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Development and Characterization of Rice Husk Ash-Reinforced Epoxy Composites for Potential Automotive Bumper Fascia Applications

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Abstract

Modern automotive components require lightweight, durable, and environmentally sustainable materials, yet conventional bumper materials rely on petroleum-based polymers and mineral fillers that increase weight, cost, and environmental impact. Agricultural waste-derived fillers provide a promising alternative because of their low density, wide availability, and potential to improve polymer composite performance. This study developed and characterized rice husk ash (RHA)-reinforced epoxy composites for potential application in automotive bumper fascia. RHA was produced through a low-temperature, acid-free process involving carbonization at 300°C followed by calcination at 350-400°C. The ash was characterized using X-ray fluorescence, X-ray diffraction, Fourier transform infrared spectroscopy, Brunauer-Emmett-Teller surface area analysis, scanning electron microscopy, and energy dispersive spectroscopy. The RHA contained 77.72 wt.% silica and exhibited a mesoporous structure with an average pore diameter of about 3 nm, indicating its suitability as a reinforcing filler. Epoxy composites containing 2-10 wt.% RHA were fabricated by hand stir casting and evaluated for tensile, flexural, impact, and wear properties. Tensile strength increased from 13.7 MPa for neat epoxy to 16.6 MPa at 10 wt.% RHA, while impact strength improved from 1.56 to 2.98 J/cm². Flexural modulus increased with filler content, although flexural strength decreased at higher loadings because of particle agglomeration. Wear resistance improved as silica-rich particles enhanced abrasion resistance. The 10 wt.% RHA composites showed the best overall combination of stiffness, impact resistance, and wear performance, demonstrating that low-temperature RHA can reinforce epoxy composites for non-structural automotive applications while promoting sustainable utilization of agricultural waste.

Key words: Rice husk ash; Epoxy composites; Automotive bumper fascia; Sustainability; Mesoporous silica; Mechanical properties

1. Introduction

The transportation sector continues to experience the need to reduce vehicle weight, improve fuel efficiency, lower greenhouse gas emissions, and minimize the environmental burden associated with material production and disposal [1–3]. These requirements have shifted automotive material development beyond the traditional emphasis on mechanical performance alone towards materials capable of combining structural efficiency with environmental sustainability throughout their service life [4–6]. Within this framework, lightweight polymer composites have received considerable attention because they provide opportunities to reduce component weight, maintaining desirable mechanical performance, corrosion resistance, manufacturing flexibility, and cost effectiveness [7]. Their ability to accommodate different reinforcement systems further allows engineers to tailor material properties for specific automotive functions, making polymer composites attractive alternatives to many conventional metallic components [8, 6, 1, 9, 10]. Among the external components of an automobile, the bumper system performs one of the most demanding engineering functions because it serves as the primary impact management structure during low velocity collisions, preserving vehicle integrity and reducing repair costs. Beyond aesthetics, modern bumper fascia materials are expected to absorb and dissipate impact energy, resist abrasion during service, maintain dimensional stability under mechanical loading, tolerate environmental exposure, and retain adequate stiffness without undergoing catastrophic fracture [11, 12, 13]. The simultaneous satisfaction of these requirements remains a major materials engineering challenge because improvements in one property often occur at the expense of another. Materials possessing high stiffness commonly suffer reduced impact resistance, whereas highly ductile materials may lack sufficient rigidity to maintain structural integrity during repeated service loading [14–16, 6].

A bumper is not a single property material problem. It must combine adequate stiffness to hold its shape under service loads, sufficient toughness to absorb impact energy without catastrophic fracture, resistance to surface wear from repeated abrasive contact, and low mass, and these requirements often work against each other, since a material stiff enough to resist deformation is frequently too brittle to dissipate impact energy in a controlled manner [11, 12, 17, 7]. Commercial bumper fascia is commonly manufactured from polypropylene based blends, thermoplastic olefins, polycarbonate alloys, and glass fibre reinforced polymers because these materials offer an acceptable balance between impact resistance, manufacturability, and production cost [15, 6, 11, 12]. Nevertheless, dependence on petroleum derived polymers and synthetic reinforcements continues to raise concerns regarding resource depletion, energy intensive manufacturing,

recycling difficulties, and environmental sustainability [5, 18, 3]. Glass fibre reinforced systems provide improved stiffness and strength but introduce higher production costs, increased component density, greater tool wear during machining, and challenges associated with end-of-life recycling [19, 8, 6]. These limitations have led to continuous efforts toward the development of lightweight composite materials incorporating renewable and waste derived reinforcements capable of delivering acceptable engineering performance while reducing environmental impact for non load bearing and semi structural automotive components [20–23, 8]. The use of particulate fillers is one of the most effective approaches for improving the mechanical and functional performance of polymer composites [24, 25]. Appropriate fillers can enhance stiffness, hardness, dimensional stability, wear resistance, thermal behaviour, and service durability while simultaneously lowering material cost through partial replacement of the polymer matrix. The magnitude of these improvements depends not only on filler loading but also on particle morphology, surface chemistry, pore structure, particle size distribution, and the quality of interfacial adhesion established between the reinforcement and the surrounding polymer matrix [26–28]. However, identifying sustainable reinforcement materials possess promising microstructural characteristics capable of promoting efficient stress transfer without compromising toughness.

Agricultural residues have been a promising reinforcement resources because they address two engineering challenges simultaneously [29]. They provide an environmentally responsible route for waste management while supplying low-cost raw materials for advanced composite development [3, 20]. Their conversion into engineering materials supports circular resource utilization, reduces dependence on virgin mineral fillers, and contributes to the sustainable manufacturing strategies promoted under global sustainable development initiatives [5, 30]. Numerous agricultural by products including coconut shell, palm kernel shell, eggshell, wood ash, banana fibre, calabash, and rice husk have therefore been investigated as reinforcement materials for polymer composites intended for structural and semi structural engineering applications [31–35]. Among agricultural residues explored, rice husk stands out because of its scale of availability and its unusually high mineral content. Rice milling generates large volumes of husk as waste, and when this husk is thermally treated the resulting ash is dominated by silica, a phase whose stiffness and hardness make it attractive as a particulate reinforcement for polymer matrices [36–38]. Rice husk ash (RHA) has therefore been studied across a wide range of applications, from supplementary cementitious material in concrete to filler in rubber, aluminium and polymer composites [36, 39–41]. Within polymer composites specifically, RHA and rice husk derived silica have been reported to improve tensile strength, hardness, thermal stability and wear resistance of epoxy systems, supporting the case for RHA as a viable filler for structural and semi structural applications [42, 14, 43, 44].

A closer reading of this body of work however reveals that overwhelming majority of RHA studies originate from the cement and concrete field, where the objective is to maximize reactive silica content so that the ash performs well as a pozzolan in calcium silicate hydrate formation [36, 38]. To meet this objective, the standard processing route calcines rice husk at high temperature and frequently applies acid or alkali leaching [43, 45–47]. to strip away potassium, calcium, aluminium and residual carbon so that the resulting ash approaches pure amorphous silica [48–50]. This route is effective for cementitious applications [51], but it is energy intensive, generates acidic effluent that must be treated or disposed of, which serve as the research gap. In a polymer matrix, the reinforcing mechanism is governed by stress transfer between filler and matrix, particle morphology, particle size, interfacial adhesion and dispersion, not by pozzolanic reactivity [17, 52], reporting tensile strength, flexural strength and hardness [42, 43, 53]. A bumper fascia does not simply need to be strong. It needs to absorb impact energy through controlled deformation, resist surface wear from years of low level abrasive contact, and do so while remaining light and inexpensive to produce [4, 7, 54]. Very few RHA reinforced polymer studies evaluate tensile, flexural, impact and wear behaviour together and interpret the results against this specific functional requirement, which means the suitability of RHA epoxy composites for bumper fascia remains largely inferred rather than demonstrated. This research lies in investigating a processing paradigm by producing RHA through a low temperature, non-acid leached route and testing whether the retained mineral and carbon content, rather than undermining performance, actively supports the mechanical property balance required for automotive fascia application. Evaluating the results against property set that a bumper must satisfy.

2. Materials and Methods

2.1 Materials

The Materials used in this research were diglycidyl ether of bisphenol-A epoxy resin (CAS No. 25068-38-6) with a specific gravity of 1.16 g/cm³ and a viscosity of 10,000 mPa·s at 25 °C, diethylenetetramine amine hardener (CAS No. 9046-10-0) with a specific gravity of 0.95 g/cm³ and a viscosity of 20 mPa·s at 25 °C. Both procured from Oilserv Nigeria Limited, Lagos State, Nigeria. Rice husks were obtained from a local rice milling facility in Abuja, Federal Capital Territory, Nigeria.

2.2 Preparation and Processing of Rice Husk Ash

Rice husks sourced manually cleaned from debris (soil, stones, grains, straw), and rinsed thoroughly with distilled water to remove surface dust and soluble impurities. The cleaned husks were then oven-dried at

105 °C for 12 h to remove residual moisture prior to thermal treatment [30]. The dried husks were carbonized in a muffle furnace at 300 °C for 2 h under a limited-oxygen atmosphere, using a heating rate of 10 °C/min as illustrated in Figure 1. This thermally decomposes the cellulose, hemicellulose, and lignin fractions of the husk, restricting full oxidation of the resulting carbon skeleton [30]. The carbonized rice husk obtained was cooled to room temperature inside the furnace before being calcined. The carbonized rice husk calcined in a muffle furnace under ambient air at 350–400 °C for 3 h, at a heating rate of 10 °C/min, to partially oxidize the residual carbon and concentrate the silica-rich fraction, keeping the temperature below the threshold associated with crystallization of amorphous silica into less-reactive polymorphs such as cristobalite [48]. The resulting ash was pale black, rather than the pale gray or white reported for Rice Husk Ash calcined at higher temperatures. This observation is consistent with the relationship between calcination temperature and ash coloration, whereby the degree of blackness or grayness of the ash serves as a visual proxy for residual carbon content and combustion completeness, with darker ash reflecting incomplete oxidation of carbon at lower-to-intermediate calcination temperatures and lighter coloration emerging only as combustion approaches completion at higher temperatures [55]. The calcined ash was gently ground with a ball mill (Denver XMQ Series, China) and sieved through a 45 µm mesh to obtain a fine, homogeneous particle fraction. This particle size was selected because reducing RHA particle size to the <45 µm range has been shown to modify the internal pore structure of the ash, improve its water demand/fluidity behavior in cementitious and composite systems, and provide a more consistent basis for comparing material reactivity across samples [50, 38].

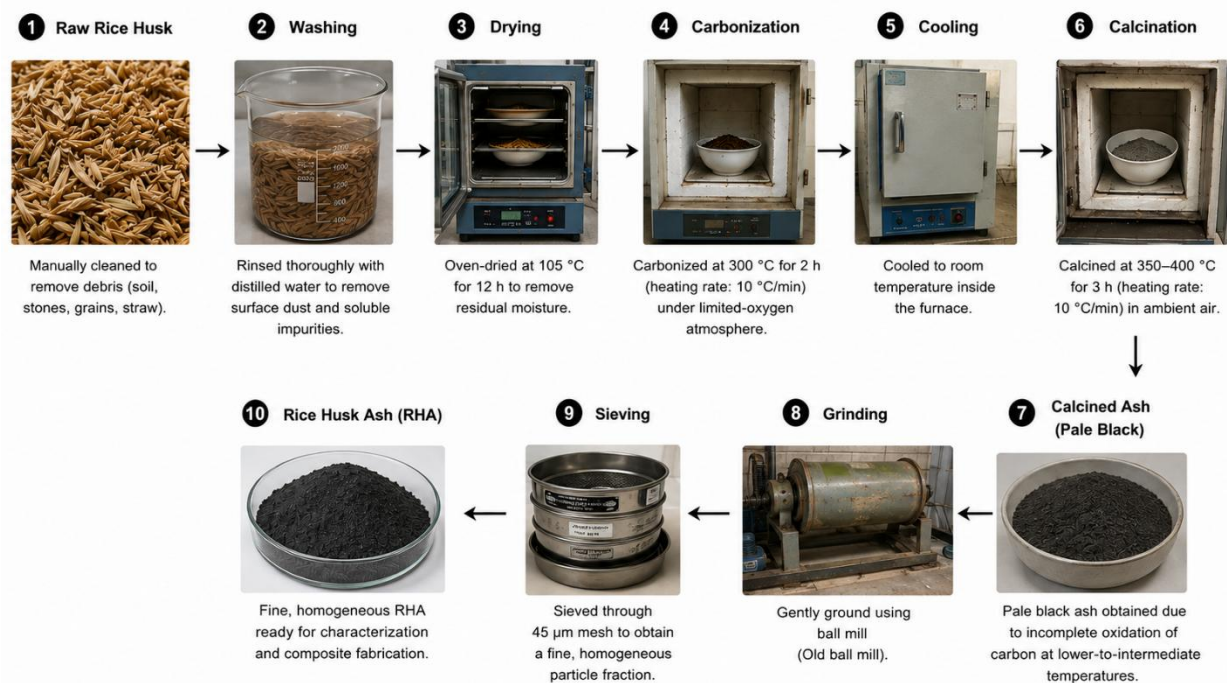


Figure 1: Schematic Illustration of Rice Husk Ash Preparation

2.3 Composite Development

Standard tensile, impact, flexural, and wear moulds were thoroughly cleaned prior to fabrication. Composite panels were prepared using the hand stir casting technique [34, 35, 56]. The weight fractions of the matrix and RHA reinforcement were pre-determined and are presented in Table 1. To prepare the polymer matrix; the epoxy resin and hardener were mixed in a 2:1 ratio (v/v) and blended using a mechanical stirrer for 5 min to achieve a homogeneous mixture and poured into the prepared moulds. The composites were allowed to cure at an ambient temperature of 24 ± 1 °C for 6 h at a relative humidity of 60% [20, 1]. The RHA weight fraction was varied from 2 to 10 wt. %. This range was selected in alignment with prior work on particulate agro-waste ash-reinforced epoxy composites developed specifically for mechanical enhancement [31, 53, 14]. After curing as seen in Figure 2, the samples were demoulded and subjected to physical, thermal, and mechanical characterization in accordance with relevant ASTM standards. Two replicated specimens were produced for statistical reliability.

Table 1: Formulation Table of Developed Rice Husk Ash Reinforced Epoxy Composite

Sample ID	Epoxy Matrix (wt. %)	Rice Husk Ash (wt. %)
A1	98	2
A2	96	4
A3	94	6
A4	92	8
A5	90	10
Control	100	0



Figure 2: Developed Rice Husk Ash Reinforced Composite Test Specimen

2.4 Test and Characterization

2.4.1 Mechanical and Abrasion Tests

Tensile properties were evaluated in accordance with ASTM D3039 using a universal testing machine (Omni mrcmesin). specimens were loaded under uniaxial tension at a constant crosshead displacement rate until failure. Flexural properties were determined by the three-point bending method in accordance with ASTM D790 using the same universal testing machine. Rectangular specimens were tested under a centrally applied load, and the flexural strength and flexural modulus were calculated from the resulting load-deflection curves. Impact strength was determined using the Izod impact method in accordance with ASTM D256 with a pendulum impact tester (JBW 300B). with absorbed energy normalized to the cross-sectional area of the specimen at the notch to yield specific impact strength values. Wear resistance was evaluated using a pin-on-disc tribometer (Ducom TR-20LE, India) in accordance with ASTM G99. The composite specimens were tested against a hardened steel disc under a constant normal load and sliding speed for a specified sliding distance, and the wear rate was determined from the mass loss measured before and after testing.

2.4.2 Morphological and spectroscopic characterization

The surface morphology and microstructural characteristics were examined using a scanning electron microscope (Model: JEOL JSN 7600F). The specimens were mounted on aluminum stubs and sputter-coated with a thin conductive gold layer prior to imaging to improve surface conductivity and image resolution. Elemental composition was determined using energy dispersive X-ray spectroscopy (EDS) integrated with it. X-ray fluorescence spectroscopy (PANalytical Axios MAX, Netherlands) was used to determine the chemical composition. XRD (Bruker AXS GmbH, Germany) with Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$) was used to determine the diffraction patterns. Functional group analysis was carried out using Fourier transform infrared spectroscopy (Agilent Cary Model 630). The spectra were recorded over a wavenumber range of $4000\text{--}400 \text{ cm}^{-1}$. The specific surface area and pore characteristics were determined using the Brunauer-Emmett-Teller (BET) method with a surface area analyzer (NOVA 1200e). Nitrogen adsorption-desorption isotherms were obtained after degassing the samples under vacuum, and the BET surface area, pore volume, and pore size distribution were calculated.

3. Results and Discussion

3.1 Elemental Composition of Rice Husk Ash

The oxide composition of rice husk ash (RHA) is presented in Table 2(a). SiO₂ is the dominant oxide at 77.72%. As the primary network former, Si⁴⁺ is tetrahedrally coordinated to four O²⁻ ions in a continuous, covalently bonded Si–O–Si, and this connectivity is responsible for the high intrinsic stiffness of silica, with elastic moduli of about 70–90 GPa and hardness values above 500 HV [57, 58]. This rigidity is the property that makes SiO₂ valuable as a reinforcing phase in a polymer matrix, responsible for improving stiffness in matrix that enables load transfer and stress redistribution under applied force, which is the fundamental mechanism by which any particulate filler improves composite mechanical performance [17, 59]. However, a fully polymerized Si–O–Si network has limited capacity for local bond rotation, so once a crack nucleates it propagates through unbroken covalent bonds, giving pure amorphous silica a low fracture toughness of around 0.7–0.9 MPa·m^{1/2} [60]. This is not a defect of silica as a reinforcing material; it is the same structural feature responsible for its stiffness, and it is the reason the weight fraction and dispersion of any silica bearing filler, rather than its silica fraction alone, is the parameter that determines whether a given composite achieves useful reinforcement or becomes prone to brittle failure [17, 26]. The remaining oxides, P₂O₅ (8.317%), K₂O (4.201%), CaO (2.738%), Al₂O₃ (2.719%), Fe₂O₃ (1.199%), and SO₃ (0.993%), modify this network structure. K⁺ and Ca²⁺ act as network modifiers, occupying interstitial positions within the silicate framework and breaking Si–O–Si bridging bonds to form non-bridging oxygen sites. Kilinc and Hand [61] showed that this depolymerization is not simply a loss of rigidity but a mechanism that increases fracture toughness, since the resulting non-bridging oxygen sites permit local structural rearrangement ahead of an advancing crack, allowing greater strain energy dissipation before failure. Al³⁺ is amphoteric and can substitute for Si⁴⁺ within the tetrahedral framework, contributing rigidity in a manner comparable to SiO₂ itself, while P₂O₅ forms PO₄ units that connect to the surrounding network through only three of four oxygen atoms, giving it a network disrupting rather than network extending role at the concentration. The combined effect of these modifying oxides is a silicate structure with a lower degree of polymerization than that of a high siliceous phase [62]. as presented in Table 2(b).

Table 2(a): Oxide composition of Rice Husk Ash

Oxide	Composition (%)
SiO ₂	77.723
P ₂ O ₅	8.317
K ₂ O	4.201

CaO	2.738
Al ₂ O ₃	2.719
Fe ₂ O ₃	1.199
SO ₃	0.993

The SiO₂ content obtained appears lower than those reported in many previous investigations. However, these comparisons should be understood within the context of the intended application rather than viewed as a pointer of the material quality. The majority of studies summarized in Table 2(b) were conducted within the fields of cement and concrete technology, where RHA was used as a supplementary cementitious material, where silica participates in pozzolanic reactions with calcium hydroxide generated during cement hydration, forming additional calcium silicate hydrate (C–S–H) gel that contributes to strength development and durability. However, maximizing reactive silica content is a primary objective, and processing routes are intentionally designed to remove non-siliceous constituents through acid leaching and high-temperature calcination [36, 38]. In this research, the RHA functions as a particulate reinforcement within an epoxy matrix intended for potential automotive structural applications, where the reinforcement mechanism is governed not by chemical reactivity only but by stress transfer between the polymer matrix and dispersed solid particles [1]. Under these conditions, the effectiveness of the reinforcement depends not only on silica content but also on particle morphology, particle size, interfacial adhesion, dispersion quality, filler loading and the ability of the composite to resist crack initiation while dissipating impact energy [17, 52]. However, maximizing SiO₂ concentration alone does not necessarily produce the optimum filler for polymer composite applications. Modern bumpers are required to satisfy several competing mechanical requirements. Besides providing adequate stiffness to maintain dimensional stability under service loads, they must also absorb and dissipate impact energy efficiently during low- and moderate-speed collisions while minimizing catastrophic fracture. These requirements have led to a balance between stiffness, toughness, lightweight construction and impact resistance [4, 7]. In such applications, excessively stiff reinforcement can become counterproductive if it tends to reduce the composite's capacity to undergo controlled deformation and absorb impact energy. Bravo-Carrasco et al. [54] reported that silica nanoparticle incorporation into a polypropylene-based bumper fascia improved both flexural stiffness and impact performance when the filler content remained within an optimum range, with excessive particle addition promoting agglomeration and increasing stress concentration. This shows that the reinforcing efficiency of silica depends primarily on how it is incorporated into the polymer matrix rather than on achieving the highest possible silica purity. The ash obtained preserves a greater proportion of naturally occurring K₂O, CaO, Al₂O₃ and Fe₂O₃ derived from the original rice husk. Potassium and calcium partially depolymerize the silicate agenda by generating non-bridging oxygen sites, while aluminium contributes to

network stabilization through tetrahedral substitution. The resulting inorganic structure remains silica-rich but is less extensively polymerized than that of purified silica, a characteristic that may provide a more favourable balance between rigidity and fracture resistance from a structural perspective [61, 62].

Table 2(b): Comparative oxide composition of Rice Husk ASH

Source	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	K ₂ O (%)	SO ₃ (%)
Cordeiro et al. [63]	82.60	0.40	0.50	0.90	1.80	0.10
Saraswathy and Song [64]	92.95	0.31	0.26	0.53	2.06	—
Kang et al. [65]	92.00	0.31	0.38	0.97	3.87	—
Zheng et al. [66]	83.70	1.65	1.43	3.19	—	0.93
Berkin et al. [41]	87.2	0.15	0.16	0.55	0.24	1.12
Sakr et al. [67]	80.0–95.9	0.4–1.4	0.2–2.9	1.1–1.5	2.8–6.6	0.7–1.2
Present study	77.72	2.72	1.20	2.74	4.20	0.99

3.2 Morphological Analysis of Rice Husk Ash

The SEM micrographs reveal that the ash consists of irregularly shaped particles with rough, and angular surfaces, retaining a fractured appearance as presented in Figure 3, reflecting the thermal decomposition of the original rice husk during carbonization and calcination. Two dominated morphological features which are elongated plate-like fragments with sharp edges, which are consistent with the fractured cellular framework of the rice husk after removal of its organic constituents and a porous, honeycomb-like structure containing numerous interconnected cavities. Similar porous morphologies have been reported for rice husk ash by Cordeiro et al. [68], Venkatanarayanan and Rangaraju [69], and Guo et al. [38], who attributed this structure to the silica-rich cellular architecture remaining after thermal decomposition. However, low carbonization and calcination temperatures used preserved this porous morphology without causing particle melting or significant densification. The observed surface characteristics are considered beneficial for particulate reinforcement in polymer composites [9]. The rough particle surfaces and interconnected pores increase the surface area for resin wetting and are expected to promote improved mechanical interlocking between the filler and the matrix [9]. Such morphological features facilitate stress transfer across the particle–matrix interface. Small clusters of fine particles are also visible in the micrographs, showing localized agglomeration that is commonly observed in fine silica-rich powders because of their high surface area. EDS reveals that Oxygen (35.30 wt.%) and carbon (25.45 wt.%) were the most abundant elements

detected, followed by potassium, silicon, aluminium, calcium and magnesium. The high oxygen content reflects the high proportion of oxide phases within the ash, and the retained carbon confirms the carbonaceous fraction remained following the low-temperature carbonization and calcination process. This observation is consistent with the pale black appearance of the ash. Silicon detected further confirms the presence of silica as the principal inorganic constituent responsible for the reinforcing potential of the RHA. The elemental composition confirms the presence of silica together with retained carbon and naturally occurring mineral constituents, complementing the bulk oxide composition determined by XRF and provide an important basis for understanding the reinforcing behaviour of the RHA.

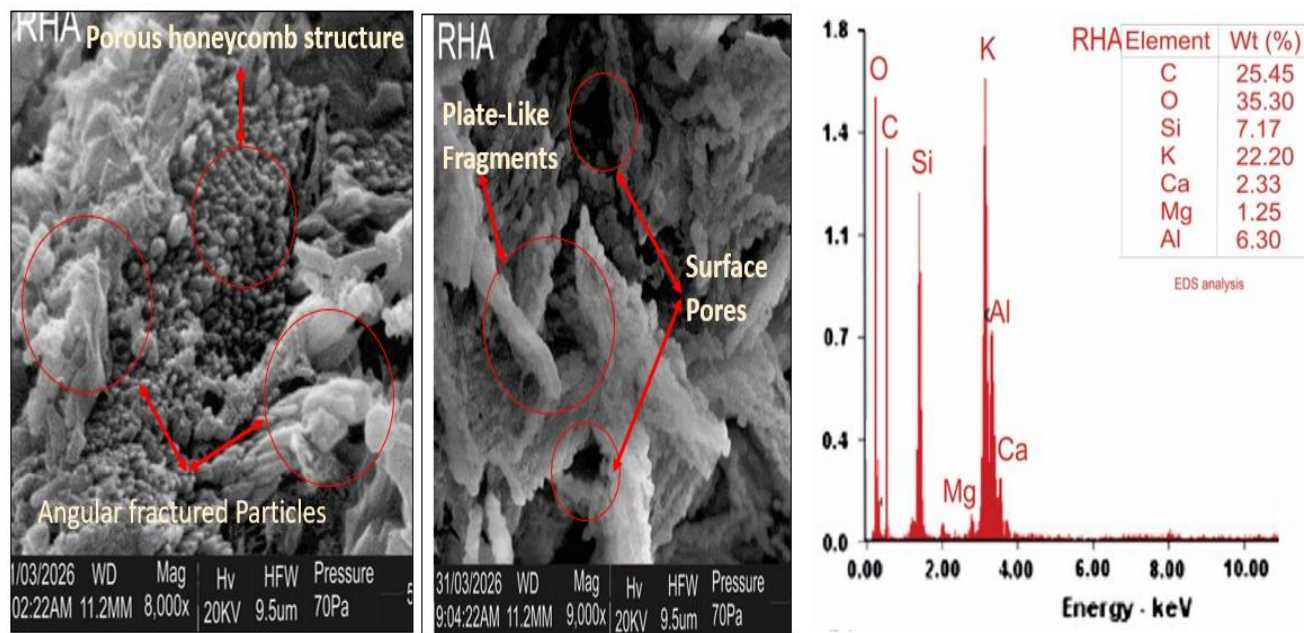


Figure 3: SEM Micrographs of Carbonized Rice Husk Ash

3.3 Functional Group-Identification Analysis of Rice Husk Ash

A broad absorption band centered at 3608 cm^{-1} is assigned to the O–H stretching vibration of surface silanol (Si–OH) groups together with hydrogen-bonded hydroxyl groups arising from physically adsorbed moisture on the ash surface as illustrated in Figure 4. This is accompanied by a band at 1608 cm^{-1} , corresponding to the H–O–H bending vibration of adsorbed water molecules. The main feature of the spectrum is the strong absorption band at 1034 cm^{-1} , attributed to the asymmetric stretching vibration of the Si–O–Si linkage, which is the principal structural signature of amorphous silica and confirms that silica is the major inorganic phase of the rice husk ash. This assignment is further supported by the band at 827 cm^{-1} , corresponding to Si–O–Si symmetric stretching, and the absorption at 675 cm^{-1} , assigned to the Si–

O bending vibration. Similar FTIR band positions have been reported for rice husk-derived silica, where the asymmetric Si–O–Si stretching vibration occurs between 1030 and 1100 cm^{-1} , the symmetric stretching and bending vibrations are observed within the 800–850 cm^{-1} and 450–800 cm^{-1} regions, respectively [47]. Surface silanol groups are said to decrease with increasing calcination temperature as neighbouring Si–OH groups undergo dehydroxylation and condensation to form siloxane (Si–O–Si) bridges, thereby reducing the hydroxyl density on the silica surface [45, 47]. Acid pretreatment prior to calcination basically removes alkali metals and other inorganic impurities, producing a cleaner and higher-purity silica surface while modifying the surface chemistry of the ash [46, 45]. However, since the RHA used in the present work was calcined at only 350–400 °C and was not subjected to acid or alkali leaching, a comparatively hydroxyl-rich silica surface is expected to be retained. The pronounced O–H stretching and H–O–H bending bands observed in the FTIR spectrum are therefore consistent with the selected low-temperature processing route. The retention of surface silanol groups is advantageous for the intended application of the ash as a reinforcing filler in epoxy composites. Silanol groups constitute the principal reactive sites on the silica surface and are capable of interacting with hydroxyl and amine functionalities generated during epoxy curing through hydrogen bonding and other interfacial interactions [45, 46]. No distinct absorption bands were observed within the 1700–1730 cm^{-1} region associated with carbonyl (C=O) groups or within the 2850–2950 cm^{-1} region corresponding to aliphatic C–H stretching vibrations. Their absence shows that the cellulose, hemicellulose and lignin constituents of the original rice husk were decomposed during carbonization and calcination. The residual carbon detected by EDS is suggested to exist as thermally stabilized carbonaceous material rather than as undecomposed lignocellulosic residue [47, 45].

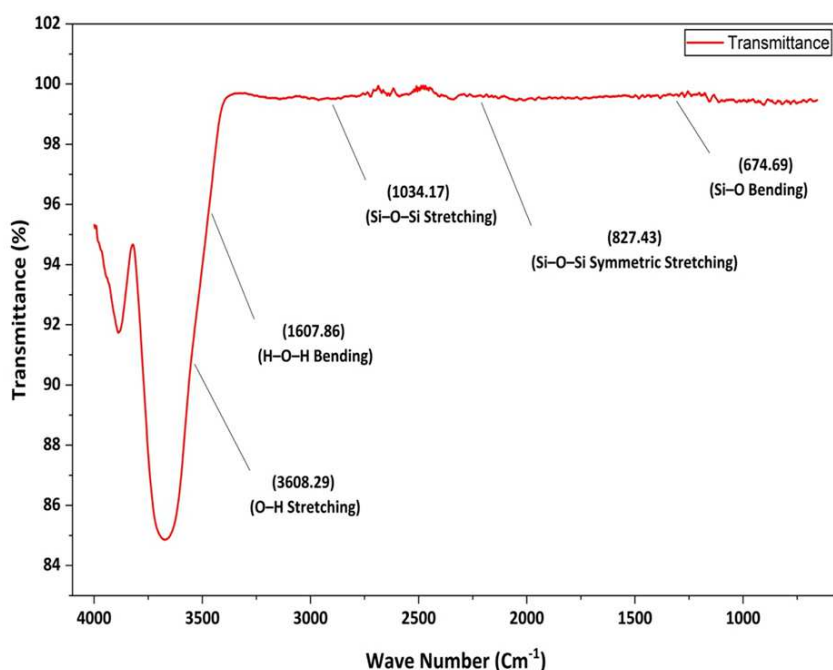


Figure 4: FTIR Spectrum of Rice Husk Ash

3.4 XRD Analysis of Rice Husk Ash

The diffraction pattern shown in Figure 5, a broad diffuse halo-centered at $2\theta = 21.26^\circ$, which is a characteristic of amorphous silica (SiO_2). Unlike crystalline materials that produce sharp diffraction peaks due to long-range atomic ordering, the broad observed here reveals the disordered arrangement of Si-O-Si tetrahedra within the silica network, confirming that amorphous silica is the major phase present in the ash [38, 30]. The diffraction peak observed at $2\theta = 26.6^\circ$ is therefore attributed to a small quantity of crystalline quartz, which is suggested to originate from naturally occurring mineral impurities within the rice husk. Another diffraction peak appears at about $2\theta = 43^\circ$. This peak is assigned to the (100) reflection of turbostratic or poorly ordered graphitic carbon, which is commonly observed in biomass-derived chars and partially carbonized agricultural residues [70, 71]. Graphitic carbon usually has two characteristic reflections: a broad (002) peak near $24\text{--}26^\circ$ and a weaker (100) reflection around $43\text{--}44^\circ$. However, In Figure 5, the (002) reflection is likely screened by the broad amorphous silica halo-centered near $21\text{--}26^\circ$, whereas the weaker (100) reflection remains distinguishable. The presence of this carbon-related peak provides further structural evidence for the retained carbon fraction already identified by EDS analysis and is also responsible with the pale black appearance of the ash. The of amorphous silica is advantageous for

the intended application because it possesses a highly disordered atomic structure, making it less susceptible to brittle cleavage and provides a larger concentration of surface silanol groups [46, 45].

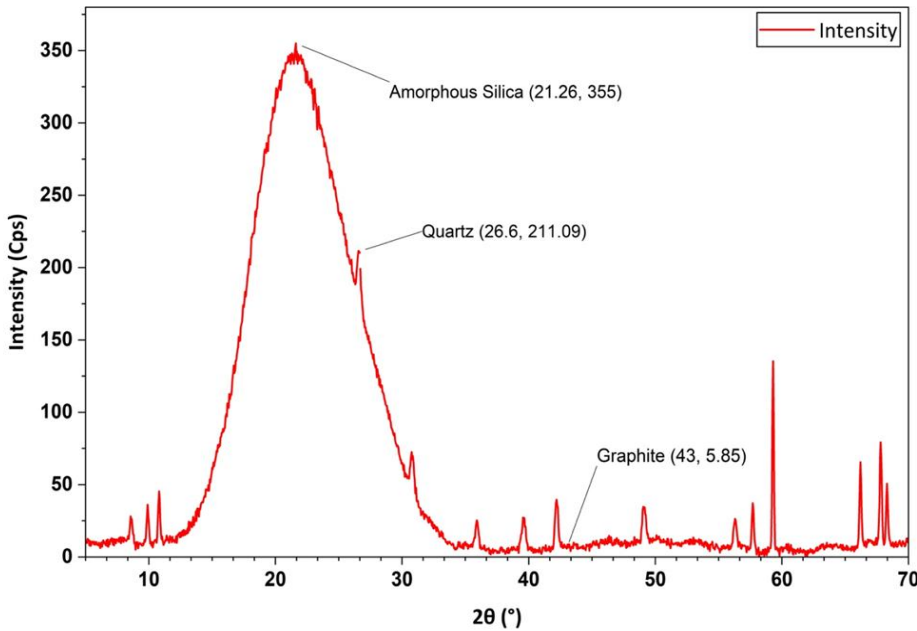


Figure 5: X-ray diffraction (XRD) pattern of rice husk ash

3.5 Surface Area and Pore Structure Analysis of Rice Husk Ash

The mesoporous nature of the RHA agrees well with the SEM observations, where numerous interconnected pores and a honeycomb-like surface morphology were identified, and with the amorphous silica phase confirmed by XRD. During thermal decomposition of rice husk, the removal of cellulose, hemicellulose and lignin leaves behind a porous silica skeleton, resulting in a high internal surface area that is characteristic of amorphous rice husk ash [38, 45, 72]. The results shows that the RHA produced by the low-temperature, non-acid-leached processing route possesses a well-developed mesoporous structure centered at about 3 nm. The BET transform plot, presented in Figure 6(a), shows a linear relationship between the BET function, $1/[V(P_0/P - 1)]$, and relative pressure over the range $P/P_0 = 0.05$ to 0.30, confirming that the assumptions of the BET model, named monolayer to multilayer adsorption on an energetically uniform surface, are satisfied for this material and that the resulting surface area value can be considered reliable. The BET function increases gradually with relative pressure, from 5.35 at $P/P_0 = 0.05$ to 7.95 at $P/P_0 = 0.30$, showing continuous, uninterrupted nitrogen uptake across the measured range rather than early saturation, which is itself an indication of pore network [73]. Srivastava et al. [72] characterized

untreated RHA of a similar unpurified, non-nanostructured type to that produced in this study, reported a BET surface area of 36.44 m²/g with a BJH pore area contribution of 80% from mesopores, values that provide a useful benchmark against which the surface characteristics obtained here can be interpreted, since both studies examine a comparatively simple, minimally processed RHA rather than a chemically synthesized or acid extracted nanosilica. The pore size distribution of the RHA was further examined using the Barrett–Joyner–Halenda (BJH) method, applied to the desorption branch of the nitrogen isotherm, with the resulting pore volume distribution presented in Figure 6(b). Over the measured range of 1.45 to 2.45 nm, pore volume increases with pore diameter, from 0.017 cm³/g·nm at 1.45 nm to 0.112 cm³/g·nm at 2.45 nm. This is consistent with the average pore diameter of 2.453 nm reported for the material, and places the RHA pore population within the mesoporous range as defined by IUPAC, which classifies pores between 2 and 50 nm in diameter as mesopores, distinct from the sub 2 nm micropore and above 50 nm macropore regimes [73, 45]. When Dubinin–Astakhov (DA) model was applied, with the resulting pore volume profile presented in Figure 6(c), across a wider pore diameter range of 1.6 to 6 nm. The DA plot shows pore volume rising sharply from near zero at 1.6 nm to a clear maximum of 0.077 cm³/g·nm at 3 nm, after which pore volume declines progressively to 0.016 cm³/g·nm by 6 nm. This confirms that the pore population of the RHA is centered at approximately 3 nm, corroborating the average pore diameter obtained

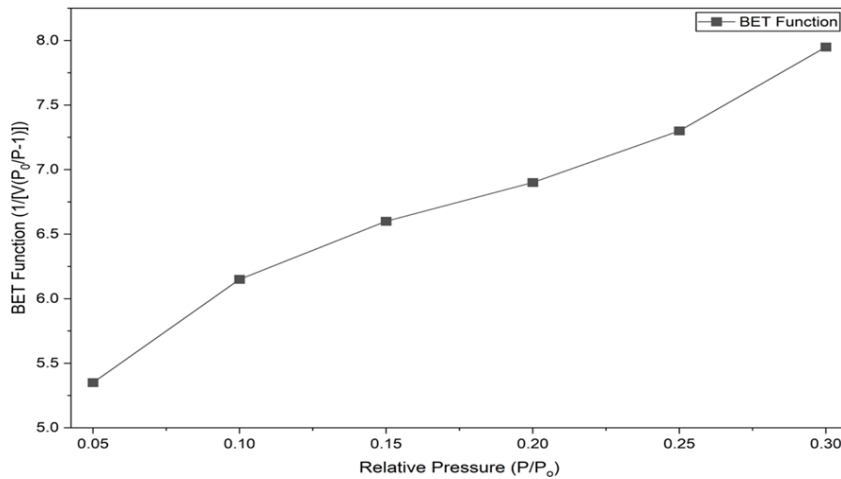


Figure 6(a): Multi-point BET plot of rice husk ash

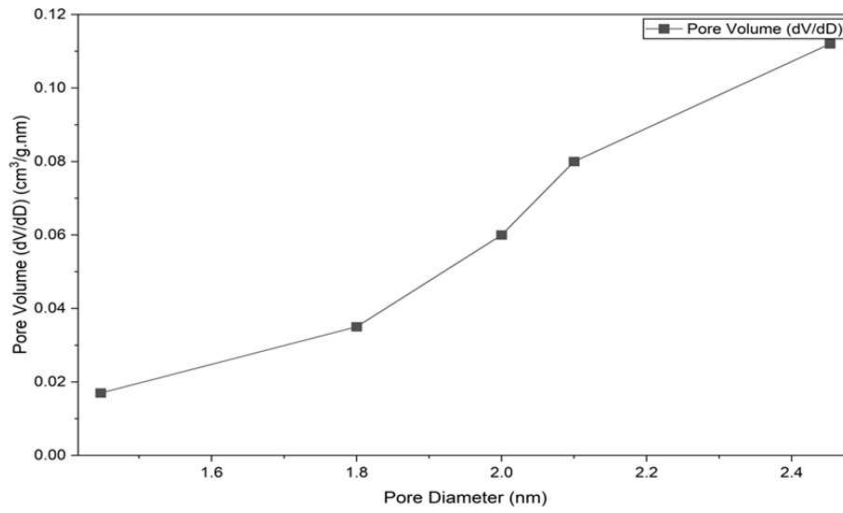


Figure 6(b): BJH Pore Volume Distribution of Rice Husk Ash.

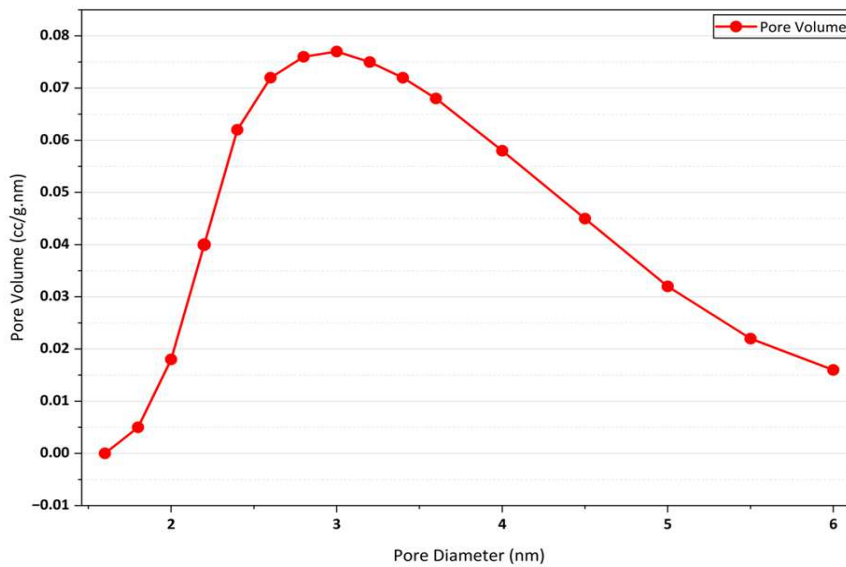


Figure 6(c): DA Plot of Rice Husk Ash.

3.6 Tensile Property

The ultimate tensile strength (UTS) and tensile modulus of the control and RHA-reinforced composites are presented in Figure 7. The UTS increased almost with RHA content, from 13.7 MPa in the control to 16.6 MPa at 10 wt. % RHA, an increase of 21%. This shows that the RHA particles acted as an effective load-bearing reinforcement. The improvement is consistent with the interfacial and morphological characteristics

established such as the rough, angular, and porous particle surfaces providing contact area for mechanical interlocking with the curing resin, and the retained surface silanol groups offer hydrogen-bonding sites capable of interacting with the hydroxyl and amine functionalities generated during epoxy cure [1], supporting efficient interfacial stress transfer from the ductile polymer matrix to the stiffer silica-rich filler under tensile load, in line with the shear-lag micromechanics that govern particulate-reinforced polymers [17, 59]. This trend agrees with reports on RHA and rice-husk-derived silica-reinforced epoxy composites, where tensile strength has similarly been shown to improve with filler incorporation [42, 14, 43, 44]. However, several of these studies report a critical weight fraction beyond which agglomeration begins to depress strength; the absence of such a decline up to 10 wt.% suggests that the critical agglomeration threshold was not reached within the range, possibly aided by the fine, sub-45 μm particle size which gives more uniform dispersion during hand stir casting [31, 53]. The tensile modulus, in contrast. Modulus is a low-strain elastic property and is disproportionately sensitive to voids, agglomerates, and interfacial defects, whereas UTS is a failure-strain property that can benefit from crack-deflection and load-redistribution mechanisms even where local defects exist [26]. Bumper structures require a balance between dimensional stiffness and the capacity to absorb impact energy through controlled deformation rather than brittle fracture [4, 7]. A composite that gains strength without a corresponding sharp rise in stiffness implies a higher strain capacity at a given stress, which supports energy dissipation under impact loading. Bravo-Carrasco et al. [54] reported a comparable balance in silica-nanoparticle-reinforced bumper fascia, where mechanical performance improved up to an optimum filler content.

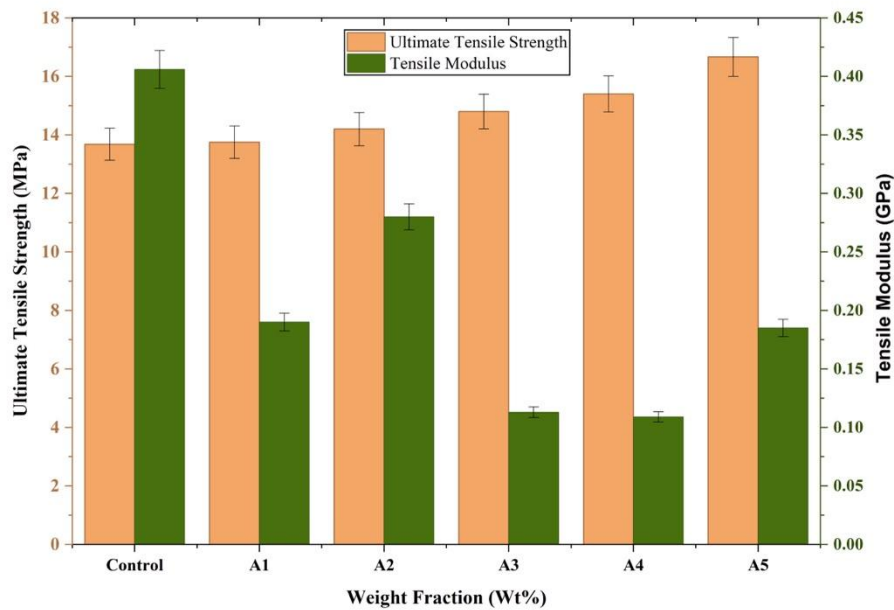


Figure 7: Variation of Tensile properties of Rice Husk Ash Reinforced Composites

3.7 Flexural Property

Flexural strength decreases with RHA addition, from 48.5 MPa for the control to 18.4 MPa for 10 wt. %, while the flexural modulus rose and stayed above the control at every weight fraction, which is inverse of the tensile trend as presented in Figure 8. This inversion follows from the different way strength and modulus are governed under three-point bending. Flexural strength is a weakest-link property because stress peaks only at the outer fibre and falls to zero at the neutral axis, so failure is triggered by whichever single flaw within that thin, highly stressed surface layer is most severe, not by the average defect content of the specimen [60, 58]. A rigid filler introduces this kind of localized critical flaw, wherever a particle sits at or near the tensile surface, it acts as a stress concentrator and preferential crack-initiation site, so even a small amount of RHA is enough to seed a flaw severe enough to dominate the outer-fibre stress field and trigger early failure. Because strength is set by the single worst flaw rather than the total flaw count [20], this also explains why the decline is steep at first and shallow thereafter. Flexural modulus, by contrast as presented in Figure 8, is measured in the small-strain elastic regime before any crack forms, so it reflects a volume-averaged stiffness response rather than the behaviour of any single flaw. The intrinsically stiffer RHA phase raises the composite's bulk stiffness in proportion to its weight fractions, consistent with standard particulate-stiffening behaviour [59].

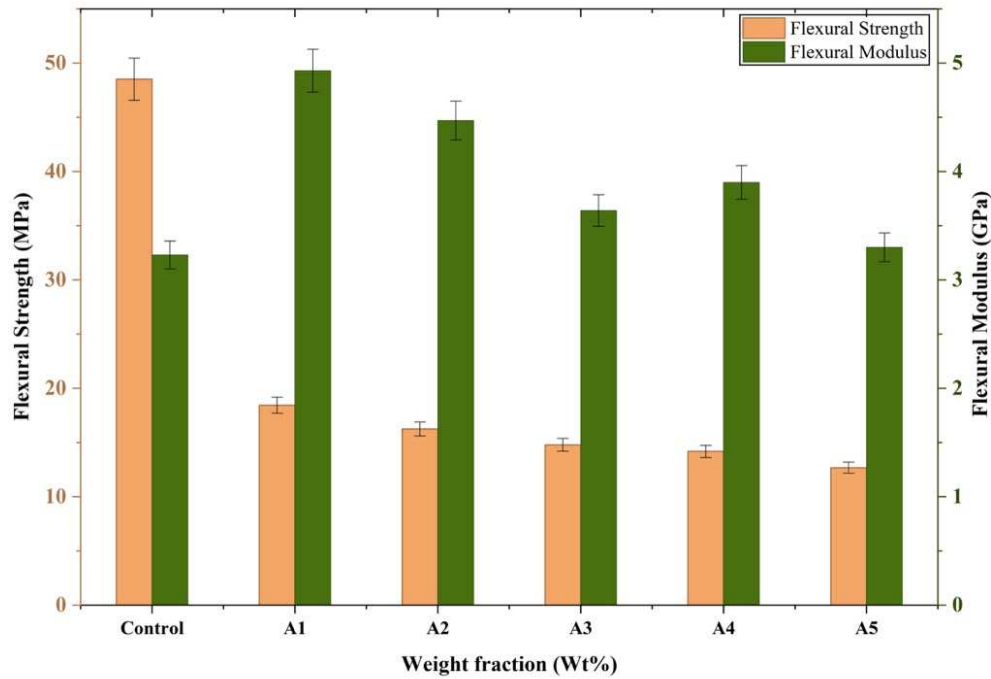


Figure 8: Variation of Flexural properties of Rice Husk Ash Reinforced Composites

3.8 Impact Strength

As presented in Figure 9, increased steadily from 1.56 J/cm² to 2.98 J/cm². A rigid particulate phase dispersed in a brittle epoxy matrix could raise fracture energy through mechanisms such as crack pinning and crack-front bowing around hard particles, which increases the tortuosity and total surface area of the propagating crack; localized interfacial debonding at the particle–matrix boundary, which nucleates microvoids ahead of the crack tip and permits limited plastic shear yielding of the surrounding matrix ligaments; and particle pull-out/frictional sliding, which consumes additional energy as the crack advances [17, 26, 59]. The crack tip encountering an internal pore network within a RHA particle is locally blunted, dissipating strain energy through the creation of new internal surface rather than propagating catastrophically through the particle, in a manner broadly analogous to toughening reported for other porous or hollow rigid fillers in thermoset matrices. This finding is consistent with rice husk/RHA–epoxy studies reporting genuine improvements in fracture toughness and impact resistance with filler incorporation [43, 74, 53]. Impact energy absorption is the primary functional requirement of an automotive bumper, which exists specifically to manage kinetic energy during low- and moderate-speed collisions while protecting the vehicle structure [4, 7, 75]. A composite that simultaneously gains tensile strength and impact toughness,

the two properties most directly tied to crashworthy energy management, while accepting reduced flexural strength represents a favourable trade-off for this specific application, since bumper fascia design prioritizes resistance to impact fracture over flexural load-bearing capacity [54, 15].

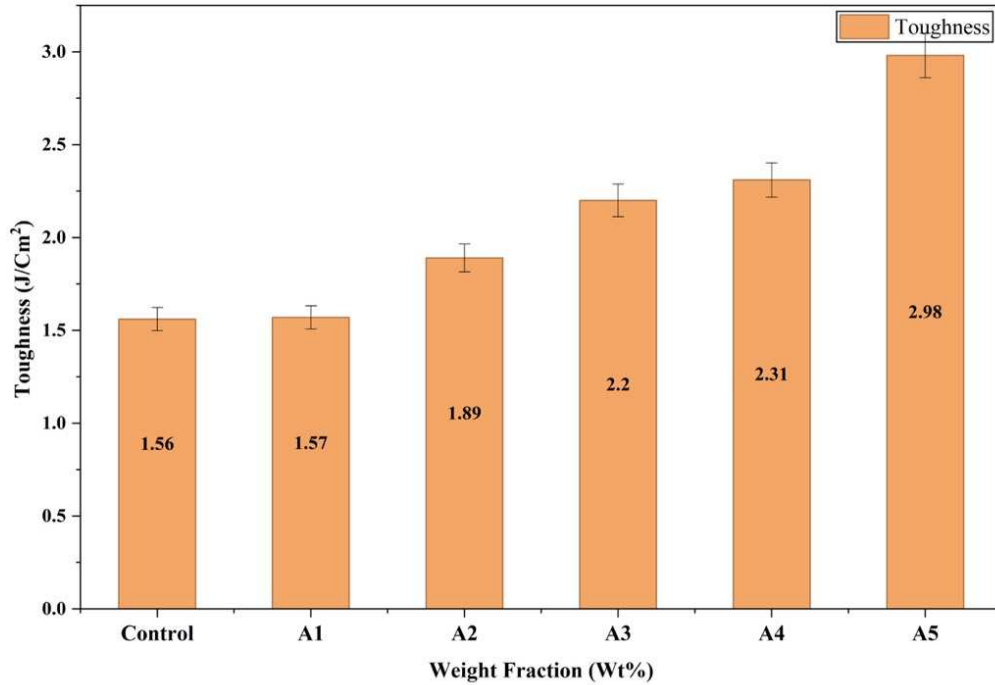


Figure 9: Variation of Impact Strength of Rice Husk Ash Reinforced Composites

3.9 Wear Behaviour

The specific wear rate of the composites is presented in Figure 10. This improvement in wear resistance is well explained by Archard's wear relation, in which wear volume is inversely proportional to the hardness of the contacting surface [17, 58]. The RHA particles, dominated by SiO_2 with an intrinsic hardness exceeding 500 HV are substantially harder than the epoxy matrix. As embedded reinforcement, they act as load-bearing asperities at the sliding contact surface, carrying the applied contact stress and shielding the surrounding, more compliant epoxy from direct abrasive and adhesive contact. This limits micro-ploughing, micro-cutting, and plastic deformation of the matrix, the dominant material-removal mechanisms in unreinforced thermosets [25], and is consistent with reports that particulate agro-waste fillers markedly improve the wear resistance of epoxy composites intended for automotive service [31, 74]. This wear behaviour at higher RHA weight fractions is a benefit alongside the impact performance, since bumper fascia

are subject to repeated low-level abrasive contact and surface degradation over service life, and improved wear resistance directly extends component durability and retained aesthetic/structural performance [7, 34, 9].

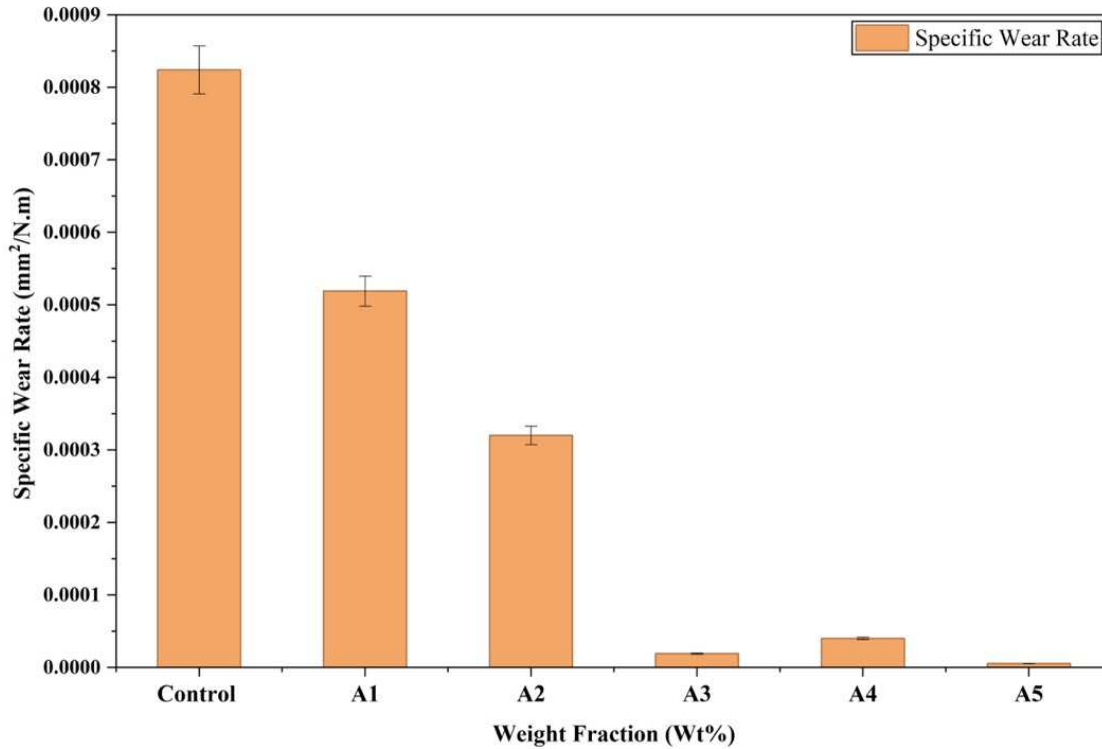


Figure 10: Variation of wear rate of Rice Husk Ash Reinforced Composites

3.10 Examination on Fracture Developed Composites

Fractographic examination of the composites (Figure 11) shows the change in fracture morphology with increase in RHA content. At low RHA contents (A1 and A2), the particles appear well distributed and closely bonded to the epoxy matrix, with little evidence of interfacial separation or particle pull-out. This suggests effective filler–matrix interaction and good stress transfer, which is consistent with the improvement in tensile strength at these compositions [17, 45, 46]. At 6 wt.% RHA (A3), the fracture surface becomes more irregular, with localized particle clustering and evidence of crack deflection around the RHA particles. This increased fracture-path tortuosity can enhance energy dissipation and is consistent with the observed improvement in impact strength [26]. With further addition of RHA (A4 and A5), larger agglomerated regions and voids become apparent. These features show less uniform particle dispersion and

provide preferential sites for crack initiation, which can account for the reduction in flexural strength at higher RHA contents. However, the rigid RHA-rich regions can also contribute to resistance against surface deformation during sliding, supporting the improvement in wear resistance observed with increasing RHA content.

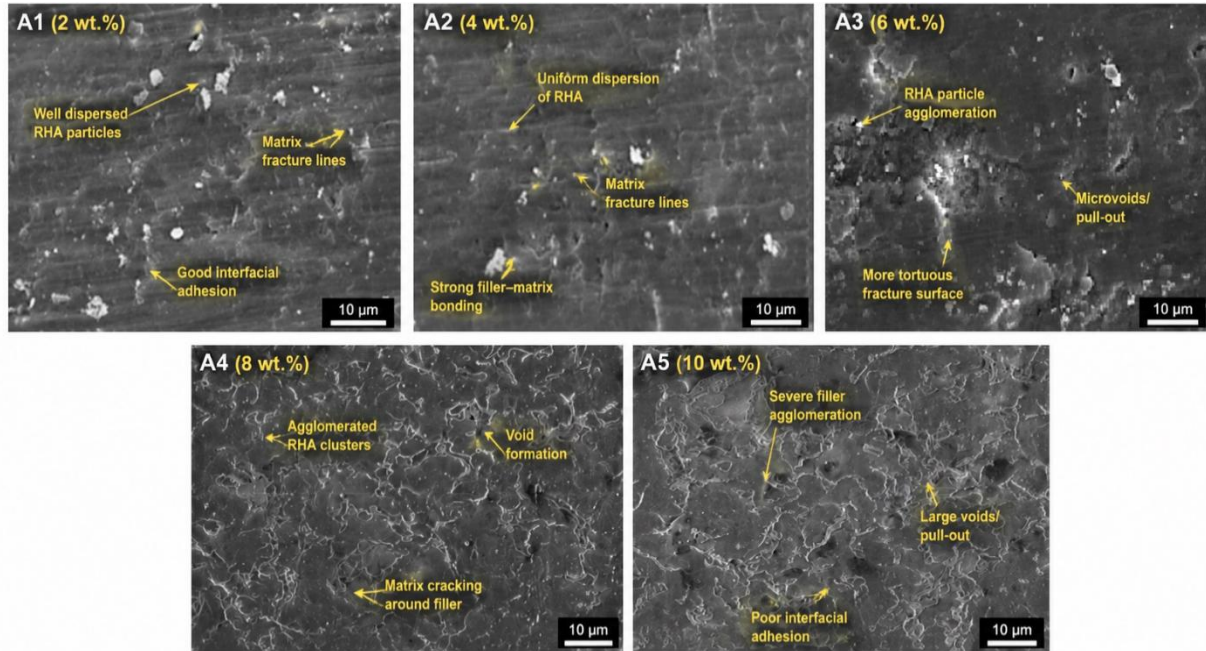


Figure 12: SEM Micrographs of the Fracture Sample across the weight fractions of developed Composites

4. Comparative Benchmark, Limitations and Future Prospects

Table 3 compares the developed RHA–epoxy composites with materials commonly used for automotive fascia bumper applications. The results are comparable with reported values for reinforced thermoplastics used in automotive applications. These results suggest that the RHA–epoxy composite has potential for stiffness-demanding and non-structural automotive components. The present study is limited to a single RHA particle-size fraction ($<45\ \mu\text{m}$), which contributed to the agglomeration observed at higher RHA contents, showing a need for improved dispersion techniques such as ultrasonication. In addition, the current evaluation was performed under quasi-static, room-temperature conditions, which do not fully represent automotive service environments. Further studies should therefore consider high-strain-rate impact behaviour, temperature-dependent mechanical performance, Fire retardation and component-level or crash-simulation assessment. Cost and life-cycle comparisons with conventional TPO and glass-fibre-reinforced systems would also be necessary to establish the practical viability of the composite for automotive applications.

Table 3: Mechanical Properties Comparison of vehicle Classes and Present Study

Vehicle class	Fascia material	Tensile Strength (MPa)	Flexural Modulus (GPa)	Impact Strength	Reference
Compact economy car	TPO (0–10 wt.%) prioritizes flexibility over stiffness	8–15	0.5–1.2	533–2,132 J/m, notched Izod, 23 °C	[11]
Mid-size sedan / crossover	Talc-filled TPO (20–40 wt.% talc), balances stiffness with impact energy management	15–25	1.8–2.5	20–40 J falling-dart, 30 °C	[11, 12]
SUV / larger passenger vehicle	Glass-fibre-reinforced long-fibre thermoplastic, used where structural bumper beam (not just fascia) load-bearing is required	80–120	4.0–6.0	Higher energy absorption than unreinforced TPO, but more brittle failure mode at very low temperature	[12]
Potential Automotive Bumper Application	Carbonized + calcined RHA, <45 µm, hand stir-cast epoxy (0 -10 wt. %)	13.8–16.6	3.3–4.95	1.57–2.98 J/cm ²	This study

5. Conclusion

Rice husk ash (RHA) reinforced epoxy composites were successfully developed using a low-temperature, non-acid-leached processing route. The resulting RHA was SiO₂-rich (77.72%) and retained its mesoporous structure and surface silanol groups, showing that the mild processing conditions were sufficient to produce a functional reinforcement. RHA incorporation improved tensile strength, impact strength, wear resistance, and flexural modulus, with tensile strength increasing from 13.7 to 16.6 MPa and impact strength from 1.56 to 2.98 J/cm². Although flexural strength decreased at higher RHA contents due to particle agglomeration, fractographic observations confirmed the contribution of interfacial bonding and crack deflection to the improved properties. The 10 wt.% RHA composites provided the best overall combination of tensile,

impact, and wear performance and was therefore identified as the most promising formulation for non-structural automotive fascia applications. The low-temperature, acid-free processing route also offers a simpler and potentially more sustainable approach to RHA valorization by reducing thermal requirements and avoiding acid-leaching effluent. The findings reveal the potential of RHA as a sustainable reinforcement for epoxy composites for potential automotive bumper application.

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Author contributions

S.S.L, and R.A.S: writing — original draft, Methodology, Formal analysis, Data curation, Conceptualization, Resources.

A.A.S: Supervision, Project administration, Conceptualization, writing — review and editing, Methodology, Formal Analysis, Visualization

M.A.A: Writing — original draft, Methodology, writing — review and editing, Formal analysis, Project administration, Data Curation, Visualization, Validation, Investigation, Conceptualization

A.A.A: Methodology, Conceptualization, Data curation.

E.N.A and S.T.O: Methodology, Conceptualization, Data curation.

Declaration of Competing Interests

The author has no known competing interests that could have appeared to influence the work reported in the paper.

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Consent to Publish Declaration

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Clinical Trial

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Data Availability Statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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