DEVELOPMENT AND MECHANICAL CHARACTERIZATION OF ALUMINIUM MATRIX COMPOSITES REINFORCED WITH SILICON CARBIDE AND PALM KERNEL SHELL NANOPARTICLES

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ABSTRACT

Aluminium matrix composites (AMCs) are widely explored for structural applications; however, their performance is often limited by the cost and availability of conventional reinforcements, creating the need for alternative, sustainable materials. This study aims to develop and evaluate the mechanical behavior of AMCs reinforced with silicon carbide (SiC) and palm kernel shell (PKS) nanoparticles as a cost-effective agro-waste–derived reinforcement. SiC and PKS were processed into nanoparticles using high-energy ball milling and characterized via Scanning Electron Microscopy (SEM), Brunauer–Emmett–Teller (BET), Dynamic Light Scattering (DLS), and X-ray fluorescence (XRF) analyses. Nine composite samples were fabricated through stir casting with varied weight ratios of SiC and PKS, with 1 wt% magnesium added to enhance wettability. Mechanical properties including tensile strength, flexural strength, hardness, and impact resistance were measured in line with ASTM standards. The composite containing 1.5 wt% SiC, 0.6 wt% PKS, and 1 wt% Mg exhibited superior performance, achieving a tensile strength of 107.34 MPa, flexural strength of 171 MPa, impact strength of 4.60 J, and hardness of 24.3 HRA. The findings highlight that PKS nanoparticles can serve as a sustainable partial reinforcement in AMCs, reducing reliance on synthetic ceramics and promoting eco-friendly materials design for lightweight structural applications.

Keywords: aluminium matrix composites, silicon carbide, palm kernel shell, mechanical properties, nanoparticle reinforcement, stir casting.

1 INTRODUCTION

In recent years, there has been growing interest in the development of sustainable materials using nanoparticles for advanced engineering applications. Nanoparticles, typically sized between 1–100 nm, exhibit remarkable physical and chemical properties such as increased surface area, quantum confinement effects, and enhanced thermal, electrical, and mechanical performance when compared to their bulk counterparts [1]. These properties have spurred their incorporation into composite materials, particularly in the development of metal matrix composites (MMCs) for structural, aerospace, and automotive applications [2]. Aluminium matrix composites (AMCs) are of particular interest due to their favorable strength-to-weight ratio, corrosion resistance, and thermal properties [3]. However, improvements in their mechanical performance often rely on the nature and distribution of reinforcements within the aluminium matrix. Traditionally, ceramic reinforcements such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) have been extensively employed due to their inherent hardness and thermal stability [4, 5]. Silicon carbide (SiC), a non-oxide ceramic, is widely used in AMCs due to its superior mechanical strength, high hardness, excellent thermal conductivity, and wear resistance [6]. Reducing SiC to nanoscale further enhances these properties through increased interfacial bonding and load transfer efficiency within the matrix [7]. Nonetheless, the high cost of ceramic powders and environmental concerns have motivated researchers to explore alternative, sustainable reinforcement sources. Agricultural waste-derived materials, such as palm kernel shell (PKS), coconut shell ash, and rice husk ash, are gaining prominence as low-cost, eco-friendly reinforcements in AMCs [8, 9]. PKS is a lignocellulosic waste generated during palm oil processing, abundant in tropical regions like Nigeria. It contains significant amounts of silica, carbon, and other minerals, making it a viable candidate for reinforcement in composite materials [10]. Studies have shown that PKS nanoparticles improve hardness, wear resistance, and stiffness of composites, while also reducing overall weight and environmental impact [11, 12]. The combination of SiC and PKS nanoparticles in a hybrid reinforcement system presents an opportunity to balance performance with sustainability. The inclusion of agro-waste particles like PKS not only reduces material costs but also promotes environmental conservation through waste valorization [13]. Moreover, the use of magnesium as a wetting agent enhances the bonding between the aluminium matrix and the ceramic/agro-waste reinforcements, leading to improved mechanical behavior [14]. Despite numerous studies on single reinforcement systems, there remains a research gap in understanding the synergistic effects of hybrid nano-reinforcements involving SiC and PKS. Furthermore, optimizing their weight ratios for maximum property enhancement in AMCs remains a challenge. This study addresses these gaps by developing and characterizing aluminium-based composites reinforced with varied proportions of SiC and PKS nanoparticles via stir casting, a cost-effective liquid state processing method. The mechanical behavior of the composites is evaluated through tensile, flexural, impact, and hardness tests, providing insight into the reinforcement effects of both particles and their potential for lightweight structural applications.

2 MATERIALS AND METHODS

2.1 Materials

The materials used for the development of the aluminium matrix composite (AMC) in this study include aluminium alloy 6061 (Al6061) as the base matrix, silicon carbide (SiC) and palm kernel shell (PKS) as reinforcement particles, and magnesium (Mg) as a wetting agent to enhance particle distribution and matrix-reinforcement bonding.

2.1.1 Aluminium 6061 Alloy

Al6061 is a precipitation-hardened aluminium alloy containing magnesium and silicon as its major alloying elements. It is widely used due to its excellent corrosion resistance, good weldability, and balanced mechanical properties. The alloy was sourced in ingot form and served as the matrix material throughout the experimental phase. The chemical composition of the Al6061 used was confirmed via X-ray fluorescence (XRF) spectroscopy and is summarized in Section 3.

2.1.2 Silicon Carbide (SiC)

Silicon carbide (SiC) powder was procured from a commercial supplier with an initial particle size of approximately 1 µm. SiC was selected as a ceramic reinforcement due to its high hardness, thermal conductivity, wear resistance, and its ability to improve the strength and stiffness of aluminium composites [5]. To achieve nano-sized particles, the SiC was processed using a high-energy planetary ball mill.

2.1.3 Palm Kernel Shell (PKS)

Palm kernel shells were locally sourced as agro-waste from a palm oil mill in Kaduna, Nigeria. The shells were sun-dried, crushed, and sieved to remove contaminants. Subsequent milling was conducted using a ball mill to achieve nanoscale powder. PKS was used as a natural reinforcement owing to its high carbon and silica content, low density, and sustainable, biodegradable characteristics [10].

2.1.4 Magnesium

Commercially pure magnesium powder (99.5% purity) was used as a wetting agent at 1 wt% of the total composite mixture. Magnesium is known to improve the wettability of ceramic particles in aluminium during stir casting and to reduce porosity formation [14].

2.2 Equipment

The key equipment used during the material preparation and experimental process included: Ball mill (for nanoparticle processing), Electric furnace and open blacksmith furnace (for melting Al6061), Stirring mechanism with impeller (for composite mixing), Sand molds (for casting), Universal Testing Machine (UTM) (for tensile, impact, and flexural testing), Rockwell Hardness Tester, Scanning Electron Microscope (SEM), Brunauer–Emmett–Teller (BET) surface analyzer, Dynamic Light Scattering (DLS) analyzer, X-ray fluorescence (XRF) spectrometer.

2.3 Preparation Methods

2.3.1 Nanoparticle Development

i. Silicon Carbide Nanoparticles (SiC-NPs): Commercial SiC powder was subjected to high-energy ball milling using a planetary ball mill for 10 h. A ball-to-powder ratio of 10:1 was maintained, with zirconia balls as the milling media. Ethanol was used as a process control agent to minimize particle agglomeration, as recommended in similar nanoparticle synthesis studies [15–17]. After milling, the slurry was dried in a vacuum oven at 60 °C for 12 h. Particle size and morphology were confirmed using scanning electron microscopy (SEM) following the guidelines of ISO 13322-1:2014 [18].

ii. Palm Kernel Shell Nanoparticles (PKS-NPs): Dried PKS was crushed, sieved to <500 µm, and subsequently ball-milled for 15 h to achieve nano-scale particle sizes, following methodologies similar to those in [19, 20]. The milled powder was calcined at 600 °C for 3 h to remove volatile organic compounds. Specific surface area was determined by the Brunauer–Emmett–Teller (BET) gas-adsorption method in accordance with ISO 9277:2022 [21], yielding a value of 216.78 m^2/g. Particle size distribution was further characterized by dynamic light scattering (DLS) following ISO 22412:2017 [22], indicating an average particle size of ~97.3 nm.

2.3.2 Composite Fabrication

Sample Composition Design: Nine composite formulations were prepared by varying SiC and PKS nanoparticle contents from 0.5 to 2.5 wt% in different combinations. A constant 1 wt% magnesium content was maintained in all compositions to improve wettability [9]. The weight fractions were selected based on prior studies indicating that excessive nanoparticle loading (>3 wt%) can cause agglomeration and hinder dispersion [23, 24]. **Stir Casting Process:** The composites were fabricated using the stir casting method, a liquid-state processing technique widely used for metal matrix composites due to its cost-effectiveness and near-net-shape capability [25]. The procedure followed the recommendations of ASTM B179-21 [26] and ASTM B26/B26M-21 [27]: **Melting:** Al6061 ingots were preheated to 750 °C in an electric resistance furnace until fully molten. **Preheating of Reinforcement:** SiC and PKS nanoparticles were preheated at 300 °C for 30 min to eliminate moisture and improve wetting [28]. **Incorporation and Stirring:** The preheated nanoparticle reinforcements were gradually introduced into the molten aluminium while stirring mechanically at 500 rpm for 10 min to achieve uniform dispersion. **Magnesium Addition:** 1 wt% magnesium was added to enhance wettability, in line with recommendations for nanoparticle-reinforced aluminium alloys [29]. **Casting:** The molten slurry was poured into preheated sand moulds (ASTM E2349-19 [30] and allowed to solidify at room temperature. The sample compositions are shown in Table 1.

Table 1: Weight formulation of sample composition

S/No	Description	PKS%	SiC%	Mg%	Al(g)
1	Sample1(control)	-	-		700
2	Sample 2	0.2	0.5	1.0	688.1
3	Sample 3	0.4	0.5	1.0	686.7
4	Sample 4	0.6	0.5	1.0	685.3
5	Sample 5	0.6	1.0	1.0	681.8
6	Sample 6	0.6	1.5	1.0	678.3
7	Sample 7	0.6	2.0	1.0	674.8
8	Sample 8	0.8	2.5	1.0	669.9
9	Sample 9	1.8	3.0	1.0	659.4
10	Sample 10	1.2	3.5	1.0	660.1

2.4 Characterization Techniques

2.4.1 Microstructural and Chemical Analysis

SEM was used to analyze the morphology and dispersion of the nanoparticles and the reinforced composites. **XRF** was used to confirm the elemental composition of Al6061, SiC, and PKS powders. **BET** surface area analysis measured the specific surface areas of SiC and PKS particles. **DLS** analysis provided the particle size distribution for both nanoparticles.

2.5 Mechanical Testing

All samples were subjected to the following tests based on ASTM standards: **Tensile Test:** Performed according to ASTM E8M-04 on machined dog-bone shaped samples using a universal testing machine. **Hardness Test:** Rockwell hardness (scale A) was measured on polished surfaces using ASTM E18 standard. **Impact Test:** Charpy impact tests were conducted according to ASTM E23 using notched specimens. **Flexural Test:** Conducted using a three-point bending setup in accordance with ASTM D790. Each test was repeated thrice for statistical reliability, and average values were reported.

2.6 Experimental Design Rationale

The stir casting method was chosen for its industrial scalability and cost-efficiency. The hybrid reinforcement of SiC and PKS nanoparticles aimed to explore the synergistic benefits of combining ceramic and agro-waste fillers. The selection of test methods and characterization techniques was guided by the need to evaluate not only the mechanical response of the composites but also the morphology and dispersion of the reinforcements.

3 RESULTS AND DISCUSSION

The various results and discussion are presented in this section;

3.1 Microstructural and Particle Characterization

3.1.1 Scanning Electron Microscopy (SEM)

The microstructures of the processed nanoparticles and composites were examined using SEM (Figures 1-3). SEM micrographs of the ball-milled silicon carbide (SiC) showed fine, angular particles with an average size range between 60–75 nm and minimal agglomeration. In contrast, the palm kernel shell (PKS) nanoparticles displayed irregular but more elongated particle shapes, averaging around 90–110 nm (Figures 4-6). The morphology of both reinforcement types was ideal for mechanical interlocking and improved dispersion within the matrix, as also observed in similar studies [12]. In composite microstructures, uniform dispersion of both reinforcements was visible, with limited clustering. The inclusion of magnesium (1 wt%) contributed significantly to the improved wetting and dispersion of the reinforcements in the aluminium matrix, in line with previous findings [14].

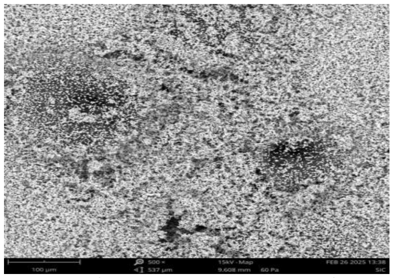
Fig 1: SEM image of SiC showing 500 x magnifications

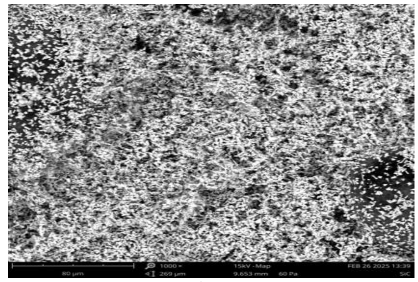
Fig 2: SEM image of SiC showing 1000x magnification

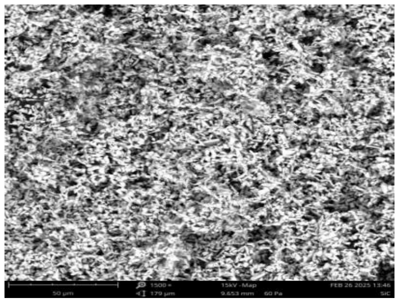
Fig 3: SEM images of SiC showing 1500x magnification

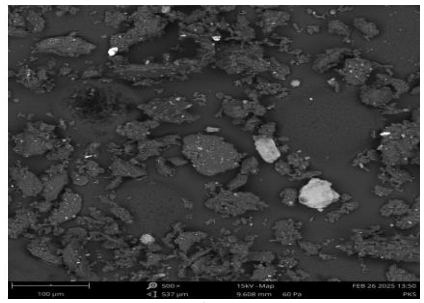
Fig 4: SEM images of PKS showing 500x magnification

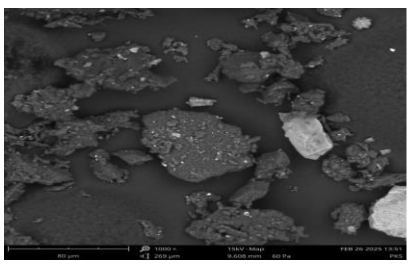
Fig 5: SEM images of PKS showing 1000x magnification

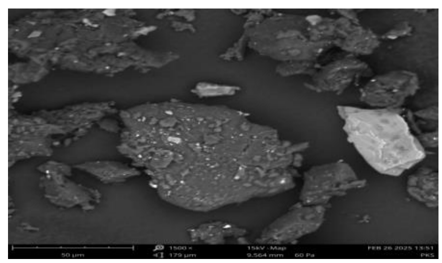
Fig 6: SEM images of PKS showing 1500x magnification

3.1.2 BET Surface Area and DLS Particle Sizing

The BET surface area analysis indicated high surface activities: SiC: 430.62 m^2/g, PKS: 216.78 m^2/g. This high surface area is critical for enhanced interfacial bonding, resulting in increased load transfer efficiency and improved mechanical performance [7]. DLS analysis showed average particle diameters of 71.62 nm for SiC and 97.3 nm for PKS, confirming the nanoscale classification of both reinforcements.

3.2 Mechanical Properties of the Composites

The mechanical properties of the fabricated composites were evaluated and are summarized in Tables 2 to 5. Trends in tensile strength, flexural strength, hardness, and impact energy are discussed below.

Table 2. Ultimate Tensile Strength of Composite Samples

Sample ID	SiC (wt%)	PKS (wt%)	UTS (MPa)
Control	0	0	79.12
S1	0.5	0.5	85.71
S2	1	0.5	92.64
S3	1	1	98.83
S4	1.5	0.3	105.1
S5	1.5	0.6	107.34
S6	1.5	1	101.82
S7	2	0.5	95.41
S8	2.5	0.5	90

Table 3. Flexural Strength of Composite Samples

Sample ID	SiC (wt%)	PKS (wt%)	Flexural Strength (MPa)
Control	0	0	103
S1	0.5	0.5	121
S2	1	0.5	130.5
S3	1	1	145
S4	1.5	0.3	158
S5	1.5	0.6	171
S6	1.5	1	160
S7	2	0.5	152
S8	2.5	0.5	138

Table 4. Impact Energy of Composite Samples

Sample ID	SiC (wt%)	PKS (wt%)	Impact Energy (J)
Control	0	0	2.8
S1	0.5	0.5	3.2
S2	1	0.5	3.25
S3	1	1	3.8
S4	1.5	0.3	4.1
S5	1.5	0.6	4.6
S6	1.5	1	4.35
S7	2	0.5	4.1
S8	2.5	0.5	3.6

Table 5. Hardness of Composite Samples

Sample ID	SiC (wt%)	PKS (wt%)	Hardness (HRA)
Control	0	0	17.9
S1	0.5	0.5	20.3
S2	1	0.5	21.8
S3	1	1	22.7
S4	1.5	0.3	23.6
S5	1.5	0.6	24.3
S6	1.5	1	23.6
S7	2	0.5	22.1
S8	2.5	0.5	21

3.2.1 Ultimate Tensile Strength (UTS)

Tensile test results (Table 2 and Figure 7) showed that all reinforced samples outperformed the control sample (79.12 MPa). UTS increased steadily with reinforcement content up to Sample S5 (1.5 wt% SiC, 0.6 wt% PKS), which exhibited the highest value of 107.34 MPa, representing a 35.6% improvement over the control. This enhancement is attributed to strong interfacial bonding, effective particle dispersion, and synergistic load-sharing between the hard ceramic and bio-based reinforcements. However, beyond this optimum (S6 to S8), the UTS began to decline, likely due to particle agglomeration and matrix saturation, which introduce stress concentration points and reduce ductility, consistent with trends observed [14, 31].

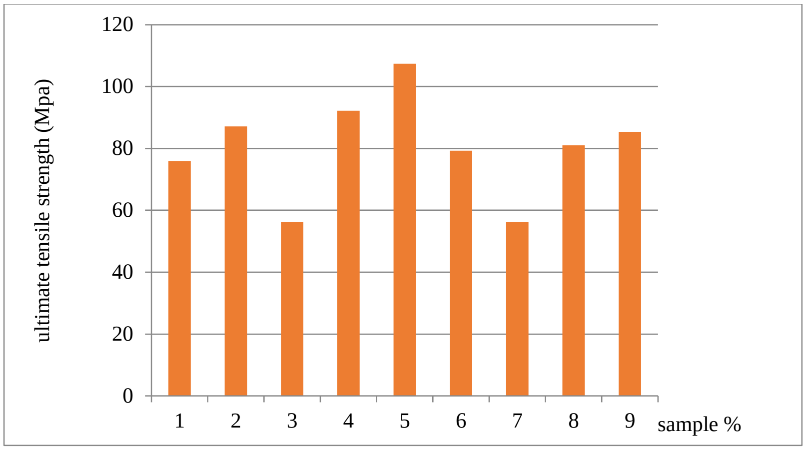

Figure 7. Variations of Tensile test for composites produced

3.2.2 Flexural Strength

The flexural strength (Table 3) followed a similar trajectory, with values increasing from 103 MPa (control) to a peak of 171 MPa (S5). This indicates that the combination of SiC and PKS effectively enhances resistance to bending stress. The decline in flexural performance beyond Sample S5 suggests that excessive nanoparticle content may disrupt matrix continuity, reducing energy dissipation during flexure [8].

3.2.3 Impact Energy

Impact strength (Table 4 and Figure 8) improved with the inclusion of reinforcements, rising from 2.80 J (control) to 4.60 J (S5). The PKS nanoparticles, due to their lignocellulosic nature, likely acted as micro-shock absorbers, enhancing the ductile phase behavior. The gradual drop in energy absorption for samples beyond S5 again suggests diminishing returns with excess filler loading, where increased stiffness may reduce overall toughness [9].

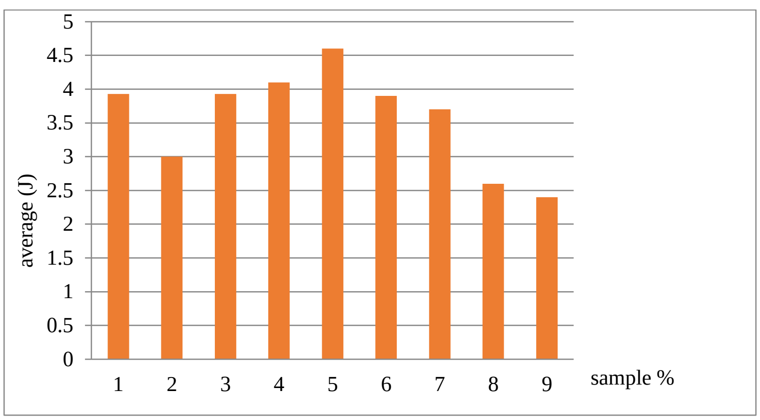

Figure 8. Variations of Impact test for composites produced

3.2.4 Hardness

Hardness values (Table 5 and Figure 9) increased from 17.9 HRA (control) to a peak of 24.3 HRA (S5). The increase can be linked to the hard SiC particles resisting localized plastic deformation. The plateau or slight decrease in S6–S8 indicates that particle clustering and possible micro-void formation may be reducing the reinforcing efficiency at higher concentrations [14].

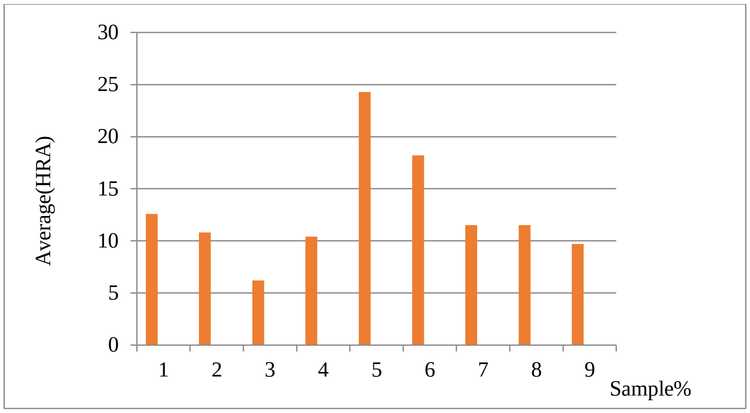

Figure 9. Variations of Hardness test for composites produced

3.3 Trends and Optimal Composition

Across all mechanical property categories, Sample S5 consistently delivered the best performance, confirming that the composition of 1.5 wt% SiC + 0.6 wt% PKS + 1 wt% Mg provides an optimal balance between strength, stiffness, impact resistance, and hardness. The results also affirm the synergistic effect of combining a ceramic (SiC) with an agro-waste (PKS) reinforcement at the nanoscale. SiC contributes to hardness and strength, while PKS introduces flexibility and energy absorption, an effect that is especially useful in applications requiring lightweight, multifunctional structural components.

3.4 Comparison with Existing Literature

The trends observed align with findings from previous studies involving hybrid reinforcements. A research work reported similar peak-property behaviors in Al composites reinforced with nano-rice husk ash and SiC [13]. Likewise, the role of magnesium as a wetting agent improving mechanical properties has been corroborated [14]. What distinguishes this work is the successful nano-integration of agro-waste PKS, which is both cost-effective and sustainable, with performance comparable to synthetic nano-fillers.

4 CONCLUSIONS

This study successfully developed aluminium matrix composites (AMCs) reinforced with hybrid nanoparticles derived from silicon carbide (SiC) and palm kernel shell (PKS) through the stir casting method. The SiC and PKS powders were processed into nanoparticles using high-energy ball milling and characterized via SEM, BET, DLS, and XRF techniques. A total of nine composite samples were fabricated with varying weight fractions of SiC and PKS while maintaining a constant 1 wt% magnesium as a wetting agent. The mechanical characterization of the composites revealed that the sample containing 1.5 wt% SiC, 0.6 wt% PKS, and 1 wt% Mg (Sample S5) exhibited the best overall performance, achieving: ultimate tensile strength of 107.34 MPa, flexural strength of 171 MPa, impact energy of 4.60 J and hardness value of 24.3 HRA. These results indicate that the integration of agro-waste-based PKS with conventional ceramic SiC nanoparticles yields a synergistic reinforcement effect, improving strength, stiffness, impact resistance, and overall durability. The inclusion of PKS as a secondary reinforcement also contributes to lightweight design, cost-effectiveness, and environmental sustainability, making the developed composites promising for applications in automotive body parts, interior components, aerospace secondary structures, and light-duty load-bearing assemblies. The research demonstrates that agricultural waste products can be valorized into functional materials for advanced manufacturing, offering both engineering and environmental benefits.

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