Journal of Metals, Materials and Minerals, Vol. 32, No. 4, pp. 37-46, 2022

Rice husk ash utilization, composition and properties: A brief review

Vignesh Nayak ULLAL[1,*], Shivaramu H T[1], and Aveen K P[1]

[1]*Department of Mechanical Engineering, Mangalore Institute of Technology & Engineering, Moodabidri-574225, Karnataka, India*

***Corresponding author e-mail:** vignesh@mite.ac.in

Received date:
27 September 2022
Revised date
9 December 2022
Accepted date:
9 December 2022

Keywords:
Rice husk ash (RHA);
Fillers;
Water treatment;
Filter;
Composites

Abstract

Asian countries rely massively on rice to feed and sustain its massive population. For long the staple food has provided nourishment to the masses and the classes. Rice is grown in large quantities in Asian countries. A by-product of its cultivation is its husk. The husk of the rice grain is mainly utilized as a fuel for the boilers in the rice mills. The uncontrolled burnt rice husk referred to as rice husk ash consists majorly of silica. silica is used in a wide variety of commercial and industrial applications. Use of rice husk ash in various products serves to reduce the pollution caused by its pileup in localities especially close to the rice mills. More sustainable and an affordable source of Si would benefit the society rather than disposing rice husk ash in the fields and landfills. This brief review provides insights into the synthesis, applications, and properties of rice husk ash incorporated products either directly in the as received conditions or under modified conditions.

1. Introduction

The production of rice in India was about 120 million tons in fiscal year 2020-2021 [1]. Rice husk is obtained on milling of the paddy grain. The weight fraction of rice husk relative to that of a grain of rice is about 20%. This implies approximately 24 million tons of rice husk was produced in FY 20-21. Burning this amount would result in about 4.8 million tonnes of rice husk ash. This would translate into approximately 720 tonnes of silica [2,3]. Majority of the rice husk obtained after the harvest is used as a fuel material in the boilers owing to its fixed carbon percentage of 10 to 15%. The ash thus obtained after the elimination of cellulose and volatile matter will consist of approximately 90% Silica. Typically, the burnt rice husk either ends up in a landfill creating disposal issues or is sprinkled over the fields to enrich the soil. From the viewpoint of utilization, the burnt by-product is used in a number of applications ranging from fillers, refractory bricks [4], flame retardants, water purifiers, elimination of certain dies from water, derivation of graphene oxide [5], paper, semiconductor, coating for protecting steel, steel making process [6] etc. due to its porous and pozzolanic nature. However, its incorporation in developing or enhancing material property markedly has inherent limitations. Proper control of temperature range during burning, purity level, size and shape of the particles, dispersion and processing challenges and optimal concentration are few of them. In the following sections use of rice husk ash (RHA) in certain applications are discussed.

2. Extraction of silica (SiO_2)

Conventionally sodium silicate which precedes the production of silica is obtained from the reaction sodium carbonate and quartz sand at a temperature ranging from 1100°C to 1300°C [7]. In the as received condition controlled burning below 600°C results in amorphous silica formation. Between 600°C to 1000°C transformation from amorphous to crystalline nature occurs in varying proportions. Above the temperature of 1200°C, a pronounced crystalline form of silica emerges [8]. The quality of the silica thus produced in strongly influenced by the presence of raw materials in the rice husk. The metal oxide impurities present in the raw rice husk can be minimized by pre-treating using acid leaching by HCl [9]. An alkaline-acid method with filtration was shown to extract silica from RHA. The method made use of 10% NaOH and 37% HCl solution followed by heating to obtain silica. Temperatures ranging from 600°C to 800°C were shown to be effective to obtain about 87% yield of Silica from RHA while those beyond 900°C were shown to be detrimental to the yield [3]. pH plays a significant role in such a process as it decides on the level of contamination in the final product. This was shown in a study [10] and the issue was overcome by synthesizing silica at an acidic pH of 4.0 instead of a 7.0 pH using citric or oxalic or hydrochloric acids. The approaches of the research to extract silica from RHA are presented in the Table 1. The processing temperature ranges from 600°C to 1000°C. Majority of them have reported the presence in amorphous silica. Variation of fluidised bed combustion system was the most convenient method used to produce silica.

3. Construction bricks

India is undergoing rapid urbanization. Rising aspirational goals with impetus on affordable housing coupled with unprecedented inflation is driving prices of key building materials to sky high levels. Construction materials are also energy intensive to develop. Bricks are broadly classified as fired and non-fired types. Based on the constituents used they are further named as concrete, calcium silicate and clay bricks

[18]. Rice husk ash has been investigated as a potential material that will increase both affordability and improve the strength of the bricks into which it is incorporated. RHA can be incorporated in three forms based on its appearance into a brick medium. RHA can be classified as fully burnt when it displays white colour under visible lighting condition. It would appear blackish grey under partially burnt condition. An uncontrolled variety would appear as a hybrid of the above two. RHA formed at temperatures beyond 1000°C (majorly whitish in appearance) proved to be better in terms of reduced water absorption, loss on ignition, and higher silica content [19]. A role of mass on processing temperature was reported to be prominent in a study involving pyrolysis. Moreover, the study showed firing at lower temperature is beneficial at higher raw material input compared to that at higher temperatures. Higher proportion of white and grey coloured RHA was found with increased input mass of RH during the controlled pyrolysis experiments. Interestingly higher proportion of completely burnt (white) ash was obtained at a lower temperature of about 700°C and at 25 $m \cdot s^{-1}$ of air flow rate within nine hours. An added benefit of using higher RH content during burning is a reduction in the time required for obtaining a completely burnt RHA. A 23% increase in completely burnt fraction was achieved on an increase of 25% in mass of RH [20]. Reduced linear shrinkage with increased porosity, reduction in flexure strength with increasing concentration of RHA and higher hygroscopic water were the characteristics of the clay bricks with RHA additions. The reduction in the flexure strength was accentuated when the concentration of RHA was increased beyond 10 wt% [21]. A 33% decrease and about 40% increase in the compressive strength and water absorption resulted respectively for the 14% RHA addition. However, the weight of the composite reduced with increased RHA [22]. Investigation on the compressive strength and water absorption for the addition of RH and RHA affirmed that lower quantity of RHA is beneficial while higher ones lead to deterioration. A 2% RHA was shown as the optimum quantity beyond which the bulk density would significantly reduce with increase in porosity [23]. The Los Angeles abrasion values were higher by 7.1%, 12% and 16% for the RHA bricks relative to the 0% RHA clay brick at concentrations of 15, 25 and 35 vol% RHA respectively. This signifies lesser crushing strength for the RHA bricks. The aggregate impact value increased from 29.22 to about 47.29 through 36 and 42 for the 0, 35, 15 and 25 vol% RHA bricks respectively [24] signifying reduced cohesion with increased RHA content. The properties resulting from processing RHA based refractories intended for specific purpose are presented in Table 2. A wide range of temperature and additives are used to invoke specific functional properties (Table 2).

4. Drinking water treatment

The Indian population is slated to reach about 1.5 billion by 2023. This would approximately translate into over 18% of the world's population [32]. Its share of water resource when compared to the world's availability is a feeble 4% only [33]. Pathogens and harmful chemicals plague Indian water bodies, the result of this is that about 0.1% of the population constituting children die by diarrhoea each year [34]. The source of pathogen is mainly due to untreated human and animal wastes that are discharged into nearby waterbodies while the chemical contaminants are either due to human activities or arise from natural causes. Fluorides, Arsenic, Iron and nitrites are the major chemical constituents present in India's water. Of these Fluorides and Arsenic pose serious threat to health. Fluorides are most rampantly found in Rajasthan, Andhra Pradesh, Gujarat, Orrisa and Karnataka. Arsenic is more dominantly detected in the waters of West Bengal, Bihar, Chhattisgarh, UP and Assam [35]. Inner sphere complexes are formed by the adsorption of As on Iron hydroxide. The adsorption is however affected by the presence of other anions like silicates and phosphates in water [36]. Dissolved fluoride and arsenic in water was filtered with the help of aluminium and iron hydroxide-infused RHA respectively. However, for effective elimination from large quantity of water would require periodic monitoring and unclogging the RHA bed [37]. Nevertheless, such an approach to the elimination of heavy metals acts as complementary to techniques such as ion exchange, floatation, coagulation etc. [38]. Another important aspect of water treatment is the elimination of pathogens in water. In the Indian context the most notorious one is the E. Coli [39]. Increased pH of 9, higher contact time of about 30 min and use of 10 $g \cdot L^{-1}$ concentration of silver nanoparticles on the magnetic element were found to be optimal conditions for the effective to eliminate E. Coli in water [40]. The outer cell wall of the E. Coli is adversely affected the by silver nanoparticles paving the way to eliminate them [41]. A controlled experiment involving water spiked with E. Coli tested against RHA infused with nano silver showed the effective significant reduction in the Coli population at dilute concentrations between 0.5 $g \cdot mL^{-1}$ to 4 $g \cdot mL^{-1}$ of nano silver [42]. Copper nanoparticles have also been reported to possess anti-microbial properties again E. Coli [43]. Though such engineered materials eliminate the threat to health by bacteriophages their influence on living species that lead to heightened toxicity levels has been a topic of debate [44]. Also, their recovery from the water sources will be a challenging issue. An eco-friendlier novelle approach to this issue would be the use of alternatives that are natural cleansers and which does not cause any adverse effect. Moringa protein was found to be effective in disinfecting E. Coli. However, a concern in this matter is their organic carbon content which if left suspended in the treated water acts as food for the residual E. Coli. This was overcome by adsorbing moringa proteins on RHA which showed reduced total organic compound by over 99.7% compared to when used in a standalone manner [45]. Absorption characteristics of modified sodium alginate derived from biological source added at various concentration into RHA-silica was investigated. The resulting sponge structure was evaluated for its ability to absorb organic liquids. The 18 vol% of sodium alginate with silica showed that the highest absorption (600 $cm^3 \cdot g^{-1}$) as it had the highest surface and pore volume compared to the other volume fractions [46]. Size constraint and desorption with role of pH to treat contaminated water remains a constraint in the successful commercial implementation of filters using RHA (Table 3).

Table 1. Routes to obtain silica from RHA.

Methods	Experimental variables	Results				Ref.
		Temperature (°C)	Silica content in ash (d.b.wt%)	Unburned carbon content (%)	Silica characteristics	
Fluidised bed combustor system	Inclined feeding & Tangential feeding	685-700	-	-	Amorphous & coarser in the form of slightly broken skeletons	[11]
Grate furnace, fluidized bed, and suspension/entrained combustion	Physical, chemical, thermal, mineralogical, and morphological characteristics of three types of RHA	-	96.71	2.96	Completely amorphous or partially crystalline	[12]
swirling fluidized-bed combustor (SFBC)	Tangential feeding	800-1000	-	0.56-1.80	-	[13]
Expanded Bed	Temperature	700-950	95.00	0.8-1.8	Most amorphous and less crystalline	[14]
Muffle furnace	Temperature residence time	500-900	80.67-91.72	1.5-6.0	Crystalline	[15]
Bubbling FBC	Air velocity temperature	834-877	-	5-9	Most amorphous and less crystalline	[16]
Circulating FBC	Air velocity	752-825	-	3-8	-	[17]

Table 2. Processing of RHA-based construction bricks.

Ref.	Purpose	Composition	Fabrication	Properties
[25]	Insulation	Sludge + URHA 5% and 10 %	Cast, dried at 95°C and Baked at different temperatures of 800, 900, 1000, 1100, and 1200°C for 2 h.	Increased compressive strength to 285 $kg \cdot cm^{-2}$. Lower weight loss on ignition with increasing RHA %. Increased water absorption with increased RHA wt%.
[26]	Sustainable construction material	Diatomaceous earth (DE) + RHA both varied from 32.5 wt% to 50 wt% in steps of 2.5 wt% + with saw dust (SD) addition	Fabricated Specimen size: 220 mm × 110 mm × 65 mm. Addition of of water (40%). Compressed at 10 MPa. Sun and oven dried (60°C) for 3 days and 24 h respectively. Heated to 1200°C and held for about 120 min.	Porosity decreased with the increased SD addition. Highest bending strength and compressive strength of 1.78 MPa and 17.35 MPa respectively were obtained with the 50 wt% concentration.
[27]		Artificial refractory clay (100 wt% to 70 wt%), RHA (10 wt%) and wollastonite microfibers (0 wt% to 20 wt%)	150 mm × 30 mm × 20 mm dimensions. UTM pressed (35 MPa). Oven dried 60°C, 80°C and 105°C until mass stabilization. Sintered at 1000°C in a ceramic fast firing furnace followed by natural cooling.	RHA and microfibres caused increase in the porosity and water absorption.
[28]	Fire-resistant coating	RHA + geopolymer binder (10 wt% to 50 wt%), paint (50 to 90 wt%) in steps of 10 wt%	An activated alkaline to RHA ratio 2.5 coating on steel plates (100 mm × 100 mm ×1.0 mm) with super gloss finish (6000-S) was used.	The optimal RHA-based geopolymer binder (GB) fire retardant (FR) additive was formulated at 50 wt% FR and 82.628 wt% paint
[29]	Thermal insulation	MgO (57 wt%), Quartz (33,23, 13,0 wt%) and RHA (10,20,30, 43 wt%)	Sieving-Dry mixing (30 min) and semi dry mixing (20 min). Water was used as medium for semi-dry mixing. Hydraulic pressed (123 MPa) and fired at 1100°C with heating and cooling rate of $5°C \cdot min^{-1}$ after a soaking period of 2 h	Forsterite phase developed due to reaction between periclase and activated Si of RHA. Increased density and decreased porosity with increased RHA resulted. Lower thermal conductivity was obtained for the higher RHA samples.
[30]	Insulation	Clay (50, 40, 30, 20, 10,0 wt%), fly ash (0, 10, 20, 30, 40, 50 wt%), rice husk (5 wt%), RHA (30 wt%) and fired refractory grog (15 wt%)	Dry ball milled for 20 min at 300 rpm. Water added and semi-dry mixed for 15 min. Rectangular (40 mm × 10 mm × 2.5 mm) samples were prepared by uniaxial hydraulic press (120 MPa). Oven dried at 110°C for 24 h. Fired at different temperatures from 800°C to 1000°C for 2 h in air with heating and cooling rate of $3°C \cdot min^{-1}$.	0 wt% Clay with 50 wt% Fly ash and other constituents mentioned in Colum 2 had the maximum apparent porosity of 53%, minimum bulk density 0.05 $gm \cdot cm^{-3}$ and lowest thermal conductivity.
[31]	Heat absorption	Soda-lime-RHA (69 wt%)	Constituents mixed for 1 h and oven heated at 1400°C for 4 h.	Improved heat absorption in the ultraviolet, visible and infrared region.

Table 3. Pollutant absorption by RHA/modified RHA/derivative of RHA.

Ref.	Absorbent	Absorbate	Instrument	Filtration parameter	Permissible level	Results
[37]	RHA + ferric hydroxide	Arsenic 250 ppb to 300 ppb	Hydride Generator Atomic absorption	Meets standard for 10 L of contaminated water	Arsenic level, WHO 10 ppb	Large quantity of material required to meet the standard of potability
[37]	RHA+ aluminium hydroxide Surface area 30 $m^2 \cdot g^{-1}$ to 50 $m^2 \cdot g^{-1}$	Fluoride 5 ppm	Spectrophotometer fluoride ion probe	Affective for 18 L of contaminated water with 6.72 pH of input water	Fluoride level, WHO 1.5 ppm	Feasible to remove fluoride
[47]	400°C burnt RHA for 1, 2, 3 and 4 h. 24 $m^2 \cdot g^{-1}$ to 201 $m^2 \cdot g^{-1}$ RHA + calcium hydroxide 3.2 $m^2 \cdot g^{-1}$	Phenol 100 $mg \cdot L^{-1}$	Agilent 1100 Series purification system with diode array detector	Up to 64% phenol absorption efficiency in 24 h. by RHA burnt at 400°C for 1 h. Others had lower capability	WHO 0.001 $mg \cdot L^{-1}$	Thermally treated RHA at 400°C between 1 h to 2 h of holding time had higher organic content and larger surface area and were best suited to remove phenol
[48]	Amorphous black RHA 30 g Dry clay 20 g Polyethylene glycol (PEG), 400 Da molecular weight 20 g and 25 g	Petroleum	UV–visible spectrophotometer Atomic absorption spectrophotometer	Reduction in polycyclic aromatic hydrocarbons (PAHs), chloride content, total dissolved solids and reduction in Cu	Cu 1.0 $mg \cdot L^{-1}$ Ni 1.0 $mg \cdot L^{-1}$	Highest reduction in PAHs was found with filter made from RHA and clay having 25 g of PEG.
[49]	Modified RHA of 200 µm, Pore volume 0.38 $cm^3 \cdot g^{-1}$ using HCl and oven dried at 80°C	Chromium, lead, and zinc	SEM with energy dispersive X-ray spectrometer Atomic absorption spectrophotometer FTIR spectroscopy with KBr pellets	Optimal conditions: pH 6 RHA concentration 2.5 $mg \cdot L^{-1}$ absorbate concentration 25 $mg \cdot L^{-1}$ Contact time 60 min. Temperature 30°C	Zinc 5.0 to 15 $mg \cdot L^{-1}$ Cu 0.05 to 1.5 $mg \cdot L^{-1}$	pH influences the absorption of Cr to the highest extent
[50]	RH and RHA 0.4, 0.8, 1.2, 1.6 and 2 $g \cdot L^{-1}$	-	pH, turbidity, electrical conductivity and total solid	79% and 66% reduction in turbidity and total solid respectively with RHA for 30 min contact time	-	Improved water quality without affecting electrical conductivity
[51]	Nano silicon oxide powder (100 nm) derived from RHA 3.125, 31.25 and 62.5 $\mu g \cdot mL^{-1}$	Gram negative E. Coli	Biochemical test	Over 5 times increase in inhibition at 62.5 $\mu g \cdot mL^{-1}$ compared to that at 3.125 $\mu g \cdot mL^{-1}$	-	Antibacterial effect to eliminate E. Coli
[52]	Nanosilica (30 nm to 50 nm) (0.5, 0.75, 1.0 and 1.25 $g \cdot L^{-1}$) from RHA covered with calcium alginate	Gram negative E. Coli	3 M Petrifilm method (PM) Column disinfection (CD)	PM: No E. Coli detected on 60 min contact for the 1.25 $g \cdot L^{-1}$ nanosilica CD: 92% elimination at hydraulic retention time of 20 min	-	Antibacterial effect to eliminate E. Coli

5. Filler material in rubber

Fillers are the class of materials that are primarily used to reduce the cost of the material into which they are incorporated. These materials need to be inert and provide modest increase in the properties of the matrix into which they are placed [53]. The most important aspect of a rubber's performance is the filler material used in it [54]. The reinforcement fillers such as carbon black and silica are mainly added to the polymers with the intention of increasing their mechanical properties. Commercial reinforcements are obtained by processing raw materials procured from unsustainable sources and undergo energy intensive processing to convert them into usable format. ESG considerations are increasingly pushing companies to rethink their use of materials and promote circularity in their usage. Silica contained in the RHA presents as an interesting candidate for such situation. The factors that govern the successful use of filler in the polymer substance includes: size, shape, concentration, purity, coupling agent, etc. used [54,55]. The commercial filler materials used to present in rubber composites are carbonaceous and siliceous along with inorganic (oxides) materials and nanomaterials [55,56]. Detailed discussion on the compounds, materials and the process of preparation of tyre tread in beyond the purview of this review. In a comparative study on commercial silica and commercial silica+RHA, the hardness of the rubber composite increased with increased RHA concentration. The tensile and tear strengths of the test pieces with higher RHA were not in tandem/agreement with the increased hardness value. The concentration of 30 phr for the silica+RHA had better mechanical properties compared to the silica filler alone [57]. Fused, crystallized silica and RHA's properties as fillers were established. The physical characteristics of each of these differed markedly. The surface area of the RHA used was comparable with the crystalline silica and was 289% smaller than that of the fused silica. Also, the average size of RHA was 50% lower than the other two filer types. Significant increase in the moisture, and over 50% reduction in the tensile strength resulted for the RHA at 60 wt% was obtained [58]. Viability and successful part replacement of carbon black with synthesised silica obtained from RHA was demonstrated in a tyre tread. The specific surface area of the derivative was comparable (~ average of commercial and synthesised 108 $m^2 \cdot g^{-1}$) with that of the commercial silica with particle sizes of approximately 5.54 μm. The properties of commercial and synthesised silica were comparable. A 4-stage long processing consisting of early addition of filler, coupling agent and peptizer with other compounder used in acceleration and hardening added in the ensuing stages was followed to achieve the end product [59]. It is evident from the publications that a dominant factor that affects the properties is the surface area of the RHA or rice husk silica (RHS) used. Larger the surface area better are the properties. But smaller the particle size higher will be the tendency towards agglomeration which would warrant the use of dispersion agents. The properties resulting from the incorporation of RHA/RHS as fillers are given in Table 4. Surface area and particle size are crucial parameters that primarily affect the dispersion of RHA in rubber. Equally important is the use of a coupling agent which improves dispersion and increases higher utilization and faster curing of rubber.

6. Reinforcement in polymer and metal matrix composites

The refractory nature, high hardness and cheap availability of silica from RHA coupled with obtainment from bio sources makes it an ideal candidate to be used as a reinforcement in composite material. Modified, processed RHA and nano silica explored for their mechanical properties lead to the findings that increased density of the epoxy composite with modified ash while tensile, flexure, and impact strengths were the highest for the 1.5 phr concentration [68]. This ascertains the significance of two parameters namely: surface area and optimum loading. A dual mode of stir casting followed by powder metallurgy was used to obtain a Hybrid composite. It comprised of various fraction of reinforcements of clay and RHA in aluminium matrix. The results of mechanical tests such as impact, tensile and hardness showed increased values of properties up to a concentration of 7.5 wt% of reinforcements which thereafter were lowered [69]. The tensile strength of AA6061 alloy was increased by about 7% on addition of 8 wt% RHA reinforcement with higher electrical conductivity of 3.6 Ωm^{-1} (125%) over the nonreinforced aluminium alloy. However, no information on the stir casting processing parameters were mentioned [70]. Contact angle measurements of Al alloys with low and high Mg content on B_4C-10% crystalline RHA substrate under two atmospheric conditions were done. The relaxation plot showed that the superior wetting (42°) at 1200°C resulted for the Al-Mg alloy with approximately 13% Mg (high Mg alloy) under N_2 atmosphere [71]. The properties of the AA6603 alloy with RHA and Areca sheath ash were higher and better dispersion in the matrix was achieved at higher concentrations of 6% and 8%. Counterintuitively poor dispersion was reported at lower concentrations despite the use of Mg as a wettability enhancer. Higher hemi cellulose in areca ash resulted in higher carbon content in the composite leading to slightly lower properties compared to RHA [72]. Evaluation of mechanical properties for the RHA and RHA+B_4C in AA6028 alloy, hybrid composites are superior to those of RHA ones. However, incorporation of RHA significantly enhanced the properties of the AA6028 alloy and were only marginally (6% for hardness and flexure and 22% for impact, at concentrations between 2.5% for RHA and 5% for the RHA+5%B_4C) lower than those of the hybrid used [73]. Increased percentage of Mg added during stir casting of RHA-AA6028 matrix resulted void free composite with 33% increase in BHN, 16% increase in tensile strength and an unusual 61% increase in elongation for the 8% (due to rod like shaped RHA with smooth edges) RHA over the base alloy [74]. AA7071-RHA-B_4C composites casted under vacuum and were tested for their mechanical and wear properties. A composition of 8% reinforcements was considered as optimum based on the incremental enhancement in hardness measurement. The tensile and flexure strength were found to be significantly enhanced by the addition of reinforcements which was mainly attributed to the presence of B_4C element. About 36% increase in wear resistance was attained with 8% reinforcements compared to the unreinforced alloy [75]. The most popular method to process metal matrix composites is casting followed by powder metallurgy (Table 5). The maximum concentration that was successfully incorporated in the matrix ranged between 10 wt% or below in most of the cases.

Table 4. Influence of RHA and coupling agent on the properties of tyre tried.

Ref.	Fillers	Concentration (phr)	Coupling agent	Properties	Result
[59]	CB Amorphous: RHA derived silica 104 $m^2 \cdot g^{-1}$ and commercial silica (CS) 112 $m^2 \cdot g^{-1}$	RHS and commercial Si 15, 30 and 50 independently Total filler 60	Si69	Comparable properties between RHS and commercial silica. 11% higher abrasion loss for the 15 phr RHA compared to 50 phr CS (89 mm^3) Least tan delta for the 15 phr concentration	Use 15phr RHS over 15 phr CS to replace CB
[60]	Superfine amorphous precipitated silica with 2.4% carbon and 81 $m^2 \cdot g^{-1}$ BET Carbon black (CB)	RHA 22.5 45.0 67.5 90.0 Total filler 90	Silane	Reduced Mooney viscosities by 21, 8, 6 and 32% for the concentrations respectively. Highest tensile strength with 22.5% RHA Lower hardness, elongation, tear strength and abrasion resistance with increased RHA	Recommends approximately substitution of 25% CB with RHA
[61]	RHA commercial silica	RHA 20 commercial silica 20	Si69	Minimal effect of Si69 (2 phr) on cure time. Least scotch time with RHA+Si69. Torque withstanding capacity enhanced for RHA+Si69 compared to silica. Lower modulus, tensile, hardness and elongation for RHA compared to commercial silica.	Reduced size of RHA with Si69 required to improve properties compared to commercial silica.
[62]	Nanosilica synthesised from RHA	2, 6 and 10 wt%	None	Significant reduction in wear rate compared to no filler material	10 wt% had the least and constant wear rate at loads of 5, 10 and 15 N.
[63]	RHA	40, 50, 60 and 70	None	Scorch time and torque characteristics increased with RHA concentration. Reduced tensile Stable compressive strength, lower elongation and increased hardness with increased concentration.	Ascertains feasibility of RHA use at concentrations lower than 40 phr.
[64]	Modified RHA (50 nm to 100 nm)	0, 1, 2, 4, 6, 8, and 10	Rare earth, DN-8102	Modulus of elongation increased (over 55% higher compared to 0 phr) with concentration of RHA. Max. tensile strength at 4 phr of RHA. Reduced elongation at break with increased RHA phr	Modification is essential for mitigation agglomeration and increasing bonding between rubber and RHA which increases mechanical strength.
[65]	Commercial silica (165 $m^2 \cdot g^{-1}$, 18 µm) White RHA. WRHA (75 $m^2 \cdot g^{-1}$, 45 µm)	Commercial Silica 10, 15, 20, 25 and 60 WRHA 15, 30, 45 and 60	Silane	60 phr WRHA- Least rebound resilience and tensile strength. Abrasion volume loss increased with WRHA phr. Hybrids of WRHA+ commercial silica were more comparable to 60 phr commercial silica	RHA+silica with 45 and 20 phr hybrid was the best blend. Implies partial substitution is preferred over complete ones.
[66]	Waste tire rubber (0.54, 1.65, and 2.8 mm) RHA (<75 µm) Starch sludge, SS (<75µm) Carbon black Commercial silica	SS, RHA 10, 20 and 30	Maleated natural rubber (2.4, 5 and 7 phr) and Si69 (5 phr)	RHA better compared to waste tire rubber and starch sludge in tensile strength	Maleated natural rubber with RHA better than Si69+RHA
[67]	RHA (3.83 µm, 0.91 $m^2 \cdot g^{-1}$) Commercial Silica (0.018 µm, 173 $m^2 \cdot g^{-1}$)	RHA-10, 20, and 30 Commercial silica 30	Si69	Faster curing with increased RHA phr with further increase in addition of couplant. Si69 significantly increased modulus for the 30 phr RH. RHA 30 phr rolling friction was the least	Oxide impurities in RHA increase degradation of rubber matrix. Commercial silica with Si69 was the best due to its smaller size.

Table 5. Properties of aluminium/polymer-RHA composites.

Ref.	Composition	Production technique	Characteristics
[76]	Al + RHA (0, 5, 10 & 15 wt%) +SiC (10 wt%)	Powder metallurgy	Maximum hardness noticed for Al+SiC+10%RHA composite. The minimum wear loss and COF was found for Al+10%SiC+ 10%RHA composite
[77]	Al alloy + RHA 0-30 vol% (rate of increment is 5 vol%)	Casting	The maximum Ultimate tensile strength of 181.140 MPa, impact strength of 155.244 $J{\cdot}m^{-2}$ at 10% RHA and hardness of 109 HRV at 25 vol% RHA was recorded.
[78]	Al + 3, 6 and 9 wt% of RHA	Stir casting	Lower density of 2.62 $g{\cdot}cm^{-3}$, higher yield strength of 61MPa, tensile strength of 115.32 MPa, and hardness of 33.6 BHN was noticed for 9% RHA reinforced composite.
[69]	A6061+RHA (2.5-10 wt%) + clay	Stir casting	Hardness (20.4 BHN) for 7.5 wt% RHA and tensile strength increased with the addition of RHA in compared to base material
[79]	Al-7068 + RHA (0,4,6,8 wt%) + SiC (0,4,6 wt%)	Powder metallurgy	Maximum Compressive strength of 198.04 MPa for Al7068 + 8% RHA + 0% SiC composite and hardness of 97 BHN for Al7068 + 0% RHA + 6% Sic was found.
[80]	Al + RHA (10% and 15 wt%)	Powder metallurgy	Higher cutting speed was suitable for the machining the prepared composites.
[81]	Al + RHA (10, 15 and 20 wt%)	Powder metallurgy	Higher tensile strength of 5.19 MPa for Al + 15 wt% RHA composition was observed.
[82]	AA6063 + RHA (1.25, 2.5, 3.75, 5, 6.25, 7.5, 8.75, 10 wt%) carbonized and uncarborized	Stir casting	Higher specific strength (65.57 kN $m{\cdot}Kg^{-1}$) for 8.75 wt%, lower thermal expansion (50.98 mm^3) for 6.25 wt% and minimum corrosion loss (0.17 mg) for 5 wt% of carbonized RHA composition composite. The 7.5 wt% carbonized RHA gave higher hardness of 89 HRB.
[83]	AA6061+ RHA (0, 2, 4, 6, 8 wt%)	Compocasting	The wear rate increased with the increase of applied and however the wear rate decreased with the increase of RHA wt%. The AA6061+ 8 wt% RHA emerged as wear resistive material.
[84]	Epoxy + Nanoclay + RHA Biosilica + 40 vol% ramie fiber	Hand layup	Tensile strength (254 MPa), Flexural strength (284 MPa), Izod impact (6.95 J), Hardness (93 Shore-D) showed for surface treated Epoxy (54) + Ramie Fibre (40) + Nanoclay (5) + Biosilica (1) vol% composite.
[85]	Polypropylene (PP) + 15 wt% rice husk (RH) and polypropylene (PP) +15 wt% rice husk ash (RHA)	Injection molding	PP/RHA composite showed 4% higher tensile strength in compared to PP/RH composite

7. Conclusions

A variety of products and applications with enhanced properties using RHA can be realized. Pileup and disposal issues related to RHA would be minimized through valorizations. Affordability of materials would be improved by the use of silica extracted from relatively cheap and widely available waste RHA especially in southeast Asian countries that primarily consume rice. This brief review provides insights into the synthesis, applications, and properties of rice husk ash incorporated productseither directly in the as-received conditions or under modified conditions. Nanoparticle infiltrated RHA filters showed that they are capable of enhancing water quality by eliminating pathogens. Composites developed using RHA have shown improved mechanical properties that meet the benchmark values. Such materials would reduce the carbon footprint involved in their manufacturing. RHA as fillers have shown their potential in enhancing mechanical and wear properties of conventional materials. A maximum limit of about 8% has been shown in the number of research publications. The role of Mg as a wettability enhancer is evidenced from the works of researchers and is vital to improve dispersion of RHA in the matrix of metals.

References

[1] "Top 10 rice producing states in india-largest rice producer," Blog - Tractor Junction, 01-Apr-2022. [Online]. Available: https:// www.tractorjunction.com/blog/top-10-rice-producing-states-in-india/. [Accessed: 23-Sep-2022].

[2] N. Phonphuak and P. Chindaprasirt, "Types of waste, properties, and durability of pore-forming waste-based fired masonry bricks", *Eco-efficient masonry bricks and blocks*, pp. 103-127, 2015.

[3] A. Daulay, and S. Gea, "Effect of variation temperature at burning rice husk to obtain silica," in *AIP Conference Proceedings*, vol. 2342, AIP Publishing LLC, 2021.

[4] S. K. Shukla, "Rice husk derived adsorbents for water purification," in *Green Materials for Wastewater Treatment*, Springer International Publishing, 2020, pp. 131-148.

[5] T.-H. Liou, and P.-Y. Wang, "Utilization of rice husk wastes in synthesis of graphene oxide-based carbonaceous nano-composites," *Waste management*, vol. 108, pp. 51-61, 2020.

[6] 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, 2021.

[7] "TIMEIS," Techno-preneur.net. [Online]. Available: https://www.techno-preneur.net/technology/new-technologies/chemicals-tec/sodium.html.

[8] L. Sun, and K. Gong, "Silicon-based materials from rice husks and their applications," *Industrial & engineering chemistry research*, vol. 40, no. 25, pp. 5861-5877, 2001.

[9] C. Real, M. D. Alcala, and J. M. Criado, "Preparation of silica from rice husks," *Journal of the American Ceramic Society*, vol. 79, no. 8, pp. 2012-2016, 1996.

[10] U. Kalapathy, A. Proctor, and J. Shultz, "An improved method for production of silica from rice hull ash," *Bioresource technology*, vol. 85, no. 3, pp. 285-289, 2002.

[11] M. Rozainee, S. P. Ngo, A. A. Salema, and K. G. Tan, "Effect of feeding methods on the rice husk ash quality in a fluidised bed combustor," *Emirates Journal for Engineering Research*, vol. 15, pp. 1-12, 2010.

[12] I. J.Fernandes, D. Calheiro, A. G. Kieling, C. A. M.Moraes, T. L. .A.C.Rocha, F. A.Brehm, R.and C.E.Modolo,"Characterization of rice husk ash produced using different biomass combustion techniques for energy," *Fuel*, vol. 165, pp. 351-359, 2016.

[13] V. I. Kuprianov, R. Kaewklum, K. Sirisomboon, P. Arromdee, and S. Chakritthakul, "Combustion and emission characteristics of a swirling fluidized-bed combustor burning moisturized rice husk," *Applied Energy*, vol. 87, no. 9, pp. 2899-2906, 2010.

[14] R. Blissett, R. Sommerville, N. Rowson, J. Jones, and B. Laughlin, "Valorisation of rice husks using a TORBED® combustion process," *Fuel Processing Technology*, vol. 159, pp. 247-255, 2017.

[15] D. K. Bangwar, A. Saand, M. A. Keerio, M. A. Soomro, and N. Bhatti, "Development of an amorphous silica from rice husk waste. Engineering," *Technology & Applied Science Research*, vol. 7, no. 6, pp. 2184-2188, 2017.

[16] L. Armesto, A. Bahillo, K. Veijonen, A. Cabanillas, and J. Otero, "Combustion behaviour of rice husk in a bubbling fluidised bed," *Biomass Bioenergy*, vol. 23, no. 3, pp. 171-179, 2002.

[17] M. A. Hamad and I. A. Khattab, "Effect of the combustion process on the structure of rice hull silica," *Thermochimica Acta*, vol. 48, no. 3, pp. 343-349, 1981.

[18] D. D. Bui, J. Hu, and P. Stroeven, "Particle size effect on the strength of rice husk ash blended gap-graded Portland cement concrete," *Cement and concrete composites*, vol. 27, no. 3, pp. 357-366, 2005.

[19] I. Johari, S. Said, R. P. Jaya, B. H. A. Bakar, and Z. A. Ahmad, "Chemical and physical properties of fired-clay brick at different type of rice husk ash," *International Conference on Environmental Science and Engineering*, vol. 8, pp. 171-174, 2011.

[20] R. Sigalingging, E. Susanto, and S. Panggabean, "The effect of rice husk mass on temperature and characteristics of its ash using a pyrolysis equipment organic-inorganic waste," *Conference Series: Earth and Environmental Science*, vol. 454, no. 1, p. 012043, 2020.

[21] F. Andreola, I. Lancellotti, T. Manfredini, F. Bondioli, and L. Barbieri, "Rice husk ash (RHA) recycling in brick manufacture: Effects on physical and microstructural properties," *Waste Biomass Valorization*, vol. 9, no. 12, pp. 2529-2539, 2018.

[22] A. A. M. Damanhuri, A. M. H. S. Lubis, A. Hariri, S. G. Herawan, M. H. I. Roslan, and M. S. F. Hussin, "Mechanical properties of rice husk ash (rha) brick as partial replacement of clay," *Journal of Physics: Conference Series*, vol. 1529, no. 4, p. 042034, 2020.

[23] J. Sutas, A. Mana, and L. Pitak, "Effect of rice husk and rice husk ash to properties of bricks," *Procedia Engineering*, vol. 32, pp. 1061-1067, 2012.

[24] R. S. Huq, and C. Farhana, "Use of rice husk ash as substitute to make clay bricks," *International Journal of Engineering Research and Applications*, no. 10, 2018.

[25] E. M. M. Ewais, R. M. Elsaadany, A. A. Ahmed, N. H. Shalaby, and B. E. H. Al-Anadouli, "Insulating refractory bricks from water treatment sludge and rice husk ash," *Refractories and Industrial Ceramics*, vol. 58, no. 2, pp. 136-144, 2017.

[26] N. H. Thang, "Novel porous refractory synthesized from diatomaceous earth and rice husk ash," *Journal of Polymer Composites*, vol. 8, pp. 128-137, 2020.

[27] D. Silva, E. Pachla, E. Marangon, M. Tier, and A. P. Garcia, "Effects of rice husk ash and wollastonite incorporation on the physical and thermal properties of refractory ceramic composites," *Matéria(Rio de Janeiro)*, vol. 25, no. 3, 2020.

[28] M. N. Abdullah, M. Mustapha, N. Sallih, A. Ahmad, F. Mustapha, and A. Dahliyanti, "Study and use of rice husk ash as a source of aluminosilicate in refractory coating," *Materials (Basel)*, vol. 14, no. 13, p. 3440, 2021.

[29] S. K. S. Hossain, L. Mathur, P. Singh, and M. R. Majhi, "Preparation of forsterite refractory using highly abundant amorphous rice husk silica for thermal insulation," *Journal of Asian Ceramic Societies*, vol. 5, no. 2, pp. 82-87, 2017.

[30] S. K. S. Hossain and P. K. Roy, "Fabrication of sustainable insulation refractory: Utilization of different wastes," *Boletín de la Sociedad Española de Cerámica y Vidrio*, vol. 58, no. 3, pp. 115-125, 2019.

[31] G. Berkin, "Heat absorbing glass from rice husk ash for a sustainable environment," in *Waste Management and the Environment IV*, 2008.

[32] "India population (2022) - worldometer," *Worldometers.info*. [Online]. Available: https://www.worldometers.info/world-population/india-population/.

[33] http://ttps://www.worldometers.info/world-population/india-population/

[34] "How water pollution in India kills millions," BORGEN, 14-Jul-2020. [Online]. Available: https://www.borgenmagazine.com/water-pollution-in-india/.

[35] "Ground water quality features of the country," Gov.in. Available: http://cgwb.gov.in/WQ/GROUND%20WATER%20QUALITY%20SCENARIO%20IN%20INDIA.pdf

[36] S. Bang and X. Meng, "Research papers : A review of arsenic interactions with anions and iron hydroxides," *Environmental Engineering Research*, vol. 9, no. 4, pp. 184-192, 2004.

[37] C. Malhotra, R. Patil, S. Kausley, and D. Ahmad, "Novel uses of rice-husk-ash (a natural silica-carbon matrix) in low-cost water purification applications," *AIP Conference Proceedings*, vol. 1538, no. 1, pp. 113-119, 2013.

[38] Ground water quality features of the country, Central ground water board report.2020.

[39] A. Bivins, S. Lowry, H. M. Murphy, M. Borchardt, R. Coyte, P. Labhasetwar, and J. Brown, "Waterborne pathogen monitoring in Jaipur, India reveals potential microbial risks of urban groundwater supply," *npj clean water*, vol. 3, no. 1, 2020.

[40] S. Asadi, and F. Moeinpour, "Inactivation of Escherichia coli in water by silver-coated NiO. 5ZnO. 5Fe_2O_4 magnetic nanocomposite: a Box-Behnken design optimization," *Applied Water Science*, vol. 9, no. 1, pp. 1-9, 2019.

[41] "Tata uses nano technology for water purifier," *Cseindia.org.* [Online]. Available: https://www.cseindia.org/tata-uses-nano-technology-forwater-purifier-852.

[42] A. M. Gutierrez, D. Hotza, G. B. Dutra, A. L. Nogueira, C. V. Franco, W. Acchar, and C. R. Rambo, "Rice husk ash impregnated with silver nanoparticles for water purification," *Materials Science Forum*, vol. 798-799, pp. 727-731, 2014.

[43] D. Longano, N. Ditaranto, L. Sabbatini, L. Torsi, and N. Cioffi, "Synthesis and antimicrobial activity of copper nanomaterials," in *Nano-Antimicrobials*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 85-117.

[44] Z. Ferdous and A. Nemmar, "Health impact of silver nanoparticles: A review of the biodistribution and toxicity following various routes of exposure," *International Journal of Molecular Sciences*, vol. 21, no. 7, p. 2375, 2020.

[45] J. Barajas, J. Latayan, S. Pagsuyoin, F. Bacani, J. Santos, R. Tan, A. Orbecido, L. Razon, and M. Almendrala, "Water disinfection using moringa protein adsorbed on rice husk ash," in *2016 IEEE Systems and Information Engineering Design Symposium (SIEDS)*, 2016.

[46] X. Han, J. Liang, S. Fukuda, L. Zhu, and S. Wang, "Sodium alginate–silica composite aerogels from rice husk ash for efficient absorption of organic pollutants," *Biomass and Bioenergy*, vol. 159, p. 106424, 2022.

[47] S. B. Daffalla, H. Mukhtar, and M. S. Shaharun, "Preparation and characterization of rice husk adsorbents for phenol removal from aqueous systems," *PLoS One*, vol. 15, no. 12, p. e0243540, 2020.

[48] J. O. Madu, F. V. Adams, B. O. Agboola, B. D. Ikotun, and I. V. Joseph, "Purifications of petroleum products contaminated water using modified rice husk ash filters," *Materials Today: Proceedings*, vol. 38, pp. 599-604, 2021.

[49] A. K. Priya., V.Yogeshwaran, S. Rajendran, T. K. A.Hoang, M. Soto-Moscosoe A. A. Ghfarf, and C. Bathula,"Investigation of mechanism of heavy metals (Cr_6^+, Pb_2^+& Zn_2^+) adsorption from aqueous medium using rice husk ash: kinetic and thermodynamic approach," *Chemosphere*, vol. 286, 2022.

[50] A. Anjitha, and D. Goerge, "Comparative study using rice husk and its ash as natural coagulants in waste water treatment," *International Journal of Scientific and Engineering Research*, vol. 7, no. 4, pp. 232-237, 2016.

[51] M. Ali, and A. A-Ali Drea, "Green synthesis and characterization of antibiotic amorphous nano silicon oxide powder extracted from rice husk ash," *International Journal of Current Research and Review*, vol. 13, no. 24, pp. 94-99, 2021.

[52] L. Ravindran, K. Jesitha, P. U. Megha, S. Anilkumar, M. S. Sreekala, and P. S. Harikumar, "Nanosilica entrapped alginate beads for the purification of groundwater contaminated with bacteria," *Silicon*, pp. 1-14, 2022.

[53] R. B. Seymour, "The role of fillers and reinforcements in plastics technology," *Polymer-Plastics Technology and Engineering*, vol. 7, no. 1, pp. 49-79, 1976.

[54] D. S. Chaudhary, M. C. Jollands, and F. Cser, "Understanding rice hull ash as fillers in polymers: A review," *Silicon Chemistry*, vol. 1, no. 4, pp. 281-289, 2002.

[55] K. Song, "Micro-and nano-fillers used in the rubber industry," in *Progress in Rubber Nanocomposites*, Woodhead Publishing, 2017, pp. 41-80.

[56] C. D. M. Dominic, A. Balan, K. V. Neenu, P. M. S. Begum, D. Joseph, P. Dileep, R. Joseph, M. J. Jaison, M. Mathew, C. S. Dhanya, M. Badawi, and J. Parameswaranpillai, "Sustainable Kerala rice husk ash for formulation of basic tyre tread: Taking first step," *Sustainable Materials and Technologies*, vol. 32, 2022.

[57] V. C. Sethuramalingam, S. Prabagaran, and K. Ganesan, "Studies on influence of silica filler and rice husk ash on the mechanical properties of vulcanized hybrid rubber composite," *Materials Today: Proceedings*, vol. 37, pp. 2207-2213, 2021.

[58] J. Suwanprateeb, and K. Hatthapanit, "Rice-husk-ash-based silica as a filler for embedding composites in electronic devices," *Journal of applied polymer science*, vol. 86, no. 12, pp. 3013-3020, 2002.

[59] N. S. Chundawat, B. S. Parmar, A. S. Deuri, D. Vaidya, S. Jaduon, P. Zarrintaj, M. Barani, and N. P. S. Chauhan "Rice husk silica as a sustainable filler in the tire industry," *Arabian Journal of Chemistry*, vol. 15, no. 9, p. 104086, 2022.

[60] M. R. S. Fernandes, A. M. F. de Sousa, and C. R. G. Furtado, "Rice husk ash as filler in tread compounds to improve rolling resistance," *Polímeros*, vol. 27, no. 1, pp. 55-61, 2017

[61] A. Boonmee, P. Sabsiriroht, and K. Jarukumjorn, "Preparation and characterization of rice husk ash for using as a filler in natural rubber," *Materials Today: Proceedings*, vol. 17, pp. 2097-2103, 2019.

[62] S. Burhan, M. Abed, M. Salih, Karbala Iraq, and Al-Furat, "Rice husk ash as a nano-filler to synthesize thermosetting polymer nanocomposites and evaluation of its tribological behavior," *Kufa Journal of Engineering.*, vol. 10, no. 1, pp. 78-91, 2019.

[63] Rahmaniar, and T. Susanto, "Impacts of rice husk ash filler loading on curing, morphological characteristics and tensile properties of natural rubber/ethylene propylene rubber blends," *IOP Conference Series: Materials Science and Engineering*, vol. 509, p. 012116, 2019.

[64] Z. Zeng, Y. Li, P. Zhao, and H. Yu, "Fabrication of rice husk ash/natural rubber composites by the latex process," *Journal of Wuhan University of Technology (Materials Science Edition)*, vol. 35, no. 1, pp. 42-46, 2020.

[65] D. Iluppalla, S. Ranatunga, and S. Siriwardena, "Silica/white rice husk ash hybrid filler for rubber composites for the manufacture of low speed castor wheel rubber treads," *Journal of the Rubber Research Institute of Sri Lanka*, vol. 100, p. 38, 2020.

[66] D. Dechojarassri, N. Ratikant, S. Charoenrat, and P. Danwanichakul, "Mechanical properties of natural rubber composites filled with starch sludge compared with other waste and commercial fillers," *IntInternational Journal of Chemical Engineering and Applications*, vol. 8, no. 3, pp. 210-215, 2017.

[67] W. Pongdong, C. Nakason, C. Kummerlöwe, and N. Vennemann, "Influence of filler from a renewable resource and silane coupling agent on the properties of epoxidized natural rubber vulcanizates," *Journal of Chemistry*, vol. 2015, pp. 1-15, 2015.

[68] E. P. Ayswarya, A. B. Nair, and E. T. Thachil, "A comparative study of mechanical, dynamic mechanical and thermal properties of rice husk ash, modified rice husk ash and nano silica filled epoxy composites," *Materials Today: Proceedings*, vol. 47, pp. 5351–5357, 2021.

[69] 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, 2021.

[70] N. E. Udoye, A. O. Inegbenebor, and O. S. I. Fayomi, "The analysis on electrical conductivity of AA6061/rice husk ash composites," *Materials Today: Proceedings*, vol. 43, pp. 2245-2249, 2021.

[71] A. Bahrami, N. Soltani, M. I.Pech-Canul, S. Soltani, L. A. González, C. A. Gutiérrez, J. Tapp, A. Möller, and A. Gurlo, "Bilayer graded Al/B4C/rice husk ash composite: Wettability behavior, thermo-mechanical, and electrical properties," *Journal of Composite Materials*, vol. 52, no. 27, pp. 3745-3758, 2018.

[72] P. P. Kulkarni, and B. Siddeswarappa, "A study on microstructure and mechanical behaviour of AA6063 metal matrix composite reinforced with areca sheath ash (ASA) and rice husk ash (RHA)," *Materials Today: Proceedings*, vol. 52, pp. 445-451, 2022.

[73] M. P. Chakravarthy, and D. Santha Rao, "Evaluation of mechanical properties of aluminium alloy (AA 6082) reinforced with rice husk ash (RHA) and boron carbide (B_4C) hybrid metal matrix composites using stir casting method," *Materials Today: Proceedings*, vol. 66, pp. 580-586, 2022.

[74] N. E. Udoye, O. J. Nnamba, O. S. I. Fayomi, A. O. Inegbenebor, and K. J. Jolayemi, "Analysis on mechanical properties of AA6061/Rice husk ash composites produced through stir casting technique," *Materials Today: Proceedings*, vol. 43, pp. 1415-1420, 2021.

[75] A. Kumar and M. Kumar, "Mechanical and dry sliding wear behaviour of B4C and rice husk ash reinfroced Al 7075 alloy hybrid composite for armors application by using taguchi techniques," *Materials Today: Proceedings*, vol. 27, pp. 2617-2625, 2020.

[76] 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, 2019.

[77] A. M. Usman, A. Raji, N. H. Waziri, and M. A. Hassan, "Aluminium alloy-rice husk ash composites production and analysis," *Leonardo Electronic Journal of Practices and Technologies*, vol. 25, pp. 84-98, 2014.

[78] 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, 2016

[79] S. A. Ali, and B. S. Motgi, *A Study on Mechanical Properties of Al7068 Based Metal Matrix Composite Reinforced with Rice Husk Ash (RHA) and Silicon Carbide (SiC)*. 2021.

[80] Z. Seikh, S. Kunar, R. Haque, S. Haidar, and M. Sekh, "WEDM machining performance of Al based metal matrix composites reinforced with rice husk ash," *Materials Science Forum*, vol. 1048, pp. 261-269, 2022.

[81] M. Ariff, A. H. Lin, O. Jung, D. W. Tahir, and S. Sulaiman, "Rice husk ash as pore former and reinforcement on the porosity, microstructure, and tensile strength of aluminum mmc fabricated via the powder metallurgy method," *Powder Metallurgy Method. Crystals*, vol. 12, no. 8, 2022.

[82] S. P. Dwivedi, and V. R. Mishra, "Physico-chemical, mechanical and thermal behaviour of Agro-waste RHA-reinforced green emerging composite material," *Arabian Journal for Science and Engineering*, vol. 44, no. 9, pp. 8129-8142, 2019.

[83] J. A. K. Gladston, I. Dinaharan, N. M. Sheriff, and J. D. R. Selvam, "Dry sliding wear behavior of AA6061 aluminum alloy composites reinforced rice husk ash particulates produced using compocasting," *Journal* of *Asian Ceramic* Societies vol. 5, no. 2, pp. 127-135, 2017.

[84] S. Mahalingam, and A. S. Babu, "Characterization of 3-aminopropyltriethoxysilane treated stacked silicate nanoclay and red Matta-RHA biosilica woven ramie fibre epoxy composite," *Silicon*, vol. 14, no. 13, pp. 8129-8139, 2022.

[85] O. E. Ezenkwa, A. Hassan, and S. A. Samsudin, "Mechanical properties of rice husk and rice husk ash filled maleated polymers compatibilized polypropylene composites," *Journal of Applied Polymer Science*, vol. 139, no. 9, p. 51702, 2022.