

Sustainable Production of Silica Nanoparticles from Rice Husk and Their Emerging Applications

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Abstract:

Rice husk is an abundant agricultural waste and a rich source of silica, makes it suitable for the sustainable production of silica nanoparticles. In this study, silica nanoparticles were synthesized from rice husk using an eco-friendly method. The prepared nanoparticles were characterized using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and scanning and transmission electron microscopy (SEM/TEM) to confirm their amorphous nature, nanoscale size, and surface morphology. The high surface area of the synthesized silica nanoparticles makes them effective for sustainable environmental applications. In particular, silica nanoparticles synthesized from rice husk showed strong potential for the adsorption of heavy metal ions from contaminated water. This sustainable approach not only reduces agricultural waste but also provides a low-cost and environmental friendly material for wastewater purification applications.

Keywords: Eco-friendly, Adsorption, Sustainable, wastewater purification.

1. Introduction:

Silica nanoparticles derived from rice husk are gaining special attention because silica present in rice husk is synthesized from naturally biogenic structure. Rice husk which is a major byproduct of rice processing industries contains silica in large quantity. Its inorganic components contains biogenic silica which can be easily converted into amorphous silica nanoparticles. These nanoparticles show their wide applications in environmental sustainability like heavy metal adsorption from wastewater. These application depends on their surface modifiability. Many recent reviews have discussed silica extraction from rice husk and their application in different fields. A 2023 review by Rodriguez-Otero, A., Vargas et al. showed physical, chemical and hydrothermal routes for extraction of silica [1], while an another studies in 2025 by Hamidu, I. et al. focuses on pretreatment, thermochemical conversion and relationship between rice husk derived silica and advanced silicon materials [4]. It also discusses how processing conditions affect silica purity and properties. The main aim of this review is to examine the complete pathway of silica nanoparticles formation from rice husk waste. It aims mainly on the physicochemical basis for using rice husk waste of silica nanoparticles. It also focus on sustainable extraction process of nanoparticle synthesis. It represents particle size, crystallinity, surface area and porosity of nanoparticles. It shows applications in various fields like environmental sustainability etc.

2. Rice Husk as a Sustainable Source of Silica:

Agricultural waste reuse has been gained much interest in various environmental and industrial aspects. Among which rice husk is a good source of silica content. The rice husk mainly contains cellulose, hemicellulose, lignin and inorganic ash forming components.

From a sustainability perspective, rice husk offers several advantages:

- It is a renewable and widely available agricultural residue.
- Its utilization can reduce the environmental burden associated with uncontrolled disposal.
- It provides an alternative to some conventional silica feedstocks.
- The intrinsic silica can be converted into high-value nanomaterials.
- Rice husk valorization supports waste-to-resource and circular-economy approaches.
- The resulting silica can potentially serve multiple environmental and industrial functions.

The sustainability of the complete process depends on acid and alkali consumption, water demand, thermal energy, washing requirements, waste-liquid treatment, reagent recovery and product yield. Therefore, a genuinely sustainable process should be evaluated from feedstock collection to final product production and its uses. Recent review studies in 2023 by P.U. Nzereogu et al. explained about Physical and chemical extraction of silica from rice husk with hydrothermal and carbonation methods [3]. It also explained about different applications of rice husk derived silica. While another review by Islam et al. in 2024 studied the production method of silica nanoparticle with its characterization like FTIR, XRD, and SEM/TEM etc.[2].

3. Sustainable Production methods for silica nanoparticle synthesis from Rice Husk:

Mineral acids like hydrochloric acid are used because many impurities were dissolved in it, but acid concentration, solid-to-liquid ratio, temperature, and treatment time must be controlled. Excessive acid use increases chemical consumption and produces acidic wastewater. So, acid concentration should be reduced for green synthesis of silica nanoparticles [6].

A generalized pretreatment sequence is:

Rice husk → Washing → Drying → Grinding/size reduction → Acid or alternative purification → Washing → Drying

As long as prior research many articles were summarized and studies were analyzed for silica nanoparticle synthesis from rice husk. Earlier investigations explained the synthesis methods in green synthesis approaches and with their characterization.

Research should focus on reducing acid and alkali intensity through dilute reagents, alternative leaching agents, reagent recycling, and closed-loop processing.

Following table shows some previous review studies done by different authors for silica nanoparticle synthesis

S.No.	Review	Studies done by Authors
1.	Rodriguez-Otero et al., 2023	SiNP synthesis with applications
2.	Hamidu et al., 2025	Advanced synthesis with sustainable methods.
3.	Hybrid Advances, 2023	Different extraction techniques.
4.	Rodriguez-Otero et al., 2020	Mesoporous silica nanoparticle synthesis.
5.	Islam et al., 2024	Synthesis with characterization.

Table 1: Different studies of different authors

Following flowchart shows the synthesis process in easy way:

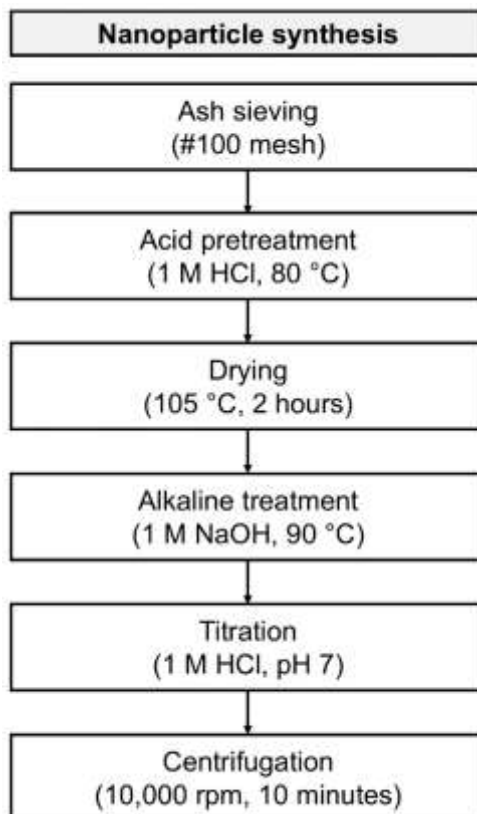


Figure 1: Flow diagram for silica nanoparticle production [14]

4. Comparison of Synthesis Routes

Comparison of major rice-husk-derived silica production strategies

Method	Main advantage	Main limitation	Nanostructure control	Sustainability potential
Direct calcination	Simple process	Energy demand; aggregation	Low	Moderate
Acid leaching + calcination	High impurity removal	Acid wastewater	Moderate	Moderate
Alkali extraction + precipitation	High purity and controllable precipitation	Chemical consumption	High	Moderate–high
Sol-gel	Excellent structural control	Drying/aggregation	High	Moderate
Hydrothermal	Aqueous processing	Pressure equipment	High	High potential

Carbonation	Potential utilization	CO ₂	Process optimization required	Moderate–high	High potential
Template-assisted synthesis	Ordered mesoporosity		Template use/removal	Very high	Application-dependent

Table 2: Comparison of major rice-husk-derived silica production strategies

5. Influence of Processing Parameters on Nano silica Properties

Calcination temperature affects:

- Organic-matter removal
- Silica purity
- Residual carbon
- Crystallinity
- Surface area
- Hydroxyl groups

Acid concentration affects:

- Removal of metallic impurities
- Increase in silica purity
- Effect on silica yield
- Effect on particle size
- Effect on surface area

Alkali extraction affects:

- Silica dissolution
- Increase in silica recovery
- Effect on surface functional groups

6. Conclusion

Rice husk is a highly promising renewable precursor for the sustainable production of silica nanoparticles. Its intrinsic biogenic silica content enables the conversion of an agricultural by-product into high-value amorphous silica, nanosilica, and mesoporous materials. Thermal processing, acid purification, alkali extraction, sol–gel synthesis, hydrothermal treatment, precipitation, and template-assisted methods offer different levels of control over silica purity, particle size, surface area, and pore structure.

Among these approaches, acid-leaching followed by controlled extraction and precipitation remains an effective route for obtaining high-purity silica, while sol–gel, hydrothermal, and template-assisted methods provide greater opportunities for engineering nanoscale morphology and porosity. However, no single method can be considered universally optimal. The preferred route depends on the desired final properties and application.

Rice husk-derived silica nanoparticles show considerable potential in water purification, particularly heavy-metal adsorption, as well as catalysis, pollutant degradation, drug delivery, sensing, polymer

composites, agriculture, and energy-related technologies. Their performance can be enhanced through control of surface area, pore structure, particle size, and surface functional groups.

The major challenge is to ensure that the use of a waste-derived precursor translates into a genuinely sustainable process. Future progress should therefore prioritize reduced chemical consumption, reagent recycling, energy integration, water conservation, standardized production protocols, realistic application testing, and rigorous techno-economic and life-cycle assessment. With these developments, the sustainable valorization of rice husk could contribute significantly to the production of advanced silica nanomaterials and the transition toward a circular materials economy.

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