EDUCATUM JSMT Volume 12 Number 2 (2025)
ISSN 2289-7070 / e-ISSN 2462-2451(1-17)
https://ejournal.upsi.edu.my/index.php/EJSMT/index

Challenges and Future Prospects of Agricultural Waste Reinforced Metal Matrix Nanocomposites: A Review

Rebecca Samaila Hamalai
Department of Mechanical Engineering Nigerian Defence Academy, Kaduna P.M.B 2109, Kaduna, Nigeria

**Corresponding author: hamalairebecca@gmail.com*

Received: 09 May 2024; **Accepted:** 22 July 2024; **Published:** 02 February 2025

To cite this article (APA): Samaila Hamalai, R. (2025). Challenges and Future Prospects of Agricultural Waste Reinforced Metal Matrix Nanocomposites: A Review. EDUCATUM Journal of Science, Mathematics and Technology, 12(2), 1-17. https://doi.org/10.37134/ejsmt.vol12.2.1.2025

To link to this article: https://doi.org/10.37134/ejsmt.vol12.2.1.2025

Abstract

The use of agricultural waste as reinforcement in metal matrix nanocomposites presents a promising avenue for sustainable materials development. The incorporation of agricultural waste materials in metal matrixes can enhance the mechanical properties and potentially reduce the environmental impact of composites. However, this approach also faces significant challenges, such as compatibility issues, interfacial bonding, dispersion, and processing techniques. This paper critically reviews the current state of research on agricultural waste-reinforced metal matrix nanocomposites, identifies key challenges, and proposes future perspectives to overcome these obstacles and unlock the full potential of these materials.

Keywords: Agricultural waste, metal matrix composites, sustainability, interfacial bonding, dispersion, processing techniques.

INTRODUCTION

The rapid growth in industrialization and urbanization has led to an escalating demand for advanced materials with enhanced mechanical properties and reduced environmental impact. The most common synthetic materials utilized as reinforcing materials for the creation of metal-matrix composites include silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B4C), graphite, tungsten carbide (WC), carbon nanotubes (CNTs), etc. These reinforcements improved the created composites' mechanical, corrosion, and wear properties while also adding weight to the composite due to their higher density [1].

Researchers are now paying more and more attention to low-cost, low-density materials that can be conveniently utilized as reinforcements in the creation of MMCs [2]. Industrial and agricultural wastes are appropriate illustrations of the kind of materials that can be employed as reinforcement for the creation of composites and are also widely accessible. This innovative approach addresses the challenges of waste disposal and holds the promise of producing eco-friendly and resource-efficient materials [3].

The utilization of agricultural waste materials, such as rice husk, sugarcane bagasse, coconut coir, and wheat straw, offers several advantages. Firstly, these waste materials are abundantly available as by-products of agricultural processes, making them a cost-effective and renewable source for composite reinforcement. Secondly, incorporating agricultural waste in metal matrices can reduce reliance on conventional reinforcements as most of them have basic reinforcement elements such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO. Thereby reducing the dependence on energy-intensive processes and their environmentally harmful extraction processes [4].

However, integrating agricultural waste as reinforcement in metal matrix nanocomposites presents challenges that require meticulous attention. This paper aims to review and address these challenges to unlock the full potential of these composites and pave the way for sustainable materials development.

RESEARCH QUESTIONS

What are the most significant challenges associated with using agricultural waste as reinforcement in metal matrix nanocomposites, and how do these challenges impact the composite's performance?
What are the innovative strategies and future perspectives that can be employed to overcome the challenges of utilizing agricultural waste as reinforcement in metal matrix nanocomposites and enhance their mechanical properties and sustainability?

OBJECTIVES

The objectives of this paper are twofold: Firstly, to comprehensively examine the challenges associated with utilizing agricultural waste as reinforcement in metal matrix nanocomposites. It will delve into the issues of compatibility between agricultural waste and metal matrixes, focusing on the chemical and physical interactions that influence the composite's performance. Interfacial bonding and adhesion challenges, such as weak interfaces and poor stress transfer, will be addressed, along with strategies to mitigate them. Dispersion and agglomeration challenges and their impact on the composite's homogeneity and mechanical properties will also be discussed. Secondly, this paper will propose future perspectives and innovative strategies to overcome these challenges and enhance the performance of agricultural waste-reinforced metal matrix nanocomposites. By integrating surface modification techniques, interfacial engineering, and optimized processing parameters, it aims to improve compatibility, interfacial bonding, dispersion, and overall mechanical properties. Additionally, we will explore emerging trends, such as the integration of nanotechnology and the use of hybrid reinforcements, to further enhance the functionality and potential applications of these composites.

Scope

The scope of this paper encompasses the most commonly used agricultural waste materials, processing techniques, and metal matrix compositions. By analyzing the existing literature and consolidating the latest research findings, this paper endeavors to provide a comprehensive and insightful review of the challenges and future perspectives in the field of agricultural waste-reinforced metal matrix nanocomposites.

METHODOLOGY

To achieve the objectives of this review, a systematic and comprehensive methodology was adopted. A thorough literature search was conducted to identify relevant research papers, journal articles, conference proceedings, and patents related to agricultural waste-reinforced metal matrix nanocomposites (with the help of search engines; like google scholar and Boolean operators). The collected literature was analyzed to extract information on the challenges and future perspectives of utilizing agricultural waste as reinforcement. Emphasis was given to recent advancements and emerging trends in the field. The study included research on metal matrix composites and excluded other matrixes like polymer matrix composites. The selected literature was also reviewed to evaluate the effectiveness of strategies and techniques to address the identified challenges. The findings were organized and presented thematically, focusing on compatibility, interfacial bonding, dispersion, and processing techniques. Comparisons between different agricultural waste materials as reinforcements were also made to highlight their unique properties and potential applications in metal matrix nanocomposites.

Through this systematic methodology, this paper aims to provide a comprehensive review of the challenges and future perspectives of agricultural waste-reinforced metal matrix nanocomposites. The insights and recommendations from this review will contribute to advancing the knowledge and understanding of these sustainable materials, paving the way for their widespread application in various industries.

FINDINGS FROM LITERATURE

Types of Agricultural Waste Used as Reinforcement in Metal Matrix Composites

Utilizing agricultural waste allows for the creation of inexpensive, lightweight composites without sacrificing their mechanical and tribological characteristics [5].

However, there is only a limited understanding of how well they perform as a service, which limits their options for wider application use. To draw conclusions about the developments made thus far and to consider how the properties of Agricultural Matrix Composites (AMCs) might be improved by the addition of such agro-based reinforcements, it is crucial to review the morphological, mechanical, and tribological properties of these materials that contain different agro-based reinforcements [6]. The most commonly used ones are;

Rice Husk as Reinforcement

Rice husk is one of the most abundant agricultural waste materials and holds great promise as reinforcement in metal matrix nanocomposites. It offers several benefits, such as being cost- effective and easily accessible due to its abundance as a by-product of rice milling processes. The presence of cellulose and lignin in rice husk also contributes to improved tensile strength and thermal stability in the composite. Researchers employ rice husk because of its lower density (0.3- 1.9 gm/cm3) and convenience of availability [7].
RHA (Rice Husk Ash) improves the hardness, tensile strength, and toughness of the produced composites by containing a larger proportion of SiO2 together with other elements like Al_2O_3, Fe_2O_3, and MgO [8]. Silicon Carbide (SiC) has greater qualities than Rice Husk Ash so several researchers have isolated SiC from this material and employed it as a reinforcing material [9]. The hardness of the produced composites can also be increased by removing silica from RHA using heat treatments and reinforcing them with recycled Al7075 chips [10].

Figure 1: Rice husk

Coconut Coir as Reinforcement

Coconut coir is obtained from coconut husks the majority of this Agricultural waste material is readily available in tropical areas and is frequently utilized as fuel in furnaces and boilers [11]. However, the combustion of Coconut shell ash causes the production of huge amounts of CO2 and methane, which significantly damages the environment [12]. Given these factors, it is preferred to use them as reinforcement when producing Aluminum composites [13]. Coconut shell ash has a density of 2.05 gm/cm3 and contains natural reinforcement elements such as SiO_2, MgO, Al_2O_3, and Fe_2O_3. Studies have shown that the characteristics of Aluminum composites are improved by the addition of coconut shell particles; In one study, Coconut shell microparticles (CMP) and Al_2O_3 were used to reinforced Al6061 using the stir casting technique and it was observed that with more reinforcing content present, the hardness and tensile strength increased [14]. Additionally, Coconut shell ash was added to an Aluminium alloy made using the compo-casting approach and an improvement in tensile characteristics was observed as a result of the production of tougher phases and good interfacial bonding between the matrix and reinforcement [15].

Figure 2: Coconut coir

Sugarcane Bagasse Ash

Bagasse is the byproduct created when sugarcane is processed to extract its juice and is one of the biggest agricultural wastes in the entire globe [16]. Due to this residue's adaptability, numerous researchers have employed it as a feedstock, biofuel (ethanol), and paper [17]. Sugar cane bagasse (SCB) is considered to be an ideal material as a reinforcement fiber in the development of new materials with extraordinary physical and chemical properties [17]. Its fibrous structure imparts excellent mechanical properties, including high tensile strength and modulus. It can effectively boost the hardness and tensile strength of Aluminium metal matrix composites (Al6061/5wt% Al2O3 based composites) [19].

Figure 3: Sugarcane Bagasse

Other Agricultural Residues as Reinforcement

In addition to the well-known agricultural waste materials, other lesser-explored agricultural residues, such as corn husk, bamboo fibers, wheat straw, and soybean stalks, offer potential benefits as reinforcements in metal matrix nanocomposites. These materials provide unique properties that can enhance the mechanical and thermal performance of the composites while simultaneously promoting sustainable waste management practices [3]. The choice of agricultural waste reinforcement significantly influences the mechanical, thermal, and structural properties of metal matrix nanocomposites. By incorporating different agricultural waste materials, researchers can tailor the composites to suit specific applications. However, the selection of the most suitable reinforcement material requires a comprehensive understanding of its properties and compatibility with the metal matrix.

Processing Techniques for Agricultural Waste-Reinforced Metal Matrix Nanocomposites

Stir Casting Technique

This is a widely used and relatively simple method for fabricating metal matrix composites. In this process, the Agricultural waste particles are mixed with the molten metal matrix material, followed by solidification to form the composite. It's an easy and cost-effective process and it has good control over the distribution of agricultural waste particles in the matrix and is suitable for producing large-sized composites. Another modification is the Double Stir Casting Technique which is an extension of the stir casting technique, where two stirring mechanisms are used to enhance the dispersion of agricultural waste particles in the matrix. It Improves wettability and bonding between the matrix and agricultural waste particles and enhances the mechanical properties of the composites [3].

Powder Metallurgy Technique

In this technique, agricultural waste particles and metal matrix powders are mixed, followed by compaction and sintering to form the composite. Its benefits include Homogeneous dispersion of agricultural waste particles, and it also can produce composites with controlled porosity and density and is suitable for producing composites with complex shapes [19].

In-situ Synthesis

In-situ synthesis is a technique where the reinforcement is formed in situ within the metal matrix during the composite fabrication process. This method involves adding suitable precursors or reactants to the molten metal, which undergoes chemical reactions to produce the reinforcement phase. In the case of agricultural waste-reinforced metal matrix nanocomposites, the precursors may include chemical compounds derived from agricultural waste materials [3,20].

Other Techniques

Apart from stir casting, powder metallurgy, and in-situ synthesis, other processing techniques have also been explored for agricultural waste-reinforced metal matrix nanocomposites. These techniques include squeeze casting, hot pressing, and extrusion. Each technique offers unique advantages and challenges, and their selection depends on factors such as the desired composite properties, cost, and complexity of the fabrication process. Various processing techniques, such as stir casting, powder metallurgy, in-situ synthesis, and others, offer versatile methods for fabricating agricultural waste-reinforced metal matrix nanocomposites [19] Each technique has its advantages and challenges, and their selection depends on the desired composite properties, the availability of equipment, and the cost-effectiveness of the process. The combination of suitable processing techniques with compatible reinforcement materials can lead to the development of sustainable and high-performance metal matrix nanocomposites for diverse industrial applications"

Microstructure of agro-waste reinforced composites

Oghenevweta *et al.* conducted a microstructural analysis of Al-Si-Mg- based composites reinforced with carbonized maize stalk waste using a stir casting technique. They reported that the reinforcements were uniformly distributed along the grain boundaries, leading to grain refinement and improved bonding. Consequently, the tensile strength and hardness values increased with higher percentages of carbonized maize stalk. However, there was a slight decrease in impact energy, elongation, and densities [21].

In another investigation Atuanya *et al.* explored the impact of breadfruit seed hull ash as reinforcement in Al-Si-Fe-based composites fabricated through stir casting. They observed a reduction in the grain size of the matrix and strong interfacial bonding between the matrix and reinforced particles. This resulted in enhanced hardness and strength, but there was a slight decrease in impact energy [22].

Saravanan and Kumar observed that incorporating RHA in the AlSi10Mg matrix led to improved hardness, compressive strength, and tensile strength due to the good dispersibility of RHA in the matrix. It also illustrated the homogeneous dispersion of reinforced particles throughout the Al matrix and grain refinement [23]. Gladstone *et al.* noticed a unique distribution of RHA particles in the AA6061 alloy matrix fabricated through compo-casting, which significantly increased the ultimate tensile strength and microhardness of the AMC. This improvement was attributed to the uniform distribution of RHA particles in the matrix material [24]. Jose *et al.* found a uniform dispersion of lemon grass ash particles in the composite matrix produced via compo-casting, resulting in improved microhardness and tensile properties of the composites [25]. Additionally, Kumar and Birru observed that Aluminum composites reinforced with Bagasse Ash (BGA) exhibited superior properties due to their effective bonding with the matrix alloy and the homogeneous distribution of BGA particles in the composites. However, there was a reduction in density and increased porosity values with an increase in the mass fraction of BGA particles [26]. Furthermore, Venkatesh *et al.* investigated the microstructural features of Aluminium composites reinforced with Groundnut Shell Ash (GSA) and boron carbide, which were developed using the squeeze casting technique. Their findings indicated a uniform distribution and improved bonding of reinforcements with the matrix materials, resulting in distinct interfaces in the reinforced composite. However, it was observed that as the number of GSA particles increased, there was a tendency for agglomeration and cluster formation to occur [27].

The key aspects to consider during the fabrication of metal-matrix composites are achieving a uniform distribution of reinforcement and preventing agglomeration. Hanumanth and Irons proposed that the reinforcement type, solidification rate, wettability, and particle introduction process in the melt influence the distribution of reinforcement in the matrix alloy and microstructural characterization through SEM images allows easy evaluation of particle distribution, whether homogenized or uniformly dispersed in the melt [28]. Lokesh *et al.* investigated the microstructure of Al-4.5wt.%Cu composites reinforced with various percentages of fly ash content produced through the squeeze casting method. The results displayed a uniform distribution of fly ash content in the matrix melt. Application of pressure during fabrication eliminated voids and resulted in a homogeneously refined grain-size microstructure [29]. In the case of Aluminium alloy reinforced with rice husk ash, Aigbodion conducted microstructural characterization and obtained a reasonably uniform distribution of reinforcement, with slight segregation at some locations. It was observed that the good interfacial bonding between the matrix alloy and rice husk ash contributed to the nearly uniform distribution of the reinforcement content [30].

Studies have indicated that achieving a fine grain size with a uniform distribution of reinforcement in the matrix alloy enhances the mechanical and wear behaviors of metal-matrix composites developed with industrial-agricultural waste as reinforcement. The literature further suggests that the successful incorporation of industrial-agricultural waste as reinforcement material is possible, but careful optimization of the fabrication process is essential to ensure a uniform distribution of the reinforcement in the developed composites.

Mechanical Properties of Agricultural-waste Reinforced Composites

Numerous researchers have investigated the impact of agricultural waste reinforcements on the mechanical properties of aluminum-based composites. Ahamed et al. found that aluminum composites reinforced with rice husk ash fabricated via stir casting exhibited decreased density but improved yield strength, ultimate tensile strength, and hardness. This trend of reduced density alongside enhanced or maintained mechanical properties is common with agricultural waste reinforcements [31]. For instance, Varalakshmi et al. used stir casting to create aluminum 6061 composites reinforced with coconut shell ash, achieving increased ultimate tensile strength and hardness despite a decrease in density. Even replacing small percentages of ceramic reinforcements with agricultural waste particles in aluminum composites can lead to significant property improvements [32]. Prasad et al. employed a two-step stir casting technique to fabricate aluminum composites reinforced with rice husk ash and silicon carbide particulates. They observed increased hardness, ultimate tensile strength, and yield strength with higher reinforcement weight fractions, accompanied by decreased densities. While the double stir casting technique improved wettability, challenges in this area persist, and the vortex method has been suggested as a potential solution for developing aluminum matrix composites [33]. Hima Gireesh et al. compared the mechanical properties of aluminum matrix composites reinforced with aloe vera and fly ash, concluding that aloe vera had a more significant positive impact [34] Devanathan et al. fabricated aluminum matrix composites reinforced with coconut ash and fly ash using stir casting, observing improved hardness, tensile strength, and elongation with increasing coconut ash weight percentage [35].Gupta and Kumar examined the mechanical properties of Al/Si12 composites reinforced with rice husk ash and Al2O3, noting enhancements in microhardness, tensile strength, and flexural strength [36].

Tribological Properties of Agricultural -waste Reinforced Composites

Shaikh et al. fabricated Al-based composites reinforced with SiC and Rice Husk Ash (RHA) using powder metallurgy. They found that increasing RHA content up to 10% decreased both hardness and wear loss [37]. Conversely, Kanayo Alaneme and Apata Olubambi demonstrated that both corrosion and wear rates increased with higher percentages of RHA and alumina reinforcement in Al-Mg-Si composites, with wear behavior shifting from abrasive to a combination of adhesive and abrasive wear as RHA content increased [38]. Oladijo et al. developed aluminum composites reinforced with silica sand and Banana Leaf Ash (BLA) using stir casting. Increasing BLA content resulted in lower density composites with reduced hardness, but the composite reinforced with both silica sand and BLA exhibited higher wear resistance than the Al6063-silica sand composite [39]. Similarly, Alaneme et al. used double stir casting to fabricate Al-Mg-Si alloy matrix composites with RHA and SiC reinforcements, observing improvements in corrosion resistance, coefficient of friction, and wear behavior [38]. Siva Prasad and Shoba investigated the dry sliding wear behavior of aluminum matrix composites reinforced with RHA and SiC particulates using the vortex method, finding that the reinforced composites exhibited higher wear resistance than unreinforced composites [40]. Deshmukh and Pathak studied the influence of varying rice husk-based SiO2 weight percentages on the mechanical and wear properties of AMCs developed via stir casting. They concluded that adding Mg during stir casting improved matrix-reinforcement wettability, and higher Vickers hardness correlated with better wear resistance [41]. Bannaravuri and Birru investigated the tribological properties of BLA-reinforced Al composites, observing decreased wear rates with increasing BLA content [42]. Alaneme et al. reinforced the Al6063 alloy matrix with BLA and reported improvements in hardness and wear resistance [43].

Challenges in Agricultural Waste-Reinforced Metal Matrix Nanocomposites

After an extensive review of the literature, a pattern emerged in the challenges encountered in working with agricultural waste-reinforced metal matrix nanocomposites and these include;

Compatibility between Agricultural Waste and Metal Matrix

One of the key challenges in utilizing agricultural waste as reinforcement in metal matrix nanocomposites is achieving compatibility between the agricultural waste material and the metal matrix. Agricultural waste materials, such as rice husk, sugarcane bagasse, and wheat straw, have complex and heterogeneous structures with varying chemical compositions. This can lead to poor adhesion and weak interfacial bonding between the reinforcement and the metal matrix [3]. Incompatibility can result in reduced mechanical properties and compromised performance of the composite and that's the reason why most researchers are particular about the compatibility before attempting reinforcements the case of rice husk-reinforced aluminum matrix composites, the high silica content in rice husk can hinder the formation of a strong interface with the aluminum matrix, leading to reduced mechanical properties and limited improvement in the composite's performance [44].Oghenevweta *et al.* used stir-casting to create Al-Si-Mg composites reinforced with carbonized maize stalk waste. They found that good metal-reinforcement compatibility and homogeneous reinforcement distribution along grain boundaries led to grain refining and improved bonding. Higher percentages of carbonized maize stalk improved tensile strength and hardness but slightly reduced density, elongation, and impact energy [21].

Interfacial Bonding and Adhesion

Weak interfacial bonding between the agricultural waste reinforcement and the metal matrix is a critical challenge in achieving high-performance composites. Poor adhesion at the interface can result in ineffective stress transfer between the reinforcement and the matrix, leading to premature failure and reduced mechanical properties [45]. Shankar *et al.* used sugarcane bagasse ash to reinforce AlSi10Mg alloy, aiming to improve material properties for various industrial applications. They focused on enhancing cohesion because inadequate interfacial bonding between bagasse fibers and the magnesium matrix can weaken load transfer and limit the composite's potential in load-bearing applications [46].

Dispersion and Agglomeration

Agricultural waste materials often have irregular shapes and high aspect ratios, which can lead to challenges in achieving uniform dispersion within the metal matrix [3]. Agglomeration of reinforcement particles during processing can create local stress concentrations and non-homogeneous distribution, affecting the overall mechanical properties of the composite. For example, Coconut coir reinforced aluminum matrix composites can experience agglomeration of coconut coir fibers, leading to non-uniform distribution and reduced mechanical properties [47].

Thermal Stability and Degradation

Agricultural waste materials contain organic components like cellulose and lignin, susceptible to thermal degradation at high processing temperatures. This can compromise the reinforcement's thermal stability, altering its mechanical properties and potentially degrading the composite. Ogah and Afiukwa [48] analyzed the thermal stability of corncob, rice hull, walnut shell, and flax shive in a nitrogen atmosphere using thermogravimetric analysis at different heating rates (5, 10, 20, and 40 °C/min) with Flynn-Wall-Ozawa and Coats Redfern (modified) methods to determine thermal degradation kinetics.

Mechanical Property Degradation

In some cases, incorporating agricultural waste reinforcement in metal matrix nanocomposites can decrease mechanical properties due to poor interfacial bonding, agglomeration, or reinforcement degradation. Kareem *et al.* [49] demonstrated that AA 6061 composite properties depend significantly on reinforcement weight fraction. Increasing it can improve mechanical and tribological properties, but excessive reinforcement leads to pore formation and agglomeration, negatively impacting properties.

Environmental Considerations

While the use of agricultural waste as reinforcement offers environmental benefits by reducing waste and promoting sustainability, it is essential to consider potential environmental concerns associated with the processing and disposal of the composites. The choice of the matrix material, processing techniques, and end-of-life disposal should be carefully evaluated to ensure a minimal environmental footprint [50,51].

Solutions to Enhance the Performance of Agricultural Waste-Reinforced Metal Matrix Nanocomposites

Surface Modification

Surface modification of agricultural waste is a promising strategy to improve the compatibility and interfacial bonding between the reinforcement and the metal matrix. Various surface treatment techniques, such as chemical treatments, plasma treatment, and silane coupling agents, can be employed to modify the surface properties of agricultural waste particles. These treatments enhance the adhesion between the reinforcement and the matrix, leading to improved mechanical properties and overall performance of the composite. For example, treating rice husk with a silane coupling agent can improve its surface adhesion and compatibility with an aluminum matrix, resulting in better stress transfer and improved mechanical properties. Jagadeesh *et al.* studied the extraction, chemical treatment, and characterization of natural fibers and their composites for potential applications [52]. Separately, Khalil *et al.* studied the use of silica-rich rice hull ash as a filler in polypropylene (PP). The dynamic rheological behaviors and the crystallinity of its composites with semi-amorphous polypropylene were used as performance indicators. The effect of coupling agents on RHA/PP compatibility was also investigated. The addition of RHA increased storage modulus (G′), the onset (T_{co}) and peak (T_c) crystallinity temperatures, and decreased the degree of crystallinity of the system. Two coupling agents, maleated polypropylene (MAPP) and an amino-functional silane, were used to improve the interfacial adhesion of RHA and PP [53].

Polypropylene (PP), recycled acrylonitrile butadiene rubber (NBRr), and rice husk powder (RHP) composites were created using silane and acetic anhydride (AC) treatment agents. The in-situ formation of RHP-filled PP/NBRr composites was achieved through a melt mixing technique. Mechanical properties of both treatment methods were assessed using Instron mechanical analysis and Fourier transform infrared. The results revealed that AC treatment exhibited superior mechanical properties in comparison to silane treatment for RHP-filled PP/NBRr composites. This superiority was attributed to the excellent compatibility and stronger interaction between the anhydride moieties and PP/NBRr. [54]. Surface modifications like silane treatment, alkali treatment, and acetic anhydride treatment can improve the compatibility and performance of agricultural waste used as reinforcement in metal matrices. These methods enhance interfacial bonding and mechanical properties by modifying the surface chemistry and structure of the agricultural waste. The optimal technique depends on the specific materials used [55,56].

Hybrid Reinforcements

Combining agricultural waste with other types of reinforcements, such as synthetic fibers or nanoparticles, can create a hybrid composite that benefits from the unique properties of each reinforcement. This can lead to improved interfacial bonding and overall mechanical performance. Hybrid reinforcements can combine the advantages of different agricultural waste materials, such as high tensile strength from one reinforcement and enhanced thermal stability from another, leading to superior overall properties in the composite. A hybrid reinforcement comprising rice husk and sugarcane bagasse in an aluminum matrix composite can synergistically improve tensile strength and thermal stability, as the rice husk provides strength, while the sugarcane bagasse enhances thermal resistance [57]. Hybrid reinforcements can provide a balanced combination of mechanical and thermal properties, reducing incompatibility issues. The studies conducted by Bodunrin et al. [62] and Devanathan et al. [35] focused on Aluminum Matrix Composites (AMCs) reinforced with various materials to improve their performance and wear resistance. Bodunrin et al. [62] emphasized the benefits of hybrid AMCs using Agricultural and industrial waste derivatives as reinforcements, leading to enhanced performance and cost reduction. They highlighted the need for corrosion testing and further research to optimize production processes and explore the potential of friction-stir processed surface AMCs and bulk AMCs.

On the other hand, Devanathan et al. [35] aimed to enhance the wear resistance of automobile components by using stir-cast aluminum matrix hybrid composites (MMHC) reinforced with coconut shell ash and fly ash. They found that increasing the percentage of coconut ash improved hardness and elongation but slightly reduced tensile strength. Their study confirmed the uniform distribution of reinforcement particles within the matrix, indicating promising possibilities for improving the durability of automobile components.

Both studies stressed the importance of exploring novel reinforcement materials and processing techniques to advance the performance and sustainability of metal matrix composites for various industrial applications. By utilizing environmentally friendly reinforcements and optimizing production methods, AMCs show great potential in meeting the demands of modern engineering challenges [73].

Interfacial Engineering

Interfacial engineering, which involves modifying the interface between agricultural waste reinforcement and the metal matrix, can enhance stress transfer and adhesion. This can be achieved by introducing nanoscale interlayers or interfacial modifiers like carbon nanotubes, graphene, or titanium carbide, which improve interfacial bonding and mechanical properties, mitigating incompatibility issues. Li et al. offer a comprehensive overview of advancements in plant-based natural fiber-reinforced composites, including strategies to enhance performance through fiber modification, hybridization, and incorporation of lignocellulosic fillers [45]. Vandeginste et al. surveyed the diverse applications of eggshell waste in various composite materials, including polymers, metals, and ceramics, as well as its use in adsorbents, catalysts, additives, and functional materials. Their study explored eggshell treatment methods and the mechanical properties of composites incorporating eggshell-derived particles [58].

Optimizing Processing Techniques

Careful control of the processing techniques can influence interfacial bonding. Proper selection of processing parameters, such as temperature, pressure, and mixing time, can promote better dispersion and adhesion of the agricultural waste in the metal matrix [59]. Certain techniques, such as in-situ synthesis or powder metallurgy, may offer improved dispersion and bonding compared to others. Also utilizing advanced processing techniques can optimize the dispersion and alignment of agricultural waste reinforcements in the metal matrix, leading to improved mechanical properties [60]. Techniques such as high-energy ball milling, spark plasma sintering (SPS), and microwave-assisted processing can aid in achieving uniform dispersion and alignment of the reinforcement, contributing to enhanced mechanical performance [61].

Particle Size Optimization

Controlling the particle size of the agricultural waste reinforcement was found to be critical in achieving better compatibility with the metal matrix. Optimal particle size led to improved dispersion and bonding at the interface Gürcan et al. [63] and Das et al. [64] provided a comprehensive review of aluminum matrix composites fabricated by incorporating abrasive particles through FSP. The study evaluated the enhanced mechanical, thermal, and tribological properties of the composites, offering new prospects for surface modification using FSP. In a critical review by Fu et al. [65], the mechanical properties of polymer-based particulate micro- and nano-composites were explored. The study examined the effects of particle size, particle/matrix adhesion, and particle loading on the stiffness, strength, and toughness of the composites. The review revealed that particle/matrix adhesion significantly influenced strength and toughness, while composite stiffness was predominantly affected by particle loading, especially with a critical particle size in the nanoscale, resulting in enhanced stiffness due to the 'nano-effect' associated with larger surface areas of nanoparticles. Sun et al. [66] investigated the effects of particle size and extrusion on SiC particle-reinforced pure aluminum composites. Their study found that a closely matched size between matrix powder and SiC particles led to a uniform distribution of SiC particles, while smaller SiC particles tended to cluster. Voids coexisted with larger SiC particles, leading to reduced density and mechanical properties. However, extrusion helped redistribute SiC particles, reducing pores and enhancing interfacial bonding. Smaller SiC particle size improved tensile and yield strength but decreased ductility in the composites.

Matrix Alloy Selection

Choosing a metal matrix alloy that has a better affinity with the specific agricultural waste material can enhance compatibility. Different metal alloys have varying chemical compositions and properties, and selecting the most appropriate one can improve interfacial bonding with agricultural waste reinforcement. Mohammed et al. [67] reviewed the existing research on surface treatments of NFRC, such as alkali, silane, acetylation, and benzoylation, which were employed to reduce moisture absorption and fiber deterioration and improve their application potential. The effects of these treatments on hydrophilicity, surface chemistry, interface bonding, mechanical characteristics, and thermal performance of NFRC were discussed. Additionally, a comprehensive evaluation of surface treatment using nanoparticles (NPs) was conducted to enhance hydrophobicity and interfacial bonding between NFRC and the polymer matrix, potentially improving strength and dimensional stability. This review article provided valuable insights for researchers interested in coating and treating NFRC to enhance their surface characteristics. Furthermore, Ardanuy et al. [68] suggested that using a magnesium matrix instead of an aluminum matrix for coconut coir reinforcement may enhance compatibility due to magnesium's stronger affinity with natural fibers.

Pre-treatment of Agricultural Waste

Pre-treating agricultural waste, such as washing or removing impurities, can improve the bonding potential at the interface by providing cleaner surfaces for adhesion Huang et al. [69] By employing these strategies, it is possible to enhance the interfacial bonding in metal matrix composites reinforced with agricultural waste, resulting in improved mechanical properties and a more reliable composite material Fatima Haq et al. [70].

Dispersion and agglomeration solution

To address dispersion and agglomeration challenges in metal matrix composites (MMCs) reinforced with agricultural waste, various techniques can be employed. Ensuring proper dispersion of the agricultural waste within the metal matrix is essential for achieving uniform properties and enhanced performance. Strategies include pre-treating the waste with methods like washing, drying, and grinding to improve particle size uniformity. The use of dispersants during mixing reduces agglomeration and enhances waste dispersion. High shear mixing breaks up agglomerates and ensures uniform distribution. Ultrasonication disperses waste particles using high-frequency sound waves [71]. Also, controlled processing parameters such as mixing time, temperature, and pressure influence waste dispersion, leading to reduced agglomeration, and combining agricultural waste with other reinforcements like synthetic fibers or nanoparticles aids in better dispersion and reduces agglomeration, achieving more uniform particle distribution. Applying functional coatings to waste particles improves compatibility with the metal matrix, enhancing dispersion and acting as a barrier against agglomeration. In-situ synthesis of the reinforcing phase during fabrication also results in improved waste dispersion within the metal matrix [72].

Improving Thermal stability of Agricultural waste reinforced Metal Matrix Nanocomposites

To enhance the thermal stability and resistance to degradation in agricultural waste-reinforced metal matrix composites (MMCs), several strategies can be employed. These include selecting agricultural waste reinforcements with higher thermal stability, applying surface treatments or coatings to protect the waste particles, choosing a metal matrix alloy that complements the thermal stability of the reinforcement, and incorporating thermal stabilizers or flame retardants into the composite formulation. Controlling processing parameters, improving interfacial bonding, using hybrid reinforcements, and adding functional fillers with high thermal stability is also beneficial. Conducting thorough thermal analysis helps evaluate the composite's thermal stability during development. By implementing these measures, the thermal properties of the composite can be significantly improved, making it more suitable for high-temperature applications [49].

Solution to Mechanical Property Degradation

To enhance the mechanical properties and prevent degradation in metal matrix composites (MMCs) reinforced with agricultural waste, several strategies can be employed. These include choosing agricultural waste reinforcements with suitable mechanical properties, applying surface treatments to improve adhesion and compatibility, considering hybrid reinforcements for synergistic effects, optimizing reinforcement content, using advanced processing techniques for better dispersion, enhancing interfacial bonding, selecting a compatible matrix alloy, conducting rigorous testing for quality control, and performing microstructural analysis for understanding reinforcement distribution. By implementing these measures, the overall mechanical performance of the composite can be improved, ensuring better reliability and performance [3].

Environmental solutions and sustainability

The use of agricultural waste as reinforcement in composites offers environmental benefits, such as waste reduction and promoting sustainability. However, addressing potential environmental concerns is crucial. Strategies include selecting eco-friendly matrix materials, employing low- energy processing techniques, minimizing waste generation, and considering recycling options for end-of-life disposal. Conducting life cycle assessments and adopting a circular economy approach can improve the environmental sustainability of the composites. Complying with environmental regulations and standards ensures responsible waste management and prevents pollution. Overall, proactive measures can reduce the environmental impact and enhance the sustainability of agricultural waste-reinforced composites [1,74].

IMPLICATIONS

The Prospects and emerging trends in Agricultural waste reinforced metal matrix nanocomposites include;

1. **Development of Novel Agricultural Waste Reinforcements**: One of the prospects in the field of agricultural waste-reinforced metal matrix nanocomposites is the development of novel agricultural waste reinforcements. Researchers are continually exploring new agricultural waste materials and finding innovative ways to convert them into reinforcement forms, such as nanoparticles, nanofibers, or nanosheets. These novel reinforcements can offer unique properties and enhanced compatibility with the metal matrix, leading to improved mechanical, thermal, and structural performance in the resulting nanocomposites. For example, researchers have recently investigated the use of nanocellulose derived from various agricultural waste materials, such as wheat straw and corn husk, as reinforcement in metal matrix nanocomposites. Nanocellulose offers exceptional mechanical properties, high aspect ratios, and good biodegradability, making it a promising and sustainable reinforcement option.

2. **Integration of Nanotechnology**: The integration of nanotechnology holds significant promise in advancing the performance of agricultural waste-reinforced metal matrix nanocomposites. Nanoparticles, such as carbon nanotubes, graphene, and metal oxides, can be incorporated into the metal matrix nanocomposites to enhance properties such as strength, toughness, and thermal conductivity. The nanoscale reinforcements also offer the potential for multifunctionality in the composites. For example, the integration of graphene nanoplatelets into rice husk ash-reinforced aluminum matrix composites can lead to improved electrical conductivity and enhanced mechanical properties, making them suitable for electronic and aerospace applications.

3. **Multi-functional Nanocomposites**: Future trends in agricultural waste-reinforced metal matrix nanocomposites involve the development of multi-functional composites that offer a combination of properties, catering to diverse application requirements. These composites can simultaneously exhibit attributes such as high mechanical strength, thermal stability, electrical conductivity, and flame retardancy. For example, Coconut coir reinforced polymer matrix nanocomposites with added functionalized nanoparticles can exhibit not only enhanced mechanical properties but also good flame retardancy and thermal stability, making them suitable for automotive and building applications.

4. **Sustainable and Circular Economy Approaches**: In the future, an increasing focus will be on adopting sustainable and circular economy approaches in developing agricultural waste-reinforced metal matrix nanocomposites. The emphasis will be on using agricultural waste materials as reinforcements to reduce waste, enhance resource efficiency, and minimize the environmental impact of composite production and disposal. Example: The implementation of a closed-loop system, where agricultural waste from agricultural processes is utilized as reinforcement in metal matrix nanocomposites and the composite materials, after their service life, are recycled or biodegraded, represents a sustainable and circular economy approach.

5. **Industry-specific Applications**: As the field of agricultural waste-reinforced metal matrix nanocomposites matures, there will be a shift towards exploring industry-specific applications. Tailoring the composites to meet the specific requirements of industries such as automotive, aerospace, construction, and packaging will drive the adoption of these sustainable materials in diverse sectors. The development of rice husk-reinforced magnesium matrix composites with enhanced mechanical properties and lightweight characteristics makes them suitable for lightweight automotive components, contributing to fuel efficiency and reducing carbon emissions.

CONCLUSION

The future of agricultural waste-reinforced metal matrix nanocomposites looks promising, with emerging trends focused on enhancing their performance, sustainability, and applicability in various industries. The critical review paper comprehensively analyzed the challenges and prospects of these materials. Although utilizing agricultural waste as reinforcements has gained attention due to its abundance and eco-friendly potential, several challenges must be addressed for optimal engineering applications. These challenges include compatibility with metal matrices, interfacial bonding, particle dispersion, thermal stability, mechanical property degradation, and environmental considerations. Various strategies like surface modification, hybrid reinforcements, interfacial engineering, and advanced processing techniques were explored to overcome these challenges and improve composite properties. Looking ahead, the development of novel agricultural waste reinforcements, integration of nanotechnology, creation of multi-functional nanocomposites, adoption of sustainable practices, and exploration of industry-specific applications will drive the growth of these materials, providing eco-friendly alternatives and contribute to a greener and more sustainable future. Overall, the review paper emphasizes the significance of agricultural waste-reinforced metal matrix nanocomposites as a viable solution for sustainable materials development, bridging the gap between environmental sustainability and engineering requirements. Their successful integration holds immense potential to address global challenges related to resource scarcity and environmental pollution, making a valuable resource for researchers, engineers, and industries exploring and utilizing these materials in diverse engineering applications.

REFERENCES

[1] S. P. Dwivedi, S. Sharma, and K. R. Mishra, “A356 Aluminum Alloy and applications- A Review,” *International Journal of Advanced Materials Manufacturing and Characterization*, vol. 4, no. 2, pp. 81–86, Jun. 2014, doi:10.11127/ijammc.2014.08.01.

[2] L. Singh, B. Singh, and K. K. Saxena, “Manufacturing techniques for metal matrix composites (MMC): an overview,” *Advances in Materials and Processing Technologies*, vol. 6, no. 2, pp. 441–457, Feb. 2020, doi:10.1080/2374068x.2020.1729603.

[3] B. Parveez, M. A. Maleque, and N. A. Jamal, “Influence of agro-based reinforcements on the properties of aluminum matrix composites: a systematic review,” *Journal of Materials Science*, vol. 56, no. 29, pp. 16195–16222, Jul. 2021, doi: 10.1007/s10853-021-06305-2.

[4] G. Arora and S. Sharma, “A review on monolithic and hybrid metal–matrix composites reinforced with industrial-agro wastes,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 39, no. 11, pp. 4819–4835, Sep. 2017, doi: 10.1007/s40430-017-0910-x.

[5] S. Tiwari and M. K. Pradhan, “Effect of rice husk ash on properties of aluminium alloys: A review,” *Materials Today Proceedings*, vol. 4, no. 2, pp. 486–495, Jan. 2017, doi: 10.1016/j.matpr.2017.01.049.

[6] P. P. Kulkarni, B. Siddeswarappa, and K. S. H. Kumar, “A Survey on Effect of Agro Waste Ash as Reinforcement on Aluminium Base Metal Matrix Composites,” *Open Journal of Composite Materials*, vol. 09, no. 03, pp. 312–326, Jan. 2019, doi: 10.4236/ojcm.2019.93019.

[7] V. S. Aigbodion, “Al-Si/SiC Nanoparticles Composites Synthesized by Double Stir Casting,” *Recent Patents on Nanotechnology*, vol. 5, no. 3, pp. 234–238, Nov. 2011, doi: 10.2174/187221051105030234.

[8] N. S. Kumar, “Fabrication and characterization of Al7075 / RHA /Mica composite by squeeze casting,” *Materials Today Proceedings*, vol. 37, pp. 750–753, Jul. 2020, doi: 10.1016/j.matpr.2020.05.769.

[9] N. Verma and S. C. Vettivel, “Characterization and experimental analysis of boron carbide and rice husk ash reinforced AA7075 aluminium alloy hybrid composite,” *Journal of Alloys and Compounds*, vol. 741, pp. 981–998, Feb. 2018, doi: 10.1016/j.jallcom.2018.01.185.

[10] N. F. M. Joharudin, N. A. Latif, M. S. Mustapa, N. A. Badarulzaman, and M. F. Mahmod, “Effect of Burning Temperature on Rice Husk Silica as Reinforcement of Recycled Aluminium Chip AA7075,” *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 68, no. 1, pp. 125–132, Mar. 2020, doi: 10.37934/arfmts.68.1.125132.

[11] R. Yevich and J. A. Logan, “An assessment of biofuel use and burning of agricultural waste in the developing world,” *Global Biogeochemical Cycles*, vol. 17, no. 4, Oct. 2003, doi: 10.1029/2002gb001952.

[12] J. K. Sarkar and Q. Wang, “Different Pyrolysis Process Conditions of South Asian Waste Coconut Shell and Characterization of Gas, Bio-Char, and Bio-Oil,” *Energies*, vol. 13, no. 8, p. 1970, Apr. 2020, doi: 10.3390/en13081970.

[13] L. Purushothaman and P. Balakrishnan, "Wear and corrosion behavior of coconut shell ash (CSA) reinforced Al6061 metal matrix composites," *Materials Testing*, vol. 62, no. 1, pp. 77–84, Dec. 2019, doi: 10.3139/120.111456.

[14] A. R. R. Kaladgi, K. F. Rehman, A. Afzal, M. A. Baig, M. Elahi. M. Soudagar, and S. Bhattacharyya, "Fabrication characteristics and mechanical behaviour of aluminium alloy reinforced with Al2O3 and coconut shell particles synthesized by stir casting," *IOP Conference Series Materials Science and Engineering*, vol. 1057, p. 012017, Feb. 2021, doi: 10.1088/1757-899x/1057/1/012017.

[15] S. A. Bello, I. A. Raheem, and N. K. Raji, "Study of tensile properties, fractography and morphology of aluminium (1xxx)/coconut shell micro particle composites," *Journal of King Saud University - Engineering Sciences*, vol. 29, no. 3, pp. 269–277, Oct. 2015, doi: 10.1016/j.jksues.2015.10.001.

[16] X. Zhuang, Q. Yu, Z. Yuan, X. Kong, and W. Qi, "Effect of hydrothermal pretreatment of sugarcane bagasse on enzymatic digestibility," *Journal of Chemical Technology & Biotechnology*, vol. 90, no. 8, pp. 1515–1520, Jun. 2014, doi: 10.1002/jctb.4467.

[17] J. M. Hernández-Salas *et al.*, "Comparative hydrolysis and fermentation of sugarcane and agave bagasse," *Bioresource Technology*, vol. 100, no. 3, pp. 1238–1245, Nov. 2008, doi: 10.1016/j.biortech.2006.09.062.

[18] A. K. Virkunwar, S. Ghosh, and R. Basak, "Study of Mechanical and Tribological Characteristics of Aluminium Alloy Reinforced with Sugarcane Bagasse Ash," *SSRN Electronic Journal*, Jan. 2018, doi: 10.2139/ssrn.3313510.

[19] N. K. Chandla, N. Yashpal, S. Kant, M. Goud, and C. Jawalkar, "Experimental analysis and mechanical characterization of Al 6061/alumina/bagasse ash hybrid reinforced metal matrix composite using vacuum-assisted stir casting method," *Journal of Composite Materials*, vol. 54, no. 27, pp. 4283–4297, Jun. 2020, doi: 10.1177/0021998320929417.

[20] P. Samal, P. R. Vundavilli, A. Meher, and M. M. Mahapatra, "Recent progress in aluminum metal matrix composites: A review on processing, mechanical and wear properties," *Journal of Manufacturing Processes*, vol. 59, pp. 131–152, Sep. 2020, doi: 10.1016/j.jmapro.2020.09.010.

[21] J. E. Oghenevweta, V. S. Aigbodion, G. B. Nyior, and F. Asuke, "Mechanical properties and microstructural analysis of Al–Si–Mg/carbonized maize stalk waste particulate composites," *Journal of King Saud University - Engineering Sciences*, vol. 28, no. 2, pp. 222–229, Apr. 2014, doi: 10.1016/j.jksues.2014.03.009.

[22] C. U. Atuanya, A. O. A. Ibhadode, and I. M. Dagwa, "Effects of breadfruit seed hull ash on the microstructures and properties of Al–Si–Fe alloy/breadfruit seed hull ash particulate composites," *Results in Physics*, vol. 2, pp. 142–149, Jan. 2012, doi: 10.1016/j.rinp.2012.09.003.

[23] S. D. Saravanan and M. S. Kumar, "Effect of Mechanical Properties on Rice Husk Ash Reinforced Aluminum Alloy (AlSi10Mg) Matrix Composites," *Procedia Engineering*, vol. 64, pp. 1505–1513, Jan. 2013, doi: 10.1016/j.proeng.2013.09.232.

[24] J. A. K. Gladston, N. M. Sherrif, I. Dinaharan, and J. D. Raja Selvam, "Production and characterization of rich husk ash particulate reinforced AA6061 aluminum alloy composites by compocasting," *Trans. Nonferrous Met. Soc. China*, vol. 25, no. 3, pp. 683–691, Mar. 2015. doi: 10.1016/s1003-632663653-6.

[25] J. Jose *et al.*, "Manufacture and characterization of a novel agro-waste based low cost metal matrix composite (MMC) by compocasting," *Materials Research Express*, vol. 5, no. 6, p. 066530, May 2018, doi: 10.1088/2053-1591/aac803.

[26] B. P. Kumar and A. K. Birru, "Microstructure and mechanical properties of aluminium metal matrix composites with addition of bamboo leaf ash by stir casting method," *Trans. Nonferrous Met. Soc. China*, vol. 27, no. 12, pp. 2555–2572, Dec. 2017. doi: 10.1016/s1003-632660284-x

[27] L. Venkatesh, T. V. Arjunan, and K. Ravikumar, "Microstructural characteristics and mechanical behaviour of aluminium hybrid composites reinforced with groundnut shell ash and B4C," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, no. 7, Jun. 2019, doi: 10.1007/s40430-019-1800-1.

[28] G. S. Hanumanth and G. A. Irons, "Particle incorporation by melt stirring for the production of metal-matrix composites," *Journal of Materials Science*, vol. 28, no. 9, pp. 2459–2465, Jan. 1993, doi: 10.1007/bf01151680.

[29] G. N. Lokesh, M. Ramachandra, K. V. Mahendra, and T. Sreenith, "Characterization of Al-Cu alloy reinforced fly ash metal matrix composites by squeeze casting method," *International Journal of Engineering Science and Technology*, vol. 5, no. 4, pp. 71–79, Mar. 2018, doi: 10.4314/ijest.v5i4.7.

[30] V. S. Aigbodion, "Al-Si/SiC Nanoparticles Composites Synthesized by Double Stir Casting," *Recent Patents on Nanotechnology*, vol. 5, no. 3, pp. 234–238, Nov. 2011, doi: 10.2174/1872210511105030234.

[31] A. A. Ahamed, R. Ahmed, M. B. Hossain, and M. Billah, "Fabrication and Characterization of Aluminium-Rice Husk Ash Composite Prepared by Stir Casting Method," *Rajshahi University Journal of Science and Engineering*, vol. 44, pp. 9–18, Nov. 2016, doi: 10.3329/rujse.v44i0.30361.

[32] K. Varalakshmi, K. Ch. K. Kumar, and A. J. Babu, "Analysis of Dry Sliding Wear Behaviour of Al 6061-Coconut Shell Ash Metal Matrix Composites Using Stir Casting," *Applied Engineering Letters Journal of Engineering and Applied Sciences*, vol. 4, no. 2, pp. 55–65, Jan. 2019, doi: 10.18485/aeletters.2019.4.2.3.

[33] D. S. Prasad, C. Shoba, and N. Ramanaiah, "Investigations on mechanical properties of aluminum hybrid composites," *Journal of Materials Research and Technology*, vol. 3, no. 1, pp. 79–85, Jan. 2014, doi: 10.1016/j.jmrt.2013.11.002.

[34] Ch. H. Gireesh, K. G. D. Prasad, K. Ramji, and P. V. Vinay, "Mechanical Characterization of Aluminium Metal Matrix Composite Reinforced with Aloe vera powder," *Materials Today Proceedings*, vol. 5, no. 2, pp. 3289–3297, Jan. 2018, doi: 10.1016/j.matpr.2017.11.571.

[35] R. Devanathan, J. Ravikumar, S. Boopathi, D. C. Selvam, and S. A. Anicia, "Influence in Mechanical Properties of Stir Cast Aluminium (AA6061) Hybrid Metal matrix Composite (HMMC) with Silicon Carbide, Fly Ash and Coconut coir Ash Reinforcement," *Materials Today Proceedings*, vol. 22, pp. 3136–3144, Jan. 2020, doi: 10.1016/j.matpr.2020.03.450.

[36] V. Gupta and R. Kumar, "Investigating the mechanical and tribological properties of aluminium metal matrix composite reinforced with rice husk ash and aluminium oxide," *International Journal of Precision Technology*, vol. 1, no. 1, p. 1, Jan. 2020, doi: 10.1504/ijptech.2020.10031819.

[37] M. B. N. Shaikh, S. Raja, M. Ahmed, M. Zubair, A. Khan, and M. Ali, "Rice husk ash reinforced aluminium matrix composites: fabrication, characterization, statistical analysis and artificial neural network modelling," *Materials Research Express*, vol. 6, no. 5, p. 056518, Jan. 2019, doi: 10.1088/2053-1591/aafbe2.

[38] K. K. Alaneme, T. M. Adewale, and P. A. Olubambi, "Corrosion and wear behaviour of Al–Mg–Si alloy matrix hybrid composites reinforced with rice husk ash and silicon carbide," *Journal of Materials Research and Technology*, vol. 3, no. 1, pp. 9–16, Nov. 2013, doi: 10.1016/j.jmrt.2013.10.008.

[39] O. P. Oladijo, M. O. Bodunrin, K. Sobiyi, N. B. Maledi, and Kk. Alaneme, "Investigating the self-healing behaviour of under-aged and 60Sn-40Pb alloy reinforced aluminium hybrid composites," *Thin Solid Films*, vol. 620, pp. 201–205, Sep. 2016, doi: 10.1016/j.tsf.2016.08.071.

[40] D. S. Prasad and C. Shoba, "Hybrid composites – a better choice for high wear resistant materials," *Journal of Materials Research and Technology*, vol. 3, no. 2, pp. 172–178, Apr. 2014, doi: 10.1016/j.jmrt.2014.03.004.

[41] P. Deshmukh and S. Pathak, "Influence of Varying SiO2 % on the Mechanical Properties of Al Based MMC," *Transactions of the Indian Institute of Metals*, vol. 65, no. 6, pp. 741–745, Oct. 2012, doi: 10.1007/s12666-012-0196-8.

[42] P. K. Bannaravuri and A. K. Birru, "Strengthening of mechanical and tribological properties of Al-4.5%Cu matrix alloy with the addition of bamboo leaf ash," *Results in Physics*, vol. 10, pp. 360–373, Jun. 2018, doi: 10.1016/j.rinp.2018.06.004.

[43] K. K. Alaneme, S. A. Babalola, L. H. Chown, and M. O. Bodunrin, "Hot deformation behaviour of bamboo leaf ash–silicon carbide hybrid reinforced aluminium based composite," *Manufacturing Review*, vol. 7, p. 17, Jan. 2020, doi: 10.1051/mfreview/2020014.

[44] B. Vinod, S. Ramanathan, and M. Anandajothi, "Effect of Organic and Inorganic Reinforcement on Tribological Behaviour of Aluminium A356 Matrix Hybrid Composite," *Journal of Bio- and Tribo-Corrosion*, vol. 4, no. 3, Jun. 2018, doi: 10.1007/s40735-018-0157-9.

[45] M. Li *et al.*, "Recent advancements of plant-based natural fiber–reinforced composites and their applications," *Composites Part B Engineering*, vol. 200, p. 108254, Aug. 2020, doi: 10.1016/j.compositesb.2020.108254.

[46] S. Shankar, A. Balaji, and N. Kawin, "Investigations on mechanical and tribological properties of Al-Si10-Mg alloy/sugarcane bagasse ash particulate composites," *Particul. Sci. Technol.*, vol. 36, no. 6, pp. 762-770, Apr. 2017.

[47] M. Arulraj and P. K. Palani, "Parametric optimization for improving impact strength of squeeze cast of hybrid metal matrix (LM24–SiCp–coconut shell ash) composite," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 40, no. 1, Dec. 2017, doi: 10.1007/s40430-017-0925-3.

[48] A. O. Ogah and J. N. Afiukwa, "Characterization and comparison of mechanical behavior of agro fiber-filled high-density polyethylene bio-composites," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 1, pp. 37–46, Nov. 2013, doi: 10.1177/0731684413509425.

[49] A. Kareem, J. A. Qudeiri, A. Abdudeen, T. Ahammed, and A. Ziout, "A Review on AA 6061 Metal Matrix Composites Produced by Stir Casting," *Materials*, vol. 14, no. 1, p. 175, Jan. 2021, doi: 10.3390/ma14010175.

[50] N. K. Bhoi, H. Singh, and S. Pratap, "Developments in the aluminum metal matrix composites reinforced by micro/nano particles – A review," *Journal of Composite Materials*, vol. 54, no. 6, pp. 813–833, Jul. 2019, doi: 10.1177/0021998319865307..

[51] S. Debnath, L. Lancaster, and M. H. Lung, "Utilization of agro-industrial waste in metal matrix composites: towards sustainability," *World Acad. Sci. Eng. Technol.*, pp. 1136-1144, 2013.

[52] P. Jagadeesh, M. Puttegowda, S. M. Rangappa, and S. Siengchin, "A review on extraction, chemical treatment, characterization of natural fibers and its composites for potential applications," *Polymer Composites*, vol. 42, no. 12, pp. 6239–6264, Sep. 2021, doi: 10.1002/pc.26312.

[53] R. Khalil, A. G. Chryss, M. Jollands, and S. Bhattacharya, "Effect of coupling agents on the crystallinity and viscoelastic properties of composites of rice hull ash-filled polypropylene," *Journal of Materials Science*, vol. 42, no. 24, pp. 10219–10227, Sep. 2007, doi: 10.1007/s10853-007-1732-5.

[54] S. Ragunathan, H. Ismail, and K. Hussin, "Comparison of processing and mechanical properties of polypropylene/recycled acrylonitrile butadiene rubber/rice husk powder composites modified with silane and acetic anhydride compound," Feb. 24, 2013.

[55] O. O. Joseph and K. O. Babaremu, "Agricultural Waste as a Reinforcement Particulate for Aluminum Metal Matrix Composite (AMMCs): A Review," *Fibers*, vol. 7, no. 4, p. 33, Apr. 2019, doi: 10.3390/fib7040033.

[56] O. S. Olusesi and N. E. Udoye, "Development and characterization of AA6061 aluminium alloy /clay and rice husk ash composite," *Manufacturing Letters*, vol. 29, pp. 34–41, Jun. 2021, doi: 10.1016/j.mfglet.2021.05.006.

[57] D. A. Ashebir, G. A. Mengesha, and D. K. Sinha, "The Role of Tetra Hybrid Reinforcements on the Behavior of Aluminum Metal Matrix Composites," J. Nanomater., vol. 2022, pp. 1–18.

[58] V. Vandeginste, "Food waste eggshell valorization through development of new composites: A review," *Sustainable Materials and Technologies*, vol. 29, p. e00317, Jul. 2021, doi: 10.1016/j.susmat.2021.e00317.

[59] M. Arulra, P. K. Palani, and L. Venkatesh, "Optimization of Process Parameters in Stir Casting of Hybrid Metal Matrix (LM25/SiC/B4C) Composite Using Taguchi Method," *JOURNAL OF ADVANCES IN CHEMISTRY*, vol. 13, no. 11, pp. 6038–6042, Mar. 2017, doi: 10.24297/jac.v13i11.5774.

[60] A. Ramanathan, P. K. Krishnan, and R. Muraliraja, "A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities," *Journal of Manufacturing Processes*, vol. 42, pp. 213–245, May 2019, doi: 10.1016/j.jmapro.2019.04.017.

[61] E. Omanović-Mikličanin, A. Badnjević, A. Kazlagić, and M. Hajlovac, "Nanocomposites: a brief review," *Health and Technology*, vol. 10, no. 1, pp. 51–59, Nov. 2019, doi: 10.1007/s12553-019-00380-x.

[62] M. O. Bodunrin, K. K. Alaneme, and L. H. Chown, "Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics," *Journal of Materials Research and Technology*, vol. 4, no. 4, pp. 434–445, Jun. 2015, doi: 10.1016/j.jmrt.2015.05.003.

[63] K. Gürcan, B. DeriN, and E. Ayas, "Effect of SiC Particle Size on the Microstructural, Mechanical and Oxidation Properties of In-situ Synthesized HfB2-SiC Composites," *Journal of Polytechnic*, vol. 24, no. 2, pp. 503–510, Apr. 2020, doi: 10.2339/politeknik.682256.

[64] S. S. Das *et al.*, "A Review on Aluminum Matrix Composites Synthesized by FSP," *Macromolecular Symposia*, vol. 407, no. 1, Feb. 2023, doi: 10.1002/masy.202200119.

[65] S.-Y. Fu, X.-Q. Feng, B. Lauke, and Y.-W. Mai, "Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate–polymer composites," *Composites Part B Engineering*, vol. 39, no. 6, pp. 933–961, Mar. 2008, doi: 10.1016/j.compositesb.2008.01.002.

[66] C. Sun, M. Song, Z. Wang, and Y. He, "Effect of Particle Size on the Microstructures and Mechanical Properties of SiC-Reinforced Pure Aluminum Composites," *Journal of Materials Engineering and Performance*, vol. 20, no. 9, pp. 1606–1612, Dec. 2010, doi: 10.1007/s11665-010-9801-3.

[67] Mohammed, M., Rahman, R., Mohammed, A. M., Adam, T., Betar, B. O., Osman, A. F., & Dahham, O. S. (2022, November). Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement. *Polymer Testing*, *115*, 107707. https://doi.org/10.1016/j.polymertesting.2022.107707

[68] M. Ardanuy, M. Antunes, and J. I. Velasco, "Vegetable fibres from agricultural residues as thermo-mechanical reinforcement in recycled polypropylene-based green foams," *Waste Management*, vol. 32, no. 2, pp. 256–263, Oct. 2011, doi: 10.1016/j.wasman.2011.09.022.

[69] Z. Huang, N. Wang, Y. Zhang, H. Hu, and Y. Luo, "Effect of mechanical activation pretreatment on the properties of sugarcane bagasse/poly(vinyl chloride) composites," *Composites Part a Applied Science and Manufacturing*, vol. 43, no. 1, pp. 114–120, Sep. 2011, doi: 10.1016/j.compositesa.2011.09.025.

[70] F. F. Haq, H. Mahmood, T. Iqbal, M. M. Ali, M. J. Khan, and M. Moniruzzaman, "Development of sustainable biocomposite panels assisted with deep eutectic solvent pretreatment of agro-industrial residue," *Journal of Molecular Liquids*, vol. 367, p. 120417, Sep. 2022, doi: 10.1016/j.molliq.2022.120417.

[71] M. B. N. Shaikh, S. Arif, T. Aziz, A. Waseem, M. A. N. Shaikh, and M. Ali, "Microstructural, mechanical and tribological behaviour of powder metallurgy processed SiC and RHA reinforced Al-based composites," *Surfaces and Interfaces*, vol. 15, pp. 166–179, Mar. 2019, doi: 10.1016/j.surfin.2019.03.002.

[72] N. K. Bhoi, H. Singh, and S. Pratap, "Developments in the aluminum metal matrix composites reinforced by micro/nano particles – A review," *Journal of Composite Materials*, vol. 54, no. 6, pp. 813–833, Jul. 2019, doi: 10.1177/0021998319865307.

[73] D. A. Ashebir, G. A. Mengesha, and D. K. Sinha, "The Role of Tetra Hybrid Reinforcements on the Behavior of Aluminum Metal Matrix Composites," *Journal of Nanomaterials*, vol. 2022, pp. 1–18, Sep. 2022.

[74] "Study of Aluminium Metal Matrix Composites – Review," *International Journal of Recent Trends in Engineering and Research*, vol. 3, no. 4, pp. 82–93, Apr. 2017, doi: 10.23883/ijrter.2017.3113.xqsxf.