; Van Wyk et al., 2016).

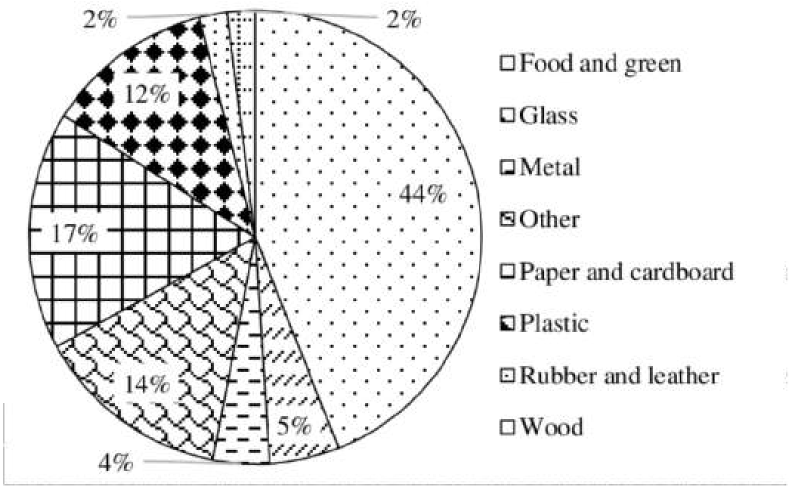

Figure 1. Global waste composition (Haq & Samiur, 2021)

In order to reduce emissions and fight climate change by reducing pollution and its effects by 2060, the international community has been forced to come together under agreements like the 2015 Paris Agreement and the 1997 Kyoto Protocol due to the threat posed by waste and other environmental issues (Matemilola et al., 2020). This has prompted international research, and businesses and academic institutions have been working to create sustainable alternatives to traditional methods in order to combat the threat by reusing and incorporating renewable processes and materials, like composites, into our daily lives (Udokpoh & Nnaji, 2023; Chaurvedi et al., 2023). Green manufacturing, which involves recycling waste and creating sustainable engineering materials from waste, is one of the many tactics that have been tried to raise environmental awareness, offer eco-based solutions, and combat the threat of climate change (Belekar, 2017; Freitas et al., 2021). The creation of sustainable engineering materials, especially composites, has been increasingly popular in recent years among these initiatives.

Composites are materials made by heterogeneous fusion of two or more materials with different phases in a certain proportion thus resulting in improved properties than the individual participating parent materials called the reinforcements and matrix. The matrix holds the composite in place in addition to transferring the load between the reinforcement while the reinforcement bears the load (Selvam et al., 2021). Composite matrix can be developed from different materials, notably among them is the polymer matrix composites (PMCs) from polymers, ceramic matrix composites (CMCs) from ceramics or metal matrix composite (MMCs). Although PMCs are the most widely used materials due to the versatility, high strength to weight ratio and high tensile strength, they pose the risk of environmental harm due to their resistance to biodegradation contributing to plastic pollution thus exacerbating global warming (Fakhrul & Islam, 2013). According to Dhanasekar *et al.* (2022) ceramics-based composites are expensive, energy intensive and often brittle which limits their applications in areas requiring flexibility while metal matrix composites are reusable and have good mechanical properties such as high strength and low weight making it a good candidate in areas such as aerospace sector where low weight and high strength is required (Parikh et al., 2023). Reinforcements can take various forms: Fibers, particulates, whiskers or nanomaterials, However, fiber reinforcements are the most common due to their ease of production(Park & Seo, 2011). Fiber reinforcement as shown in Figure 2 are either synthetic (man-made) or natural. While synthetic fibers such as fiber glass are known for having high initial processing costs, issues of biodegradability, high energy consumption, difficulty in recyclability, high carbon footprint and health hazards (Bhalla, 2017), natural fibers obtained from either plants or animals has important characteristics such as light weight, non toxicity, high specific modulus, relative ease of processing and reduced cost of manufacture which gives it an edge over its synthetic counterpart (Karimah et al., 2021;Samanth & Subrahmanya Bhat, 2023). Natural fibers Their composition includes polar components such as lignin, cellulose, hemicellulose, pectin, and waxy substances, which allow them to absorb moisture from the environment. This moisture absorption leads to inadequate or poor adhesion and bonding with the matrix due to phase differences, resulting in ineffective load transfer throughout the composite. However, this shortcoming can be mitigated by treating the surface of the fibers with chemicals like NaOH, as suggested by Li *et al.* (2007) and Samanth & Subrahmanya Bhat (2023). Metal matrix composites (MMCs) comprises various metals such as aluminum, copper, magnesium, titanium, nickel, and steel, with aluminum metal matrix composites (AMCs) standing out due to several factors.

Aluminium is one of the most prevalently used metals in engineering due to its outstanding properties such as low cost, low density, high corrosion resistance. It is highly abundant comprising nearly 8% of the total earth crust (Islam et al., 2021). This makes it a widely used metal second only to steel with a global demand of 29 million tons per year (Yang et al., 2018). According to (Fernandez et al., 2018), it has a good electric conductance property making it a good candidate for use in housing construction and aerospace sectors. Aluminium in its pure form, is ductile, soft, light weighted and highly resistant to corrosion which limits its use in high performance applications thus the need to combine it through alloying and reinforcement in with various materials creating aluminium matrix composites (AMC) so as to enhance its physical and mechanical properties (Dwivedi et al., 2023)
According to Alaneme (2013), AMCs are the most versatile among MMCs, attracting significant research interest because of their ease of processing, enhanced corrosion resistance, improved strength-to-weight ratio, better wear resistance, and superior

thermal expansion properties. Additionally, their cost efficiency further boosts their appeal. MMCs, in general, offer flexibility and find applications across diverse fields due to their favorable mechanical and physical properties (Singh *et al.*, 2023;*Akbar et al., 2020;*Li *et al.*, 2007). Furthermore, their unique combination of high strength-to-weight ratio, excellent wear resistance, and long-term durability makes them ideal materials for the aerospace and automotive industries. Aluminium based composites are often reinforced with ceramic based materials which are mostly expensive, unsustainable and increases its weight and making it difficult to be used where heavy weight is not required. This drives the need for sustainable lightweight alternatives such as agricultural waste-based reinforcements.

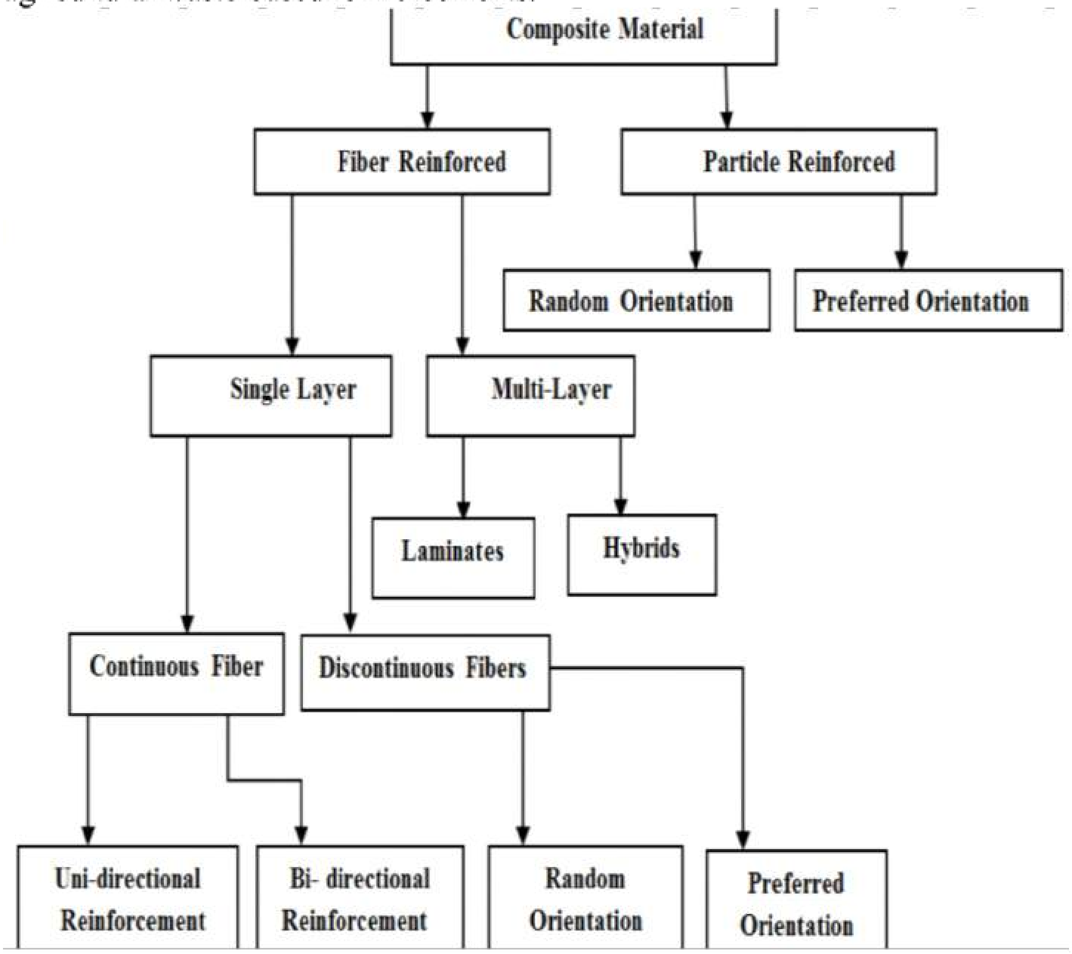

Figure 2. Classification of fibers (Haq & Samiur, 2021)

Khalid et al. (2021) explains that agricultural waste consists of the leftover materials produced from farming activities such as crop cultivation, livestock rearing, and food processing. These wastes include plant debris, animal by-products, and other organic substances remaining after harvest or processing. While the generation of such waste is often inevitable in agriculture, its improper disposal poses serious environmental challenges. Notably, it contributes to the release of greenhouse gases like methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). Furthermore, when these wastes accumulate in landfills, they hinder rainwater absorption into the soil, which can lead to environmental issues such as flooding and land degradation (Maji et al., 2020).

These agro wastes can be repurposed for numerous applications, including as sources of energy such as biogas (Zapalowska & Bashutska, 2019), production of biochar (Wahi et al., 2016), and as biomaterials to support a circular economy (Shanmugam et al., 2021; Santolini et al., 2021). They are also being increasingly considered as reinforcements in composite materials. Recent studies, as highlighted in Table 1, have examined various agricultural wastes as potential reinforcing agents in aluminium matrix composites. Each waste type contains a distinct lignocellulosic makeup, which influences its performance in specific applications. Given the limited research available on aluminium composite reinforcement using agricultural waste, this study aims to review the influence of different agro-waste materials—sourced from both agricultural and industrial by-products—on aluminium composites. It further explores emerging trends and the potential of these materials in developing sustainable aluminium-based composites. The overarching objective is to support both academic and industrial innovation in sustainable materials, in alignment with Sustainable Development Goals 12 (Responsible Consumption and Production) and 13 (Climate Action).

1.1 Industrial and Agricultural Waste Materials

Industrial and agricultural wastes are increasingly being recognized as promising reinforcement materials for high-performance composite systems due to their exceptional functionalities. According to Ortega et al. (2022), their rising popularity is largely attributed to their cost-effectiveness, biodegradability, and renewability. The composition of these agro-wastes varies depending on the plant or animal source, typically containing different proportions of cellulose, hemicellulose, lignin, pectin, and lignocellulosic compounds (Khaire et al., 2021). These components not only enhance the mechanical strength of composites but also maintain other desirable material properties. Moreover, the utilization of agro-wastes aligns with the principles of a circular economy, thereby supporting sustainable development and environmental conservation.

1.1.1 Fly ash

Fly ash, an industrial byproduct of coal combustion in thermal power plants, is produced during electricity generation through the transformation of mineral particles. It is rich in alumina, silica, and other oxides (as shown in Table 1), which makes it a promising and widely researched reinforcing material for aluminium matrix composites (AMCs). Its low cost and density have also led to extensive use in the cement and concrete industries to enhance material performance. These properties have encouraged researchers to explore the potential of fly ash in developing metal matrix composites. For instance, Mishra et al. (2014) demonstrated that incorporating fly ash particles into aluminium enhances mechanical properties such as hardness, tensile strength, and wear resistance, while also helping reduce greenhouse gas emissions. However, Mahendra and Radhakrishna (2007) noted that higher fly ash content may increase corrosion rates. Overall, the use of fly ash not only improves material performance but also mitigates the environmental challenges associated with its disposal, supporting waste recycling and contributing to sustainability efforts.

Table 1. Chemical composition of fly ash(Nizar et al., 2014)

Element	CaO	Al_20_3	Fe_20_3	$Si0_2$	K_2O	Na_2O	MnO	TiO_2	P_2O_5	SO
Wt %	2.61	23.59	7.39	52.11	0.42	0.78	0.49	0.88	0.8	1.31

1.1.2 Bottom ash

Similar to fly ash, bottom ash is another byproduct of coal combustion, distinguished by its coarser particle size. Despite this, bottom ash has demonstrated potential in enhancing the mechanical properties—particularly the wear resistance—of aluminium matrix composites, owing to its high silica (SiO2) and alumina (Al2 O3) content, as shown in Table 2. In a study by Joshi et al. (2021), the behavior of Al-7075 reinforced with Al2 O3 and bottom ash was investigated using the stir casting method. While the bottom ash content was kept constant, the Al2 O3 content was varied from 2–6 wt%. The results revealed significant improvements in impact strength, tensile strength, compressive strength, and wear resistance compared to the unreinforced alloy. Similarly, studies by Nur et al. (2017) and others have confirmed the efficacy of bottom ash as a reinforcement material, highlighting its contribution to both mechanical and thermal performance improvements. These enhancements are largely attributed to the densification of the composite structure. Consequently, bottom ash presents itself as a cost-effective, sustainable alternative to conventional reinforcements while simultaneously addressing environmental concerns related to industrial waste disposal.

Table 2. composition of bottom ash (Joshi et al., 2021)

Element	CaO	MgO	Al_20_3	Fe_20_3	$Si0_2$	K_2O_5	TiO_2	LOI
Wt %	4.2	0.35	28.5	8.49	54.8	0.45	2.71	Rem

1.1.3 Rice husk

Rice husk is found in abundant quantity in many states of Northern Nigeria. The annual rice husk production on a global scale is approximately 70 million tone which increases its environmental pollution globally on both waterways and on land thus affecting aquatic and terrestrial ecosystem. the ash of rice husk is rich in silica (Table 3) which makes it a perfect candidate for aluminium composite reinforcement. This material assists in improving the mechanical properties of aluminium. Researches such as Ramesh *et al.* (2014), Chowdhury *et al.* (2016) and Udoye et al. (2019) have proven that rice husk ash greatly improves wear resistance, hardness and tensile strength of the composite material. Over and above this, it also serves to support sustainable agricultural recycling initiative thus helping to encourage SDG12; responsible consumption and production.

Table 3. Chemical composition of rice husk ash (Gladston et al., 2017)

Element	CaO	LOI	MgO	Al_20_3	Fe_20_3	$Si0_2$	K_2O
Wt %	1.58	2.29	0.53	3.54	0.21	90.23	0.39

1.1.4 Bean pod ash

Bean pod ash is obtained from the combustion or burning of bean pod, the bean pod ash with chemical composition as shown in Table 4 has considereable amount of oxides capable of improving the properties of aluminium alloys. Although this materials has not been extensively explored due to its novelty in the area of aluminum composite potential, studies by Singh et al. (2020) shows that it can improve some mechanical properties of aluminium composites such as hardness and tensile strength. Just as others listed, this material in line with responsible consumption and production, will serve to offer a sustainable solution to agricultural waste management and improvement of materials for sustainable development.

Table 4. Chemical composition of Bean pod ash

Element	Na_2O	K_2O	MgO	Pb_2O_5	Fe_2O_3	Al_2O_3	CaO	Sio_2	LOI
Wt %	1.21	5.62	2.01	5.82	11.51	13.05	15.71	39.01	6.00

1.1.5 Coconut shell ash

The coconut shell is an abundant agricultural product found in many tropical countries globally. In many of these countries, they are used in generation of power for boilers in industries. Although, it has been found to constitute environmental pollution, research is still ongoing to find alternative application of the coconut shell ash. Coconut shell ash powders are however good materials that can be used as reinforcements for metal matrix composites due to oxides that it constitutes from as shown in Table 5. Addition of 8% wt coconut shell ash increases the strength and hardness of aluminium composites and 6% wt addition increases its compressive strength. Additionally, wear resistance of Al6061-SiC composites is improved by addition of CSA

Table 5. Chemical composition of coconut shell ash (Madakson & Apasi, 2012)

Element	CaO	ZnO	MgO	Al_20_3	Fe_20_3	$Si0_2$	K_2O	Na2O	MnO
Wt %	0.57	0.3	16.2	15.6	12.4	45.05	0.52	0.45	0.22

1.1.6 Egg shell ash

This is obtained from the egg of chicken littered all around the world as a waste product. The chicken egg shell usually constitute environmental pollution globally thus the need for it to be used for productive purposes. This material contains calcium 95 percent and has a relatively low density compared to many synthetic fibers (Kumar et al., 2020). For use as reinforcements in metal matrix composites, it is mostly converted to powder and calcinated at 1200 degree centigrade. Islam et al. (2021) reported an increase in tensile strength and hardness of AA6101 at 47.14% and 45.45% friction stir parameters for egg shell and SiC combination.

1.1.7 Sugar cane bagasse ash

Sugarcane bagasse ash (SBA) is found after combustion in industries that have used sugarcane bagasse as fuel sources due to high cost of traditional fuels. This ash contains quartz $SI0_2$ and silicon carbide (Table 6) in large quantity and has a low density of $1.9 g/cm^3$. SBA also contains water, methane and cellulose fiber which are important energy sources (Madakson & Apasi, 2012). Results from EDS has shown that SBA is rich in oxides such as, SiO, Al_2O_3, Fe_2O_3, and CaO. Additionally, it has a specific gravity of 1.234g/cm^3 (Imran & Anwar Khan, 2018).

Table 6. Chemical composition of bagasse ash (Usman et al., 2014)

Element	CaO	MgO	Al_20_3	Fe_20_3	$Si0_2$	SO_3	K_2O	Na_2O	LOI
Wt %	2.008	1.489	10.951	3.660	77.286	0.487	3.159	0.381	3.277

LOI= Loss on Ignition

1.1.8 Palm oil clincker

The palm oil clinker is a waste product of palm oil usually obtained after processing palm oil which usually results in clinker after combustion. The potential of this material to be used as composite reinforcement has been explored by several researchers for various applications. For example, Yaro et al. (2024) investigated the feasibility of waste palm oil clinker powder as filler substitute for ecofriendly hot mix asphalt pavement. For aluminium metal matrix composites, the palm oil clinker can serve as reinforcement for tribological applications due to the presence of graphitic carbon which helps to serve as solid lubricant thus reducing wear rate and crack propagation in the aluminium composite material.

1.2 Comparative Analysis

The comparative analysis of these agricultural wastes as reinforcements has shown several common benefits, including improved mechanical properties, reduced environmental impact, and cost-effectiveness. However, the specific properties and performance enhancements vary based on the type of agricultural waste used. For instance, fly ash and bottom ash are particularly effective in enhancing wear resistance (Bharathi et al., 2017), while rice husk ash and bean pod ash are good candidates in improving tensile strength and hardness of aluminium based composites. Table 7 presents a summary of waste Industrial and Agri waste materials used as reinforcement for Aluminium based composites.

Table 7. Summary of waste Industrial and Agri waste materials used as reinforcement for Aluminium based composites.

Reference	Developed material	Reinforcing agent used	Technique used	Conclusion
Mahendra and Radhakrishna. (2007)	Al- 4.5%	Copper alloy and silicon carbide and fly ash (5-15%)	Conventional foundry technique	Hardness, tensile compressive strength increase with increase i fly ash. Density reduce with increase in fly asl Corrosion and resistanc to dry wear and slurr wear increases witl increase in flyasl concentration.

Canute and Majumder , (2018)	A356 Al alloy	4% Boron Carbide powder and 4% flyash (hybrid)	Stir casting	Increase in tensile an compression strengt while ductility reduced.
Sathish et al. (2024)	LM25 Alloy	5% of flyash and 4%, 8%, 12% of TiB2	Stir casting technique	Improved strength an ductility of the composit LM25
Ramachandra	Al-Si	15% wt flyash	Liquid metallurgy	Density reduced from 2.62 gm/cm^3 to 1.613 gm/cm^3
Kumar et al. (2020)	AA7075 metal matrix composiste	Egg shell	Friction stir casting	Process parameters affect mechanical properties of the composite
Bose et al. (2019)	Hybrid composite	Waste egg shell, cow dung ash, snail shell ash and boron carbide	Stir casting technique followed by squeeze pressure	Increase in tensile hardness and fatigu strength with increase i fiber loading. Decrease i ductile, corrosion an toughness with increase fiber loading.
Naveen Reddy and Sandeep Raj (2020)	AA7075 graphite metal matrix composite	2.5% and 5 % wt SiC processed	Stir casting	Reduced density
Islam et al. (2021)	Hybrid composite	Egg shell and SiC	Friction stir	Optimum tensile strength and hardness with 47.14% and 45.45% friction stir process parameters
Mishra et al. (2014)		$Al2O_3$	Continuous stir casting method	Improved mechanical properties
Hiremath et al., (2018)	Glass fiber reinforced plastic (GFRP) composite	Egg shell	Hand layup process	Increase in mechanical properties with increase in fiber loading from 5-10%
Jannet et al. (2021)	AA2024 composite	Egg shell powder	In-Situ melting	7% egg shell powder was found to be more desirable for high tensile and compression application.
Usman et al. (2014)	Al 7% Si-rice husk ash and Al 7% Si-baggasse	Rice ash and Baggasse ash	Stir casting method	Rice ash additio performed better in term of mechanical properties

Reference	Developed material	Reinforcing agent used	Technique used	Conclusion
Alaneme et al., (2014)	Al-Mg-Si alloy hybrid composites	Rice husk ash and Silicon carbide	Double stir casting process	Production of low-cost Al Mg-Si alloy composit using rice husk as complementing reinforcement to silico carbide has great potentia for corrosion and wea resistance
Bharathi et al. (2017)	Aluminium matrix composite	Fly ash	stir-squeeze cast method	Improved abrasiv properties

Table 8 Summary of different agro reinforcement and their processing technique in literature.

Reference	Area of Application	Agro-Reinforcements	Processing Technique	Benefits
Bharathi et al. (2016) ; Jannet et al. (2021);Khan et al. (2024)	Automotive	LM25, Al2024 and flyash,	Squeeze cast technique	Improved mechanical properties, Weight reduction Improved fuel efficiency.
Jannet et al. (2021)	Aerospace	Al 2024 composite	Stir casting	Light weight Fuel economy
Osunmakinde et al. (2023)	Oil and Gas	rice husk ash (RHA), and cassava peel ash (CPA)	Two-step-stir casting technique	Improved physicomechanical properties
Hassanpour et al. (2018)	Biomedical	Aluminium oxide nanoparticles	A review	Lower cost and ease of handling

6. Conclusions and future direction

The incorporation of agricultural and green waste materials—such as rice husk ash, bagasse ash, bean pod ash, palm oil clinker, eggshell ash, and fly ash—into aluminium matrix composites (AMCs) is emerging as a sustainable and eco-friendly alternative to conventional reinforcement materials used across various industries. This approach promotes recycling and reuse of materials typically regarded as waste, thereby offering a viable substitute to traditional engineering materials. It also reduces reliance on nonrenewable resources and helps minimize carbon emissions. While previous studies have reported significant improvements in mechanical properties from these reinforcements, issues such as contamination and non-uniform dispersion of the reinforcements—which can compromise product quality and performance—need to be carefully addressed. Moreover, conducting a comprehensive life cycle assessment is essential to evaluate the true sustainability of these materials. This review focuses on select agricultural wastes suitable for reinforcing aluminium matrices in diverse applications. The findings of this study underscore its potential to contribute meaningfully to climate change mitigation by lowering carbon output and improving energy efficiency. It also supports sustainable agriculture and aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goals 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action). The valorization of agro-waste for this purpose represents a promising step toward environmental and economic sustainability, reinforcing the "waste-to-wealth" innovation paradigm.

7. Future Direction

Composite materials offer a compelling alternative to traditional engineering materials due to their superior performance across various applications. Unlike conventional materials, which often pose challenges related to high cost, toxicity, and environmental harm, agro-based composites stand out for being eco-friendly, non-toxic, and biodegradable. However, the adoption of agro-composites has remained relatively slow, primarily due to limited awareness and the lack of standardized guidelines. As global efforts intensify toward achieving the Sustainable Development Goals (SDGs), particularly Goals 9, 12, and 13, there is a growing recognition of the need to develop sustainable materials that address climate change and promote responsible consumption and production. This review underscores the potential of repurposing agricultural wastes—such as fly ash, bagasse, and bean pods—which are otherwise difficult to manage and contribute to environmental degradation. By transforming these wastes into valuable engineering materials, we can support sustainable development and environmental conservation. Future research should prioritize life cycle assessments of these materials to evaluate their environmental advantages, long-term performance, and how they compare to conventional materials in similar applications.

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