EDSU Journal of Engineering and Technology
(EDSUJET)

Synthesis and Evaluation of Rice Husk-Derived Silica: A Mini Review

Mamudu Yahaya[a,*], Otoikhian Kevin Shegun[a].
[a] *Department of Chemical Engineering, Edo State University, Iyamho, Edo State, Nigeria*
[*] Corresponding author: Mamudu Yahaya, Email: *yahayaagim@gmail.com

Received: 05 September 2025, Accepted: 30 September 2025, Published: 30 November 2025

KEYWORDS

Rice Husk
Synthesized Silica
Acid Leaching
Waste Valorization
Nanotechnology

ABSTRACT

Rice husk silica (RHS) has emerged as a sustainable and high-value material derived from rice husk ash (RHA), an abundant agricultural by-product. With rice husk accounting for nearly 20% of global paddy production, its transformation into silica offers a compelling solution to waste management and resource efficiency. Rice husk (RH) is rich in silicon dioxide and can be synthesized through various techniques including acid-leaching, controlled calcination, alkaline extraction, hydrothermal processing, and emerging green methods such as microbial leaching and pyrolysis-integrated recovery. These approaches yield amorphous silica with high surface area, thermal stability, and functional surface chemistry, making it suitable for diverse applications. Evaluation of RHS reveals its unique physical and chemical properties such as high porosity, modifiable surface groups, and structural resilience, which support its use in industrial sectors like cement, rubber, and ceramics, as well as in environmental remediation and advanced technologies including drug delivery, energy storage, and carbon capture. Environmentally, RHS production reduces reliance on mined quartz, lowers carbon emissions, and supports circular economy models. Industrially, it offers a cost-effective alternative with scalable potential. Despite challenges in purity control, scalability, and market integration, RHS continues to gain traction as a versatile material for sustainable innovation.

5. INTRODUCTION

Rice husk (RH), a byproduct of rice milling, has emerged as a promising source of silica due to its high silica content and global abundance (Hafez, 2022). With rice production exceeding 600 million tons annually, majorly produced in Asia as shown in Figure 1, RH accounts for nearly 20% of the total paddy weight, translating into a massive volume of agricultural waste (Hafez, 2022). Traditionally discarded or incinerated, RH contributes to environmental degradation through air pollution and land contamination (Singh *et al.*, 2021). However, its transformation into high-purity silica offers a sustainable solution that aligns with circular economy principles (Gaayathri *et al.*, 2023).

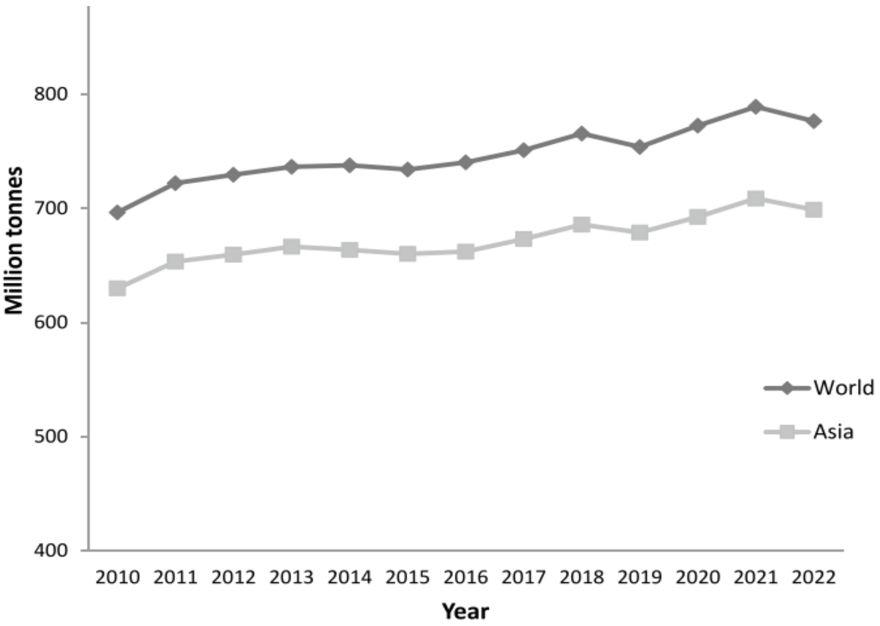

Figure 1: Global Rice Production (Hafez, 2022)

Silica (SiO_2) derived from RH is typically extracted through processes such as acid leaching, controlled combustion, and sol-gel synthesis (Kumar and Prasad, 2020). These methods yield amorphous silica with high surface area and reactivity, making it suitable for applications in cement, rubber, electronics, and even biomedical fields (Islam *et al*., 2024). The quality of silica depends heavily on parameters like combustion temperature, acid concentration, and purification techniques. For instance, calcination at 600–700°C under controlled conditions produces white, amorphous silica with minimal carbon content (Gaayathri *et al*., 2023). while temperatures around 800°C maintain ash purity but may initiate slight crystallization (Sekifuji *et al.,* 2017).. At low temperatures (100–400°C), partial decomposition of organic components occurs, leaving silica embedded in residual matter and resulting in low purity and poor reactivity (Mukhtar *et al*., 2020). At higher temperatures (900–1000°C), silica begins transitioning into crystalline forms, reducing its solubility and reactivity, with structural changes such as shrinkage and surface melting becoming evident (Sekifuji *et al*., 2017). Beyond 1000°C, silica fully transforms into crystalline quartz or cristobalite, which, although thermally stable, loses the porosity and chemical reactivity desirable for many industrial applications (Sekifuji *et al*., 2017).

Table 1: Chemical Composition of Rice Husk

Component	**Approximate Content (%)**	**Source**
Silica (SiO_2)	15–25	Fernandes *et al*. (2017)
Cellulose	35–45	Wu *et al*. (2015)
Hemicellulose	20–25	Moin *et al*. (2023)
Lignin	20–30	Hafez (2022)
Ash	15–20	Abdullahi (2022)

6. CHARACTERISTICS OF RICE HUSK

Rice husk (RH), a by-product of rice milling, is a fibrous, lignocellulosic material with distinctive physical, chemical, structural, thermal, and mechanical properties that make it valuable for industrial applications (Wu *et al*., 2015; Fernandes *et al*., 2017; Moin *et al*., 2023). RH is lightweight with a bulk density ranging from 90 to 150 kg/m³ and a moisture content typically between 8–15%, depending on environmental conditions and storage practices (Wu *et al*., 2015; Moin *et al*., 2023). Its particle size varies from 0.2 to 2 mm, contributing to its high surface area and porosity, which are advantageous in adsorption and composite applications (Fernandes *et al*., 2017).

Primarily, RH is composed of silica (SiO_2), cellulose, hemicellulose, and lignin (Hafez, 2022). Silica content ranges from 15–25%, making RH a prime candidate for biosilica extraction, while the organic matrix supports its use in bio-composites and energy conversion (Fernandes *et al.,* 2017; Hafez, 2022). Table 1 summarized the chemical composition of rice husk.

The structure of RH is rough, waxy surface with embedded silica bodies visible under scanning electron microscopy (Moin *et al*., 2023). RH exhibits good thermal stability, with ignition temperatures around 250–300°C and ash melting points near 1400°C, making it suitable for pyrolysis and combustion processes (Wu *et al*., 2015; Sekifuji *et al*., 2017). Thermogravimetric analysis shows multi-stage decomposition due to its complex organic composition, which includes cellulose and lignin (Islam *et al*., 2024).

RH has moderate tensile strength and stiffness, with tensile strength ranging from 5–15 MPa and Young's modulus between 0.5–1.5 GPa which make it suitable as a filler in polymer composites used in automotive, construction, and furniture applications (Abdullahi, 2022; Olusesi and Udoye, 2021). Table 2 outlined mechanical and thermal properties of RH.

Table 2: Mechanical and Thermal Properties of Rice Husk

Property	**Value/Range**	**Source**
Bulk density	90–150 kg/m³	Wu *et al*. (2015)
Moisture content	8–15%	Moin *et al*. (2023)
Ignition temperature	~250–300°C	Sekifuji *et al*. (2017)
Ash melting point	~1400°C	Islam *et al*. (2024)
Tensile strength	5–15 MPa	Abdullahi (2022)
Young's modulus	0.5–1.5 GPa	Olusesi and Udoye (2021)

2.1 Proximate and Ultimate Analysis of Rice Husk

The proximate and ultimate analysis of rice husk is given in Table 3. The moisture content across studies ranges from 9.5% to 12.7%, which is typical for air-dried rice husk and affects its combustion efficiency (Wu *et al*., 2015; Fernandes *et a*l., 2017; Sekifuji *et al*., 2017; Moin *et al*., 2023). Volatile matter is consistently high (65–78%), indicating good potential for pyrolysis and gasification (Rodriguez-Otero *et al*., 2023). Ash content varies between 10.2% and 18%, reflecting the silica-rich nature of rice husk. Lower ash values are often associated with cleaner combustion, while higher values (e.g.,) suggest greater potential for silica recovery and the Fixed carbon values are generally low (Hafez, 2022; Wu *et al*., 2015).

Table 3: Proximate and Ultimate Analysis of Rice Husk

Proximate analysis (%)				**Ultimate analysis (%)**					**References**
Moisture	Volatile Matter	Ash	Fixed Carbon	C	H	O	N	S	
10.5	65.2	17.8	6.5	42.1	5.2	50.1	1.1	0.2	Wu *et al*. (2015)
9.8	68.0	16.5	5.7	45.0	5.5	48.0	1.0	0.2	Fernandes *et al*. (2017)
11.2	66.5	15.9	6.4	44.3	5.3	49.0	1.2	0.2	Moin *et al*. (2023)
12.0	67.5	14.8	5.7	43.5	5.1	49.8	1.3	0.3	Elinge *et al*. (2021)
10.7	69.2	13.5	6.6	46.2	5.6	46.5	1.1	0.2	Adekunle *et al*. (2015)
12.7	68.2	16.1	15.7	45.2	5.8	47.6	1.0	0.2	Oladeji (2021)
9.5	78.8	10.2	1.5	41.8	5.0	51.0	1.0	0.2	Heo *et al*. (2014)
10.0	66.0	18.0	6.0	43.0	5.4	49.5	1.1	0.2	Hafez (2022)
11.5	67.0	15.0	6.5	44.0	5.2	49.5	1.3	0.2	Islam *et al*. (2024)
10.2	65.5	17.0	7.3	42.8	5.3	50.0	1.2	0.2	Sekifuji *et al*. (2017)
9.9	66.8	16.2	7.1	43.7	5.5	49.0	1.1	0.2	Rodriguez-Otero *et al*. (2023)

2.2 Application of rice husk

In recent years, countries such as India, Pakistan, Bangladesh, Sri Lanka, Australia, Thailand, Indonesia, and the United States have significantly advanced the utilization of rice husk as a valuable resource with support from governments and various organizations ((Moin *et al*., 2023; Islam *et al*., 2024). What made rice husk stand out among agricultural residues was its high silica content (87–97 wt.% SiO_2), lightweight nature, high porosity, and exceptionally large external surface area(Soltani *et al*., 2015). These unique properties positioned it as a promising material for numerous industrial applications, ranging from construction and insulation to the production of silicon-based compounds. Figure 2.3 depicts some of the applications of rice husks in different industrial fields, taking advantages of special characteristics of rice husk.

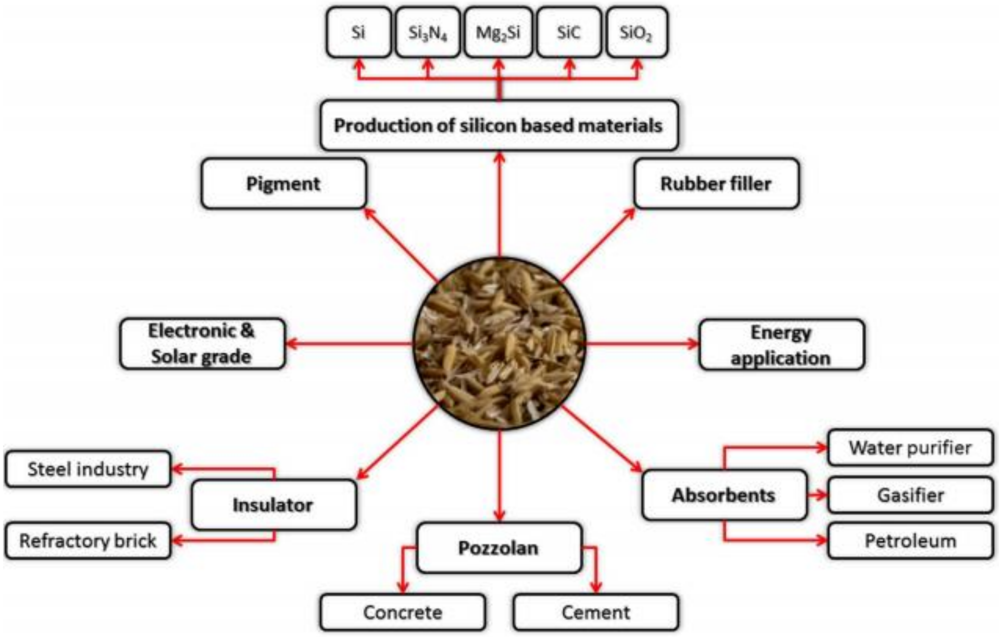

Figure 2: Schematic of Applications of Rice Husk (Rodriguez-Otero *et al*., 2023)

1. Absorbent

Rice husk is a widely available agricultural byproduct with proven potential as a low-cost, sustainable adsorbent for water treatment. Its high silica content, porous structure, and large surface area contribute to its chemical stability and effectiveness in removing contaminants such as heavy metals, nutrients, and organic pollutants from aqueous solutions (Daffalla *et al*., 2020; Okoro *et al*., 2022). Studies show that pre-treatment methods (thermal or chemical) can enhance its adsorption capacity, achieving removal efficiencies up to 99% for nitrogen and phosphorus (Lugo-Arias *et al*., 2024). These properties make rice husk a viable eco-friendly solution for industrial and environmental wastewater applications (Soltani *et al*., 2015; Liu *et al*., 2016).

2. Coating

Recent studies have explored rice husk transformation into functional materials (such as silica-based ceramics and geopolymer fillers) for enhancing the mechanical, thermal, and adhesive properties of coatings used in construction, aerospace, and marine industries (Daffalla *et al*., 2020). The coating demonstrated excellent mechanical strength, wear resistance, and thermal stability, making it suitable for protecting building materials. The inclusion of silane-treated Si_2N_2O particles improved tensile strength (up to 107 MPa) and thermal decomposition temperature (up to 440 °C), while also enhancing hydrophobicity with a contact angle of ~126° (Dhengare *et al*., 2024). Studies show that incorporating rice husk ash-based geopolymer (GP-RHA) significantly improved adhesive strength under dry conditions (up to 3.9 MPa) (Abdullah *et al*., 2024). Nanoparticles from rice husk offer high surface area, chemical stability, and functionalization potential, making them ideal for coatings with anti-corrosive, hydrophobic, or UV-resistant properties (Rodriguez-Otero *et al*., 2023).

3. Cement industries

Rice husk ash (RHA), derived from the controlled combustion of rice husk, is gaining prominence as a sustainable supplementary cementitious material due to its high amorphous silica content and excellent pozzolanic properties. Incorporating RHA into concrete mixes, typically up to 15% replacement, has been shown to enhance compressive strength and environmental resistance, contributing to more durable and eco-friendly construction (Alieu *et al*., 2024). Advanced formulations combining RHA with carbon nanotubes have demonstrated improved structural performance, including increased stiffness, delayed shear failure, and enhanced ductility in concrete beams (Jing, Lee, Moon, Ng, *et al*., 2025). Furthermore, ternary and quaternary blends containing RHA have been found to reduce permeability and significantly lower CO_2 emissions, while maintaining or improving mechanical properties (Jing, Lee, Moon, Jin, *et al*., 2025).

4. Energy

The continued reliance on fossil fuels undermines sustainable development due to their pollutant emissions and finite nature. In contrast, rice husk, a renewable agricultural residue, offers a promising alternative for clean energy production. Through thermochemical processes such as gasification, pyrolysis, torrefaction, and hydrothermal carbonization (HTC), rice husk can be converted into energy-rich products like syngas, bio-oil, biochar, and hydrochar (Nawaz *et al*., 2023; Quintero-Naucil *et al*., 2024). Studies show that combining torrefaction and pyrolysis can yield up to 85 MW of power annually from rice husk in Bangladesh (Imtiaz Anando *et al*., 2023). Pyrolysis efficiency depends on temperature and residence time, with optimal conditions producing up to 73.3% syngas (Bakari *et al*., 2020). Gasification, especially in fluidized bed reactors, generates syngas rich in CO, H_2, and CH_4, with performance influenced by air-to-fuel ratios and operating temperatures (Cerone and Zimbardi, 2021; Manop Chalermchat *et al*., 2022). HTC offers a low-temperature, wet biomass conversion route that reduces air pollution and enables silica-carbon separation for high-value applications (Abe *et al*., 2023). Biochemical methods like fermentation and transesterification also contribute to biofuel production, particularly ethanol and biodiesel (Elhussiny *et al*., 2023; Johnson *et al*., 2023). Rice husk combustion emits fewer NO_x and SO_x due to its low sulfur content and has a heating value comparable to sawdust and lignite (X. Lu *et al*., 2022; Zhang, 2013). Its use mitigates methane emissions and supports circular energy systems (Bhurse *et al*., 2024).

3. RICE HUSK AS A SOURCE OF SILICA

Rice husk (RH), traditionally considered waste, it has gained attention as a sustainable feedstock for high-purity silica production due to its high silica content and global availability. The valorisation of RH into silica not only addresses waste management challenges but also offers an eco-friendly alternative to conventional silica sources.

3.1 Composition of Rice Husk and Rice Husk Ash

Rice husk (RH), a byproduct of rice milling, typically constitutes 20–30% of the total paddy weight and is composed of both organic and inorganic materials (Korotkova *et al*., 2016). The organic fraction includes cellulose (35–45%), hemicellulose (20–25%), and lignin (20–30%), which contribute to its fibrous structure and thermal behavior (Kalapathy *et al*., 2002). The inorganic portion is dominated by silicon dioxide (SiO_2), which accounts for approximately 15–20% of the total mass, although this varies depending on rice variety, soil conditions, and geographic origin (Real *et al*., 1996; Korotkova *et al*., 2016).

Upon combustion, RH is converted into rice husk ash (RHA), with the organic matter largely eliminated and the inorganic content concentrated (JMMM, 2022). RHA is primarily composed of silica, which can reach up to 90–95% under controlled combustion conditions below 700°C (Kalapathy *et al*., 2002; Real et al., 1996). The remaining constituents include alumina (Al_2O_3), ferric oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), potassium oxide (K_2O), and sodium oxide (Na_2O), typically present in trace amounts ranging from 0.2% to 5% depending on combustion temperature and oxygen availability (Korotkova *et al*., 2016; Olusesi and Udoye, 2021).

3.2 Comparative Analysis with Other Silica Sources

Commercial silica is often produced from quartz sand via high-temperature reactions with sodium carbonate, followed by acid precipitation—a process that is energy-intensive and generates significant CO_2 and liquid effluents (Fernandes *et al.*, 2017). Other agricultural residues, such as sugarcane bagasse ash and wheat husk ash, also contain silica, but typically at lower concentrations (50–70%) and with higher impurity levels, requiring more extensive purification (Chindaprasirt and Rattanasak, 2011; Ochieng and Obonyo, 2023; Miller *et al.*, 2018). In contrast, RH offers higher silica yield per unit biomass, lower impurity content after simple acid pre-treatment and amorphous structure under controlled calcination, enhancing reactivity. These advantages make RH a more efficient and sustainable silica source compared to both mineral and other biomass-derived alternatives (Pal *et al.*, 2025).

3.3 Sustainability Aspects

The transformation of rice husk (RH), an abundant agricultural byproduct, into high-value silica represents a compelling example of circular economy. Traditionally considered waste, RH is now being valorised for its rich silica content, offering both environmental and economic benefits. This shift not only addresses the issue of agricultural residue disposal but also contributes to sustainable material development. One of the most significant sustainability advantages of RH utilisation is waste valorisation. Instead of being discarded in landfills or subjected to open-air burning, practices that contribute to particulate emissions and greenhouse gas release, RH is repurposed into a functional industrial input (Pal *et al.*, 2025). This approach mitigates environmental pollution while creating value from biomass that would otherwise be wasted. Another key benefit lies in energy integration. The combustion of RH can be harnessed for energy generation, and the resulting ash serves as a feedstock for silica extraction. This dual-purpose strategy enhances process efficiency and supports renewable energy goals, particularly in regions where biomass is a viable energy source (Fernandes *et al.*, 2017). Furthermore, the use of RH-derived silica offers a sustainable alternative to quartz sand, which is traditionally mined for industrial silica production. Mining operations are often associated with land degradation, habitat destruction, and biodiversity loss. By substituting quartz with RH silica, industries can reduce their ecological footprint and promote more responsible resource use. In terms of climate impact, RH-based silica production has a lower carbon footprint compared to conventional methods. The calcination temperatures required for RH are significantly lower than those needed for quartz processing, resulting in reduced energy consumption and lower CO_2 emissions (Fernandes *et al.*, 2017). This makes RH silica an attractive option for industries seeking to decarbonise their supply chains.

Despite these advantages, several challenges remain. Scaling up eco-friendly extraction methods is technically demanding, particularly when aiming to minimise the use of chemical reagents. Additionally, the quality and consistency of RH silica can vary depending on rice variety, cultivation conditions, and regional practices, posing hurdles for standardisation and commercial adoption (Yuan *et al.*, 2024). In conclusion, the utilisation of rice husk for silica production exemplifies the principles of circular economy by turning agricultural waste into a valuable resource. While the sustainability benefits are clear; from waste reduction to climate mitigation, addressing the technical and logistical challenges will be essential to unlock its full potential at scale.

4 SYNTHESIS OF SILICA FROM RICE HUSK

Rice husk, an abundant agricultural by-product in rice-producing regions, has emerged as a promising raw material for the sustainable synthesis of silica. Rich in silicon dioxide, rice husk ash (RHA) obtained through controlled combustion offers a low-cost and eco-friendly alternative to conventional silica sources. The transformation of rice husk into high-purity silica involves several key techniques, each with distinct advantages and limitations (Pode, 2016).

4.1 Overview of Synthesis Techniques

The initial step in the synthesis of silica from rice husk involves thorough washing and acid-leaching to eliminate metallic impurities that can compromise the purity and structural quality of the final product. These impurities; commonly iron (Fe), calcium (Ca), and magnesium (Mg) can interfere with the formation of amorphous silica during calcination. To address this, various acids are employed depending on the desired balance between effectiveness and environmental impact. Hydrochloric acid (HCl) is widely used due to its strong ability to remove Fe, Ca, and Mg ions. Nitric acid (HNO_3), with its oxidative properties, offers an alternative that also aids in breaking down organic residues. More recently, acetic acid (CH_3COOH) has gained attention as a greener option, offering sufficient impurity removal with lower toxicity and environmental burden (Dhaneswara *et al*., 2020). This acid pre-treatment step is critical not only for enhancing silica purity but also for minimizing the risk of crystalline phase formation during subsequent stages discussed below, thereby ensuring the production of high-quality amorphous silica suitable for industrial applications.

i. Controlled calcination

Controlled calcination is a critical step in the conversion of rice husk (RH) into high-purity silica. This process involves combusting RH at temperatures typically ranging between 500°C and 800°C. The temperature range directly influences the structural characteristics of the resulting silica. When calcination is conducted below 700°C, the product is predominantly amorphous silica, which is highly desirable for applications in adsorption and catalysis due to its high surface area and reactivity. However, temperatures exceeding 800°C can lead to the formation of crystalline quartz, a phase that is significantly less reactive and poses environmental and health hazards, particularly through inhalation of fine particles (Yuvakkumar *et al*., 2014).). For instance, Raphael *et al*. (2022) achieved mesoporous silica gel with a surface area of 407.6 m^2/g by calcining RH at 750°C after acid treatment, Sankar *et al.* (2021) produced spherical amorphous silica nanoparticles at 700°C and Wang *et al*. (2020) demonstrated that even at 800°C, short-duration calcination could retain amorphous characteristics, enabling effective use in composite materials. In contrast, Kenechi *et al*. (2016) showed that uncontrolled burning leads to carbonized ash with lower purity and surface area, while controlled furnace calcination produces white rice husk ash (WRHA) rich in amorphous silica. To mitigate the environmental impact of this thermal process, electric furnaces and biomass-powered kilns are increasingly employed, offering a more sustainable approach by reducing carbon emissions associated with conventional combustion methods.

ii. Alkaline extraction and acid precipitation

Alkaline extraction followed by acid precipitation is the most widely adopted method for synthesizing high-purity silica from rice husk ash (RHA). The process begins with sodium hydroxide (NaOH) digestion, where RHA is treated with a 1–2 M NaOH solution at temperatures between 80°C and 100°C. This reaction dissolves the silica content, forming soluble sodium silicate. Subsequently, acid precipitation is carried out by introducing hydrochloric acid (HCl) or acetic acid (CH_3COOH) to the solution, reducing the pH to approximately 4. This shift in pH triggers the formation of a silica gel, which is then subjected to filtration, washing, and drying at 100–120°C to obtain the final product. Numerous studies have validated the effectiveness of this method, for instance, Rahim et al. (2024) optimized the leaching and precipitation conditions using RHA, the resulting silica gel exhibited a purity of 94–99%, with minor impurities such as potassium, calcium, and phosphorus remaining in trace amounts. Similarly, Ajeel *et al*. (2020) reported that this method is not only cost-effective but also energy-efficient compared to conventional calcination. Their study emphasized that the acid precipitation step is critical for achieving high-purity amorphous silica. The method is known to yield silica with a purity range of 94–99%, making it suitable for various industrial applications. However, it also generates chemical waste and demands precise pH control to ensure consistent quality and minimize environmental impact (Dhaneswara *et al*., 2020).

iii. Hydrothermal synthesis of silica

Hydrothermal synthesis presents a sustainable and energy-efficient alternative for extracting silica from rice husk ash (RHA). This method involves treating RHA with sodium hydroxide (NaOH) under elevated pressure conditions ranging from 0.15 to 0.2 MPa and temperatures between 110°C and 120°C (Yuvakkumar *et al.*, 2014). Under these conditions, silica dissolves into the alkaline solution and subsequently precipitates upon cooling and acidification. Unlike conventional calcination, which requires high temperatures and substantial energy input, hydrothermal synthesis significantly reduces energy consumption and eliminates the need for combustion. This makes it particularly suitable for decentralized rural setups where energy resources may be limited and environmental considerations are paramount (Hindarso *et al.*, 2021). Raphael, Johnson, and Aderonke (2022) conducted a study where they synthesized biosilica under hydrothermal conditions of 0.15–0.2 MPa and 110–120°C and the biosilica synthesizd exhibited a surface area of 407.6 m²/g, a pore volume of 0.1886 cm³/g, and a pore width of 2.92 nm. Another investigation by Wang *et al.* (2020) explored the hydrothermal synthesis of sodium silicate from RHA and found that the resulting silicate oligomers, monomers, dimers, and trimmers were comparable in performance to commercial sodium silicates when used in alkali-activated concrete. The process not only aligns with green chemistry principles but also offers a scalable pathway for producing high-purity silica in low-resource environments.

4.2 Emerging Green Methods for Silica Extraction

As the global push for sustainable industrial practices intensifies, researchers have turned to green methodologies for extracting silica from rice husk ash (RHA), aiming to reduce chemical waste, energy consumption, and environmental impact. Traditional acid–alkali extraction methods, while effective in yielding high-purity silica (94–99%) with surface areas ranging from 204 to 236 m²/g, are often criticized for their reliance on corrosive reagents and the generation of hazardous waste (Rahim *et al.*, 2024). In response, several innovative techniques have emerged that offer cleaner, more resource-efficient alternatives. These methods vary in scalability, environmental footprint, and silica quality, but all share a commitment to circular economy principles and reduced ecological harm.

a) Reflux-Based Green Synthesis

Reflux-based synthesis offers a low-energy, resource-efficient pathway for silica recovery from rice husk ash (RHA). This method utilizes electric furnaces for controlled calcination, followed by refluxing the ash in sodium hydroxide (NaOH) solution. The resulting sodium silicate is then acidified using hydrochloric acid (HCl), leading to the formation of silica gel. The process is notable for its minimal reagent consumption and reduced energy input, making it a promising alternative for sustainable silica production (Kumar *et al.*, 2019). Silica produced via this method typically achieves purities between 92–96% and surface areas around 200 m²/g, with scalability ranging from laboratory to pilot-scale operations (Kumar *et al.*, 2019). Kumar et al. (2019) demonstrated that this method not only reduces operational costs but also avoids the high-temperature demands of conventional calcination, aligning well with sustainable production goals.

b) Pyrolysis with Bio-oil Recovery

Pyrolysis-based methods integrate silica extraction with the recovery of bio-oil and syngas, thereby enhancing the overall utility of rice husk biomass. During pyrolysis, RHA is thermally decomposed in an oxygen-limited environment, producing volatile compounds alongside solid residues rich in silica. This approach supports circular economy principles by maximizing biomass utilization and generating multiple value-added products from a single feedstock (Singh et al., 2020). Although the silica yield and purity are slightly lower, typically 85–90% with surface areas around 150 m²/g, the environmental impact is significantly reduced due to the absence of chemical reagents and the recovery of renewable fuels. Singh *et al*. (2020) reported that integrated pyrolysis systems could be scaled to medium-sized plants, offering a balanced trade-off between silica quality and holistic biomass utilization.

c) Enzymatic and Microbial Leaching (Experimental)

A more experimental but highly innovative technique is enzymatic and microbial leaching, which employs microbial consortia to selectively remove metallic impurities from RHA. Unlike acid-leaching processes, this method avoids harsh chemicals entirely, relying instead on biological agents to purify the ash (Hindarso *et al*., 2021). Hindarso *et al.* (2021) explored this approach using locally isolated microbial strains capable of solubilizing iron, calcium, and magnesium from RHA. Although still in its developmental phase, the method shows promise for achieving near-zero chemical waste and significantly lower energy demands. Preliminary results suggest silica purities in the range of 90–95%, with surface areas comparable to those obtained via hydrothermal synthesis. However, scalability remains limited to laboratory settings, and further optimization is needed before industrial deployment.

5 CHARACTERIZATION OF RICE HUSK SILICA (RHS)

Characterization of rice husk silica typically involves techniques such as Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Brunauer-Emmett-Teller (BET) and Thermogravimetric Analysis (TGA), which help determine its structural, morphological, and thermal properties (Islam *et a*l., 2024).

5.1 Fourier Transform Infrared Spectroscopy (FTIR) for RHS

Fourier Transform Infrared Spectroscopy (FTIR) is a widely used analytical technique for characterizing rice husk-derived silica, particularly in identifying functional groups and assessing structural purity. FTIR operates by detecting the vibrational modes of chemical bonds, producing a spectral fingerprint that reveals the molecular composition of the sample (Alizor *et al*., 2025). From Figure 3, rice husk silica (RHS) FTIR spectra display strong absorption bands around 1090–1100 cm⁻¹, attributed to asymmetric stretching vibrations of the Si–O–Si network, confirming the presence of amorphous silica. Additional peaks near 370 cm⁻¹ correspond to symmetric stretching of Si–O bonds (Bhatia and Sahu, 2024). These bands are considered diagnostic markers for silica purity and structure.

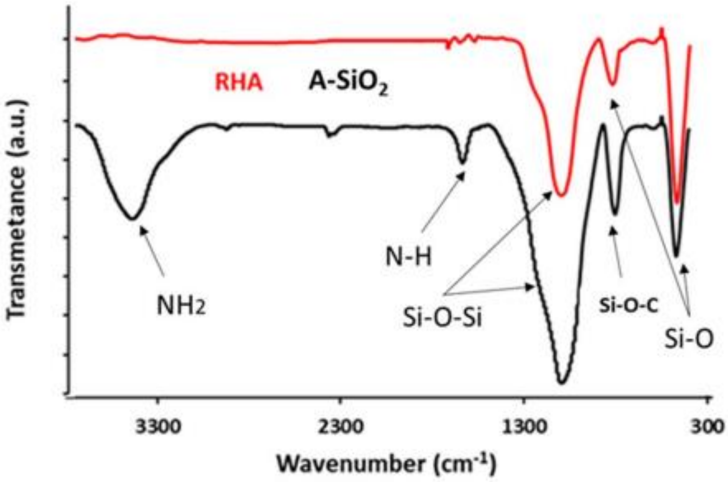

Figure 3: FTIR Analysis of RHA and RHS (Alizor *et al*., 2025).

5.2 X-ray Diffraction (XRD) for RHS

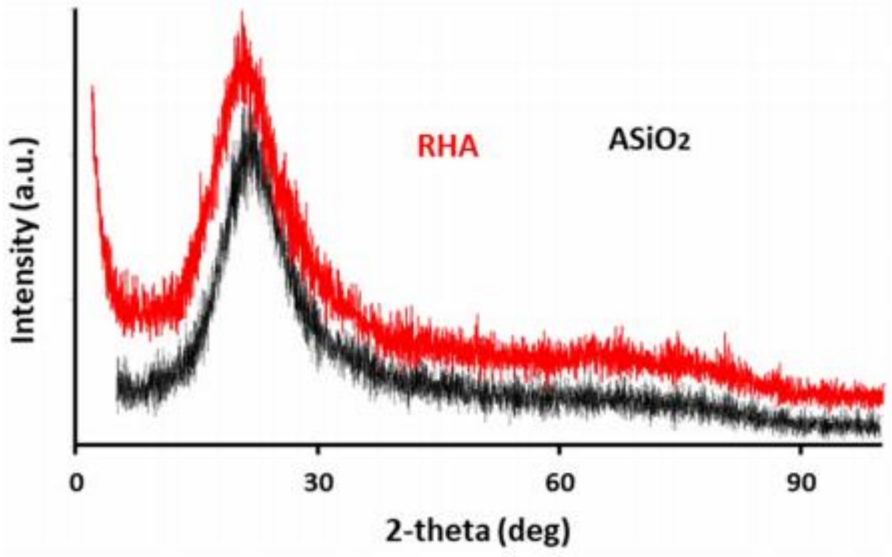

Figure 4: XRD patterns of RHA and ASiO2 (Quintero *et al*., 2024).

X-ray Diffraction (XRD) is a key method for analyzing the structural properties of silica extracted from rice husk (RH). Figure 4 shows broad peaks around 22° 2θ for both RHA and $ASiO_2$ samples, confirming the presence of amorphous silica, which is highly reactive and ideal for industrial uses like adsorbents and cement additives. The RHA sample shows higher intensity, suggesting better silica dispersion or purity (Quintero *et al*., 2024).

Recent studies (Islam et al., 2024; Bello et al., 2024) emphasize that maintaining combustion temperatures between 500–700 °C and using acid leaching improves silica quality. These structural differences, revealed through XRD, are crucial for tailoring rice husk silica to applications in catalysis, composites, and environmental remediation (Quintero *et al*., 2024).

5.3 Scanning Electron Microscopy (SEM) of RHS

Scanning Electron Microscopy (SEM) is an essential technique for analyzing the surface morphology and microstructural features, it provides high-resolution images that reveal the texture, porosity, and particle shape (Bhatia and Sahu, 2024). Considering Figure 5, rice husk silica typically exhibits a porous and irregular surface structure, which is a direct result of its amorphous nature and the combustion or chemical treatment processes used during extraction. SEM images often show granular and fibrous textures, indicating a high surface area and reactive surface sites (Alizor *et al*., 2025).

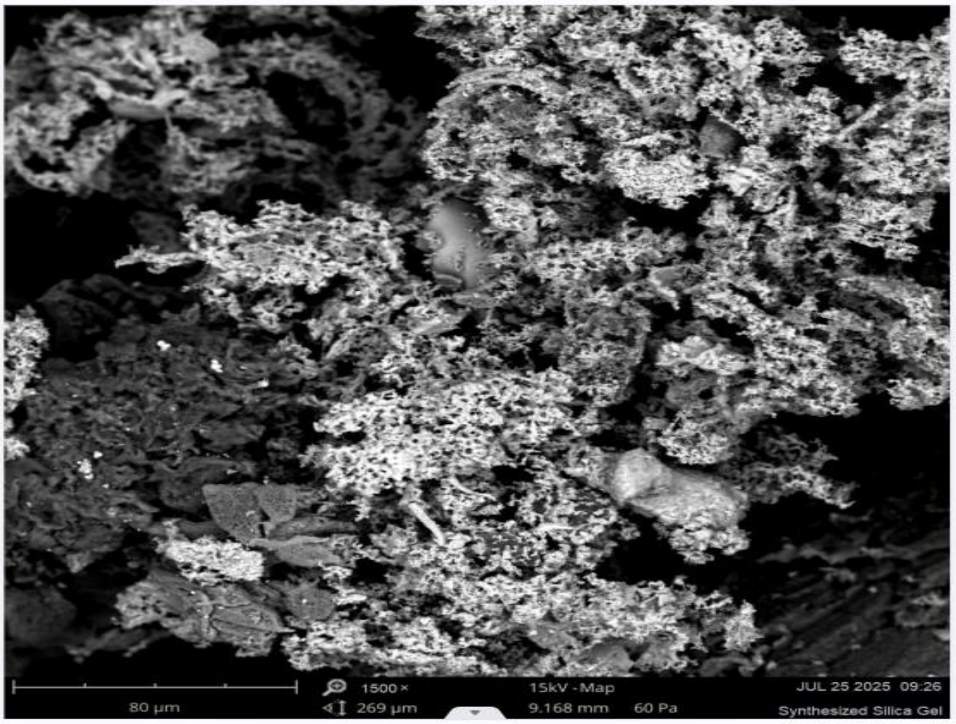

Figure 5: SEM Image of RHS

6 PHYSICAL AND CHEMICAL PROPERTIES OF RICE HUSK SILICA

When rice husk (RH) is combusted under controlled conditions, it yields rice husk ash (RHA), which contains up to 90–95% amorphous silica (Korotkova *et al.*, 2016). The physical and chemical characteristics of rice husk-derived silica make it suitable for a wide range of industrial applications, including catalysis, adsorption, and composite reinforcement.

6.1. Physical Properties and Morphology of Rice Husk Silica

Rice husk silica typically appears as a fine, white or grey powder with high surface area and porosity, characteristics attributed to its biogenic origin and the processing route employed (Zahan *et al.*, 2024). Its morphology is strongly influenced by the combustion temperature and chemical extraction method used during synthesis (Springer Materials, 2024). Scanning electron microscopy (SEM) reveals that silica particles derived from rice husk ash (RHA) exhibit irregular, porous structures with rough surfaces, which enhance their adsorption capacity (Zahan *et al.*, 2024). The particle size generally ranges from nanometers to a few microns, depending on synthesis conditions such as acid concentration, temperature, and aging time (Springer Materials, 2024). The bulk density of rice husk silica is relatively low, and its moisture content is minimal after drying, contributing to its lightweight nature (Zahan *et al.*, 2024). These properties make it suitable for use in lightweight composites and insulation materials, where low density and thermal resistance are desirable (Arshad and Moin, 2025).

6.2 Chemical Composition and Structural Features of Rice Husk Silica

Chemically, rice husk silica is composed predominantly of silicon dioxide (SiO_2), often exceeding 90% purity after acid leaching and controlled calcination. Minor constituents include trace amounts of potassium, calcium, magnesium, and iron, which can be removed through pre-treatment processes (Korotkova *et al.*, 2016). Structurally, rice husk silica is amorphous when produced at temperatures below 700 °C. X-ray diffraction (XRD) analysis confirms the absence of crystalline peaks, indicating a disordered atomic arrangement. This amorphous nature enhances its reactivity and compatibility with polymers and other matrices (Wu *et al.*, 2015). A study conducted by researchers from Indonesia investigated the extraction and characterization of silica from rice husk using an alkali fusion method.

The resulting silica was analyzed using Fourier-transform infrared spectroscopy (FTIR), which revealed a strong absorption band near 1099 cm^{-1}, corresponding to Si–O–Si stretching vibrations. The presence of Si–OH groups was also confirmed, indicating silanol functionalities that enhance surface activity. Additional characterization using XRD analysis confirmed the amorphous nature of the product.

6.3 Unique Features of Rice Husk Silica

Rice husk silica exhibits a range of distinctive features that set it apart from conventional silica sources, making it a highly attractive material for advanced industrial applications. Several studies have confirmed that silica derived from rice husk ash (RHA) exhibits exceptionally high surface area, often exceeding 200 m^2/g, which directly contributes to its effectiveness in adsorption and catalysis. One notable example is the work by Raphael et al. (2022), who synthesized silica gel from rice husk using controlled calcination followed by alkaline extraction and acid precipitation. Their BET analysis revealed a surface area of 407.6 m^2/g, along with a pore volume of 0.1886 cm^3/g and an average pore diameter of 2.92 nm. These properties made the material highly effective as a desiccant, with an adsorption capacity of 24.34%. Another study by Saleh *et al.* (2022) used response surface methodology (RSM) to optimize the extraction of silica from rice husk. Although their BET surface area results varied depending on treatment conditions, they confirmed that properly processed rice husk ash could yield silica with surface areas well above 200 m^2/g, especially when calcination and leaching parameters were finely tuned. This high porosity not only increases its reactivity but also broadens its utility in environmental remediation and chemical synthesis. Another compelling advantage of rice husk silica lies in its eco-friendly origin. As a derivative of agricultural waste, it embodies the principles of the circular economy by transforming an abundant by-product into a valuable resource. This sustainable sourcing reduces dependence on mined quartz and lowers the environmental footprint associated with silica production. Thermal stability is also a key feature of rice husk silica. Thermogravimetric analysis (TGA) has demonstrated that it remains structurally stable at temperatures up to 800 °C (Wu *et al*., 2015). This resilience makes it suitable for high-temperature applications such as refractory materials, thermal insulation, and catalyst supports. In addition to its physical robustness, rice husk silica possesses functional surface chemistry that enhances its adaptability. The presence of silanol (Si–OH) groups on its surface facilitates chemical modification, allowing for tailored interactions in nanocomposites, drug delivery systems, and biosensors. These reactive sites enable bonding with polymers, metals, and other functional groups, thereby expanding its versatility across multiple disciplines. Collectively, these features; high surface area, sustainable origin, thermal stability, and modifiable surface chemistry, position rice husk silica as a competitive and environmentally responsible alternative to commercial silica. Its unique properties not only meet the demands of modern material science but also contribute to the development of greener technologies.

7 APPLICATIONS OF RICE HUSK SILICA

Rice husk silica (RHS), derived from the combustion and chemical treatment of rice husk ash (RHA), has emerged as a versatile material with wide-ranging applications. Its high surface area, amorphous structure, and eco-friendly origin make it a valuable alternative to conventional silica (Singh *et al*., 2018). As industries seek sustainable and cost-effective materials, RHS offers promising solutions across sectors, from construction and manufacturing to environmental remediation and nanotechnology.

7.1 Industrial Applications

Rice husk silica is widely used in industrial processes due to its reinforcing, insulating, and filler properties. In the rubber and polymer industries, RHS serves as a reinforcing agent, improving tensile strength and durability of products such as tires and gaskets (Patil and Sharanagouda, 2017). In paint and coatings, it acts as a filler to enhance opacity and reduce production costs. The cement and concrete industry also benefits from RHS as a pozzolanic material. Its reactive silica content contributes to improved compressive strength and durability of concrete, while reducing reliance on Portland cement—a major source of CO_2

emissions (Rodriguez-Otero *et al.*, 2023). Additionally, RHS is used in ceramics and refractory materials due to its thermal stability and low thermal conductivity.

7.2 Environmental Applications

RHS plays a significant role in environmental remediation, particularly in water purification and wastewater treatment. Its high surface area and porous structure make it an effective adsorbent for heavy metals such as lead, cadmium, and arsenic (Haripriya *et al.*, 2023). Functionalized RHS has also been used to remove dyes and organic pollutants from industrial effluents. In air filtration systems, RHS-based composites are being explored for capturing particulate matter and volatile organic compounds. Moreover, its use in soil amendment helps improve water retention and nutrient availability, supporting sustainable agriculture while recycling agricultural waste (Patil and Sharanagouda, 2017).

7.3 Advanced Applications

Recent advances have expanded the use of RHS into high-tech domains. In nanotechnology, RHS is used to synthesize mesoporous silica nanoparticles for drug delivery**,** biosensors, and tissue engineering. Its biocompatibility and modifiable surface chemistry allow for targeted delivery and controlled release of pharmaceuticals (Rodriguez-Otero *et al.*, 2023). In energy storage, RHS-derived silica is being incorporated into lithium-ion battery anodes and supercapacitors, offering lightweight and thermally stable alternatives to traditional materials. RHS is also being explored in carbon capture technologies, where its porous structure facilitates CO_2 adsorption and sequestration. Furthermore, RHS is used in the synthesis of zeolites**,** silicon carbide, and silicon nitride, which are critical components in electronics, catalysis, and high-temperature applications (Haripriya *et al.*, 2023).

8 CHALLENGES OF RICE HUSK SILICA

Rice husk silica (RHS) has gained attention as a sustainable and cost-effective alternative to conventional silica. Extracted from rice husk ash (RHA), RHS offers environmental and industrial benefits. However, several challenges hinder its widespread adoption. Key obstacles in RHS utilization and future directions for research, innovation, and commercialization are outlined below.

8.1 Extraction Complexity and Purity Control

One of the primary challenges lies in the extraction process. Conventional methods such as acid leaching and alkali treatment require precise control over temperature, pH, and reagent concentration to yield high-purity silica. Impurities like metallic oxides and carbon residues can compromise the quality of RHS, limiting its use in high-tech applications (Pal *et al.*, 2025).

8.2 Environmental and Safety Concerns

The use of strong acids and bases in extraction poses environmental risks and safety concerns. Disposal of chemical waste and energy-intensive calcination processes contribute to the carbon footprint, undermining the sustainability of RHS production (Rodriguez-Otero *et al.*, 2024).

8.3 Scale-Up and Commercial Viability

While lab-scale synthesis of RHS is well-documented, scaling up for industrial production remains a challenge. Issues such as equipment corrosion, process optimization, and cost-effectiveness hinder large-scale adoption. Moreover, the low bulk density of rice husk complicates transportation and handling logistics (Haripriya *et al.*, 2023).

8.4 Limited Market Integration

Despite its versatility, RHS has not yet penetrated mainstream markets. Lack of standardization**,** regulatory frameworks, and awareness among manufacturers restrict its integration into commercial products. Additionally, competition from synthetic silica and other industrial fillers limits its economic appeal (Pal *et al.*, 2025).

9 FUTURE PERSPECTIVES AND OPPORTUNITIES

As global industries increasingly prioritize sustainability, the future of rice husk silica (RHS) lies in its potential to serve as a cornerstone of green innovation. Derived from agricultural waste, RHS offers a renewable and versatile alternative to conventional silica, with applications spanning construction, catalysis, energy storage, and environmental remediation. To fully harness its value, ongoing research and development are exploring advanced extraction techniques, circular economy integration, functional enhancements, and supportive policy frameworks. These future directions aim to elevate RHS from a niche material to a mainstream solution in sustainable manufacturing and technology.

9.1 Green and Sustainable Extraction Methods

Future research is focused on eco-friendly extraction techniques, such **as** bio-acid leaching**,** microwave-assisted pyrolysis, and enzyme-mediated processes, which reduce chemical usage and energy consumption. These methods aim to enhance purity while minimizing environmental impact (Pal *et al*., 2025).

9.2 Integration into Circular Economy Models

RHS aligns well with circular economy principles, transforming agricultural waste into high-value materials. Innovations in waste valorization, co-product generation (e.g., bio-oil, syngas), and life-cycle assessment can make RHS a cornerstone of sustainable manufacturing (Rodriguez-Otero *et al*., 2024).

9.3 Advanced Functionalization and Applications

Functionalizing RHS with nanostructures, metal ions, or organic groups can expand its applications in catalysis**,** biomedicine, and energy storage. Research into mesoporous silica, zeolite synthesis, and battery-grade silicon offers promising avenues for high-tech integration (Haripriya *et al*., 2023).

9.4 Policy Support and Industry Collaboration

To unlock RHS's full potential, policy incentives**,** industry-academia partnerships, and public awareness campaigns are essential. Establishing quality standards**,** certification systems**,** and supply chain networks will facilitate commercialization and global adoption.

10 CONCLUSION

Rice husk silica (RHS) represents a transformative opportunity to convert agricultural waste into a high-value, multifunctional material. With rice husk being abundantly available and rich in silicon dioxide, its valorization into silica aligns with both environmental sustainability and industrial innovation. The synthesis of RHS through techniques such as acid-leaching, controlled calcination, alkaline extraction, and emerging green methods; including hydrothermal processing, reflux-based synthesis, and microbial leaching, demonstrates a growing shift toward eco-conscious material engineering. Physically, RHS offers high surface area, porosity, and thermal stability, while chemically it boasts high purity and an amorphous structure ideal for reactivity and surface modification. These properties underpin its wide-ranging applications: from reinforcing agents in rubber and cement, to adsorbents in water purification, and advanced uses in nanotechnology, energy storage, and biomedical systems. Despite its promise, challenges remain in scaling up production, managing chemical waste, and ensuring consistent quality across rice varieties and processing conditions. Addressing these issues requires continued research into green extraction methods, policy support, and industry collaboration. Looking ahead, RHS is poised to play a pivotal role in circular economy models, offering a sustainable alternative to conventional silica and contributing to the development of greener technologies across sectors.

Abbreviations

RH	Rice Husk
RHA	Rice Husk Ash
RHS	Rice Husk Silica

HTC	Hydrothermal Carbonization
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction
FTIR	Fourier Transform Infrared Spectroscopy
BET	Brunauer–Emmett–Teller
TGA	Thermogravimetric Analysis

ACKNOWLEDGEMENTS

The authors acknowledge the Faculty of Engineering, Edo State University, Iyamho for providing laboratory facilities and technical support.

REFERENCES

Abdullahi, U. (2022). Utilization and mechanical properties of rice husk as useful agro waste and reinforcement in composites fabrication: A critical review. *African Journal of Engineering and Environment Research*, 3(2).

Adekunle, A.S., Adedeji, A.O. and Olatunde, O.O. (2015). Characterization of rice husk for energy production through thermochemical conversion. *International Journal of Engineering and Technology*, 5(2), pp.123–130.

Aharipour, N., Nemati, A, and Khachatourian, A.M. (2022). Green synthesis of silica extracted from rice husk ash. *Advanced Ceramics Progress*, 8(4), pp. 15 – 20. https://www.acerp.ir/article_159416.html

Ajeel, A., Joni, H. and Panatarani, R. (2020) 'Optimization of silica extraction from rice husk ash using alkaline leaching and acid precipitation', *Springer Materials Science Reports*. https://doi.org/10.1007/s11696-024-03541-z

Alieu, A., Zhang, Y., Chen, L. and Wang, Q. (2024). Experimental investigation on the mechanical performance of concrete incorporating rice husk ash as partial cement replacement. *Construction and Building Materials*, 320, p.126045

Alizor, S.O., Okonkwo, C.C. and Adeyemi, T. (2025). Effects of process conditions on the production and characterization of silica from rice husk. *Exploratematics Journal*, 5(2), pp.134–145.

Arshad, H. and Moin, A. (2025). Physical and Chemical Properties of Rice Husk. In: *Rice Husk Biomass*. Springer, pp.27–42.

Bello, A., Olatunji, A. and Ojo, T. (2024). Synthesis and characterisation of rice husk and palm fruit bunch silica for industrial applications. *Biomass Conversion and Biorefinery*.

Chindaprasirt, P. and Rattanasak, U. (2011) 'Utilization of sugarcane bagasse ash in cement production', *Materials and Design*, 32(5), pp. 354–360.

Daffalla, H.A., Mukhtar, H. and Rahman, R.A. (2020). Rice husk as a low-cost adsorbent for wastewater treatment: A review. *Environmental Technology Reviews*, 9(1), pp.1–15.

Dhaneswara, D., Fatriansyah, J.F., Situmorang, F.W. and Haqoh, A.N. (2020). Synthesis of amorphous silica from rice husk ash: Comparing HCl and CH_3COOH acidification methods and various alkaline concentrations. *International Journal of Technology*, 11(1), pp.200–208.

Elinge, M.R., Muhammad, A., Atiku, F.A., Itodo, A.U., Peni, I.J., Sanni, O.M. and Mbongo, A.N. (2011). Proximate, mineral and anti-nutrient composition of rice husk. *International Journal of Scientific and Technology Research*, 1(1), pp.1–4.

Fernandes, I.J., Calheiro, D., Sánchez, F.A.L., Camacho, A.L.D., Rocha, T.L.A.C., Moraes, C.A.M. and Sousa, V.C. (2017). Characterization of silica produced from rice husk ash: Comparison of purification and processing methods. *Materials Research*, 20(2), pp.512–518.

Gaayathri, P., Ramesh, S. and Kumar, V. (2023) 'Sustainable extraction of silica from rice husk: A review of methods and applications', *Journal of Cleaner Production*, 412, pp. 1–12.

Gaayathri, H. K., Debnath, R., Roy, M. and Saha, M. (2023). Recent Progress of Rice Husk Derived Silica for Industrial Applications. *Letters in Applied NanoBioScience*, 13(1), pp.7–20. https://doi.org/10.33263/LIANBS131.007

Hafez, M. (2022) 'Agricultural waste valorization: Rice husk as a source of high-purity silica', *Environmental Science Advances*, 18(3), pp. 45–59.

Heo, H.S., Park, H.J., Park, Y.K. and Ryu, C. (2014). Influence of feedstock type on the performance of biochar derived from biomass pyrolysis. *Renewable Energy*, 65, pp.296–303.

Hindarso, H., Nugroho, W. and Sari, D. (2021) 'Microbial leaching of rice husk ash for green silica synthesis: A preliminary study', *Biotechnology Reports*, 30, e00645. https://doi.org/10.1016/j.btre.2021.e00645

Hindarso, H., Epriliati, I., Hoerudin, D. and Yuliani, S. (2021). Synthesis and characterization of biosilica from rice husks as a catalyst for the production of biodiesel. *Fine Chemical Engineering*, **1(1),** pp. 1–10

Indochembull Research Group (2023) 'Separation and Characterization of Silica from Rice Husk with Varying Heating Times', *Indo Chemical Bulletin*. https://indochembull.com/index.php/fulerene/article/download/647/254

Islam, M., Chowdhury, T. and Rahman, S. (2024) 'Circular economy and nanomaterials: Transforming rice husk into functional silica', *Materials Today Sustainability*, 7, pp. 100–112.

Jing, Y., Lee, C., Moon, H., Ng, T. and Chen, Z. (2025). Shear behavior of sustainable concrete beams incorporating rice husk ash and carbon nanotubes. *Journal of Cleaner Production*, 412, p.138765.

Jing, Y., Lee, C., Moon, H., Jin, S. and Chen, Z. (2025). Ternary and quaternary cementitious composites with rice husk ash: A review of mechanical performance and environmental benefits. *Cement and Concrete Composites*, 142, p.106543

JMMM (2022) 'Rice husk ash utilization, composition and properties: A brief review', *Journal of Metals, Materials and Minerals*, 32(4). https://www.jmmm.material.chula.ac.th/index.php/jmmm/article/view/1544

Korotkova, T.G., Ksandopulo, S.J., Donenko, A.P., Bushumov, S.A. and Danilchenko, A.S. (2016). Physical Properties and Chemical Composition of the Rice Husk and Dust. *Oriental Journal of Chemistry*, 32(6).

Kumar, A., Singh, R. and Sharma, P. (2020). Rice husk ash-derived silica: Characterization and applications in environmental remediation. *Scientific Reports*, 10, p.19145. https://doi.org/10.1038/s41598-020-76460-0

Kumar, R., Singh, S. and Patel, A. (2019) 'Green synthesis of silica from rice husk ash using reflux-based methods', *International Journal of Sustainable Materials Processing*, 7(2), pp. 112–120. https://doi.org/10.1016/j.ijsmp.2019.04.005

Kumar, R., Patel, M. and Sharma, A. (2019). Low-energy reflux-based synthesis of silica from rice husk ash. *Green Chemistry Letters and Reviews*, 12(3), pp.210–218.

Kumar, R. and Prasad, B. (2020) 'Sol-gel synthesis of silica from rice husk and its industrial relevance', *International Journal of Materials Research*, 111(9), pp. 789–798.

Liu, J., Wang, S. and Zhao, Q. (2023) 'Pilot-scale continuous biogenic silica extraction from rice husk using hydrothermal and ball-milling methods', *Chemical and Biological Technologies in Agriculture*, 10(1), pp. 1–12. https://chembioagro.springeropen.com/articles/10.1186/s40538-023-00479-4

Liu, Y., Wang, J., Zheng, Y. and Zhang, Y. (2016). Preparation of rice husk-derived activated carbon and its application in water purification. *Journal of Environmental Chemical Engineering*, 4(1), pp.123–131.

Lugo-Arias, E., Rodríguez, J., Martínez, A. and Gómez, C. (2024). Nutrient removal from aqueous solutions using biosorbents derived from agro-residues. *Water*, 16(11), p.1543.

Moin, A., Arshad, H. and Khachatourian, A.M. (2023). Physical and chemical properties of rice husk. In: *Rice Husk Biomass*. Springer.

Mukhtar, Y., Askaruly, K., Seytkhan, A. and Bekalsu, B. (2020) 'Obtaining and Characterization of Amorphous Silica from Rice Husk', *Journal of Chemical Technology and Metallurgy*, 55(1), pp. 88–97.

Miller, A., Moumin, G. and Minnu, M. (2018) ‘Environmental impact of cement production and the role of agricultural waste as supplementary cementitious materials’, *Journal of Sustainable Construction Materials and Technologies*, 3(2), pp. 45–52.

Natural Publishing (2023) ‘Synthesis of Silica and Silica Compounds Based on Rice Husk Ash’, *International Journal of Nanomaterials and Chemistry*, 12(3), pp. 45–58.

Okoro, D., Nworie, O.E. and Eze, V.C. (2022). Adsorptive removal of heavy metals from wastewater using rice husk: A sustainable approach. *Journal of Environmental Management*, 305, p.114334.

Oladeji, J.T. (2011). The effects of some processing parameters on physical and combustion characteristics of rice husk briquettes. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 33(7), pp.636–645.

Olusesi, O.S. and Udoye, N.E. (2021) ‘Development and characterization of AA6061 aluminium alloy/clay and rice husk ash composite’, *Manufacturing Letters*, 29, pp. 34–41.

Pal, A., Karande, Y. and Dhokpande, S. (2025). Latest review on extraction of silica from rice husk ash. *International Journal of Creative Research Thoughts*, 13(6), pp.182–190.

Patil, N.B. and Sharanagouda, H. (2017). Rice Husk and Its Applications: Review. *International Journal of Current Microbiology and Applied Sciences*, 6(10), pp.1144–1156.

Pham, V.H., Ve, Q.L., Vo, C.A., Ngo, Q.T., Do, T.T. and Nguyen, A.D. (2025). Optimizing bio-nano-silica synthesis processes from rice husk for industrial-scale applications. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 12, pp.991–1004.

Pode, R. (2016). Potential applications of rice husk ash waste from rice husk biomass power plant. *Renewable and Sustainable Energy Reviews*, 53, pp.1468–1485.

Quintero-Naucil, D., Rodríguez, J., Martínez, A. and Gómez, C. (2024). Assessment of thermochemical pathways for rice husk conversion: Gasification and pyrolysis comparison. *Environmental Science and Pollution Research*, 31(7), pp.8456–8472.

Rahim, A., Joni, H. and Panatarani, R. (2024) ‘Silica precipitation from rice husk ash leachate: optimization and kinetics’, *Chemical Papers*. https://doi.org/10.1007/s11696-024-03541-z

Raphael, A., Johnson, M. and Aderonke, T. (2022) ‘Production of Silica Gel from Rice Husk for Laboratory Application’, *African Journal of Science, Innovation and Technological Research*, 26(9), pp. 112–125.

Real, C., Alcala, M.D. and Criado, J.M. (1996) ‘Preparation of silica from rice husks’, *Journal of the American Ceramic Society*, 79(8), pp. 2012–2016.

Rodriguez-Otero, A., Vargas, V., Galarneau, A., Castillo, J., Christensen, J.H. and Bouyssiere, B. (2023). Sustainable harnessing of SiO_2 nanoparticles from rice husks: A review of the best synthesis and applications. *Processes*, 11(12), p.3373.

Rodriguez-Otero, A. et al. (2024). Towards Achieving Circular Economy in the Production of Silica from Rice Husk as a Sustainable Adsorbent. *Processes*, 12(11), p.2420.

Saleh, T.A., Al-Saadi, A.A. and Al-Hammadi, S.A. (2022) ‘Optimization of silica extraction from rice husk using response surface methodology’, *Applied Nanoscience*, 12(3), pp. 789–799. https://doi.org/10.1007/s13204-021-02078-2

Sankar, R., Wang, Y. and Liu, H. (2021) ‘Preparation of amorphous silica from rice husk ash by calcination and chemical activation’, *Academia.edu*. https://www.academia.edu/57180344

Sekifuji, R., Le, V.C., Liyanage, B.C. and Tateda, M. (2017) ‘Observation of Physio-Chemical Differences of Rice Husk Silica under Different Calcination Temperatures’, *Journal of Scientific Research and Reports*, 16(6), pp. 1–11.

Singh, A., Patel, R. and Mehta, D. (2021) ‘Environmental impact of rice husk disposal and potential for silica recovery’, *Waste Management & Research*, 39(5), pp. 623–631.

Singh, P., Verma, R. and Gupta, S. (2020). Integrated pyrolysis for silica and bio-oil recovery from rice husk biomass. *Renewable Energy*, 145, pp.987–995.

Singh, R., Kumar, A. and Kumar, S. (2018) ‘Rice husk/rice husk ash as an alternative source of silica in ceramics’, *Journal of Asian Ceramic Societies*, 6(3), pp. 1–12. https://doi.org/10.1080/21870764.2018.1539210

Soltani, S.M., Bahrami, H. and Maleki, A. (2015). Rice husk-derived adsorbents for water purification: A review. In: *Environmental Nanotechnology*. Springer, pp.145–168.

Springer Materials (2024) *Biogenic silica synthesis and characterization*. https://materials.springer.com.

Wang, Y., Zhang, L. and Chen, H. (2020) 'Hydrothermal synthesis of sodium silicate from rice husk ash: Effect of synthesis on silicate structure and transport properties of alkali-activated concrete', *University of Technology Sydney Repository*. https://opus.lib.uts.edu.au/bitstream/10453/185913

Wu, G., Qu, P., Sun, E., Chang, Z., Xu, Y. and Huang, H. (2015). Physical, chemical, and rheological properties of rice husks treated by composting process. *BioResources*, 10(1), pp.227–239.

Yuan, S., Hou, Y., Liu, S. and Ma, Y. (2024). A comparative study on rice husk, as agricultural waste, in the production of silica nanoparticles via different methods. *Materials*, 17(6), p.1271.

Yuvakkumar, R., Hong, C.H., Venkatachalam, P. and Rajendran, V. (2014). Green synthesis of silica nanoparticles from rice husk ash. *Materials Letters*, 116, pp. 275–277. https://doi.org/10.1016/j.matlet.2013.11.034

Yuvakkumar, R., Elango, V., Rajendran, V. and Kannan, N. (2014). High-purity nano silica powder from rice husk using a simple chemical method. *Journal of Experimental Nanoscience*, 9(3), pp.272–281.

Zahan, M., Rahman, M. and Sarker, P. (2024) 'Synthesis and characterization of silica from rice husk ash for industrial applications', *Journal of Cleaner Materials*, 12(3), pp. 145–158. Available at: https://doi.org/10.1016/j.jclemat.2024.145 (Accessed: 23 September 2025).