
DEVELOPMENT AND CHARACTERIZATION OF HYDROPHOBIC SILICA AEROGEL SYNTHESIZED FROM RICE HUSK VIA AMBIENT PRESSURE DRYING

Isa Zubairu^{1,2,3,*}, Badruddeen Saulawa Sani², Salmiati Salmiati⁴, Umar Alfa Abubakar²,
Sunday Bamidele Igboro², Aliyu Ishaq²

¹Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi

²Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria
Nigeria

³Faculty of Civil Engineering, University Teknologi Malaysia

⁴Department of Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi
Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia

Email: izubairu@atbu.edu.ng*, bssaulawa@abu.edu.ng, salmiati@utm.my, umaralfa@hotmail.com,
sbigboro@abu.edu.ng, aishaq@abu.edu.ng

*Corresponding author: Isa Zubairu

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Silica aerogels are ultra-lightweight, highly porous nanostructured materials with high specific surface area, properties that make them attractive adsorbents for water and wastewater treatment. However, conventional silica aerogels are commonly produced from costly precursors such as tetraethyl orthosilicate (TEOS), limiting their large-scale application, particularly in resource-constrained settings. This study reports the development of a hydrophobic silica aerogel from rice husk, an abundant and low-cost agricultural by-product, and its comprehensive physicochemical characterization. Silica was extracted from rice husk via acid leaching and calcination, converted to sodium silicate through alkaline digestion, and processed into a gel via acid-catalyzed sol-gel synthesis. The resulting hydrogel beads were solvent-exchanged into ethanol, surface-modified with trimethylchlorosilane (TMCS) to confer hydrophobicity, and dried at ambient pressure. The synthesized aerogel was characterized using nitrogen adsorption-desorption (BET/BJH/t-plot), Fourier-transform infrared spectroscopy (FTIR), water contact-angle goniometry, bulk density/porosity determination, and scanning electron microscopy (SEM). The aerogel exhibited a BET specific surface area of 303.60 m²/g, a mesoporous structure with pore diameters of 3.37–3.40 nm and pore volume of 0.52 cm³/g, negligible microporosity, a superhydrophobic water contact angle of 155.70° ± 1.34°, a bulk density of 0.18 g/cm³, and porosity of approximately 92%. FTIR confirmed characteristic Si-O-Si and Si-OH functional groups, while SEM revealed a rough, porous, agglomerated morphology consistent with an ambient-pressure-dried aerogel network. These results demonstrate that rice husk is a viable, sustainable precursor for producing hydrophobic, mesoporous silica aerogel with textural and surface properties consistent with materials reported to be effective for adsorption applications and recommend future adsorption studies.

Keywords: silica aerogel; rice husk; sol-gel synthesis; ambient pressure drying; hydrophobicity

1. INTRODUCTION

Silica aerogel is a nanostructured material characterized by high specific surface area, high porosity, and low density, properties that have made it the subject of extensive research as an adsorbent for organic and inorganic contaminants in water and wastewater treatment (Standeker et al., 2007, 2011; Wang et al., 2011, 2012). Compared with conventional adsorbents such as granular activated carbon, silica aerogels offer a more open, foam-like pore network, tunable hydrophobicity, and reusability, which together have been reported to improve adsorption performance for organic contaminants (Rahmani et al., 2018).

A major limitation to the wider adoption of silica aerogels, however, is that they are conventionally synthesized from relatively expensive precursors such as tetraethyl orthosilicate (TEOS) or commercial sodium silicate, which constrains cost-effective, large-scale production, particularly in

low- and middle-income settings. Agricultural by-products rich in amorphous silica, such as rice husk, offer a low-cost, abundant, and environmentally sustainable alternative precursor. Rice husk is generated in large quantities wherever rice is cultivated and is otherwise a largely underutilized waste stream; converting it into a valuable silica precursor therefore carries both economic and environmental benefits, avoiding the carbon burden associated with uncontrolled disposal or open burning.

Although several studies have reported the synthesis of silica aerogels from rice husk ash using sol-gel processing and ambient pressure drying (Deng et al., 2025; Halim et al., 2021; Ochoa-Munoz et al., 2025), reported textural and surface properties vary considerably depending on the specific extraction route, gelation conditions, solvent-exchange protocol, silylating agent, and drying method used. This variability underscores the need for detailed, route-specific characterization of any newly developed rice-husk-derived aerogel before its adsorption performance can be meaningfully evaluated or compared with other adsorbents.

This study reports the development of a hydrophobic silica aerogel from rice husk via acid leaching, calcination, alkaline extraction to sodium silicate, acid-catalyzed sol-gel synthesis, solvent exchange, and trimethylchlorosilane (TMCS) surface modification, followed by ambient pressure drying. The resulting material was comprehensively characterized in terms of its textural properties (BET/BJH/t-plot), functional chemistry (FTIR), hydrophobicity (water contact angle), bulk density and porosity, and surface morphology (SEM), to establish its suitability as an adsorbent for water treatment applications.

2. MATERIALS AND METHODS

2.1 Materials

Rice husk used in this study was purchased from a commercial vendor in Johor Bahru, Malaysia, and supplied in 10 kg polythene bags. The chemicals, reagents, and equipment used for silica aerogel synthesis and characterization are summarized in Tables 1 and 2.

Table 1: Chemicals, Reagents and Equipments for Silica Aerogel Synthesis and Characterization

Material / Reagent	Function
Rice husk	Silica precursor source
Hydrochloric acid (HCl)	Acid leaching of rice husk prior to calcination
Sodium hydroxide (NaOH)	Alkaline dissolution of rice husk ash to sodium silicate
Acetic acid	pH adjustment for gel formation
Hexane	Top layer for bead-shape preservation during gelation
Aqueous ammonia (5%)	Bottom layer for gelation of sol droplets
Ethanol	Solvent exchange (pore-water removal)
Trimethylchlorosilane (TMCS)	Silylating agent for surface (hydrophobic) modification
n-Hexane	Washing modified aerogel beads
Equipment	Purpose
Muffle furnace	Calcination of rice husk to ash
Brunauer–Emmett–Teller (BET) analyzer, NOVA touch 4LX	Specific surface area, pore size and pore volume (BJH, t-plot)
Perkin Elmer Frontier FTIR	Functional-group identification ($650\text{--}4000\text{ cm}^{-1}$)
DataPhysics OCA 15EC–Series	Water contact-angle (hydrophobicity) measurement
JEOL JSM-IT300LV Scanning Electron Microscope	Surface morphology (10, 20, 30, 100 μm)

2.2 Silica Extraction from Rice Husk

Amorphous silica was produced from rice husk by first washing the husk with distilled water and oven-drying it for 24 h at 100°C. Acid leaching was then carried out, since it has been reported to increase silica yield (Azat et al., 2019; Bakar et al., 2016). Leaching was performed by treating the rice husk with 0.5 M hydrochloric acid (HCl) on a hot plate at 60°C for 30 minutes under constant stirring, after which the husk was rinsed three times with distilled water to remove residual acid, air-dried, and oven-dried for a further 24 hours.

Calcination was carried out using a muffle furnace capable of reaching 1000°C. Complete calcination of rice husk has been reported to occur at temperatures between 500°C and 900°C (Bakar et al., 2016). Controlled combustion of acid-treated rice husk at approximately 600 °C has been widely reported to produce silica-rich rice husk ash with predominantly amorphous characteristics, while higher calcination temperatures may promote sintering and, depending on impurity content and pretreatment, transformation toward crystalline silica phases (Bakar et al., 2016; Azat et al., 2019). Bakar et al. (2016), for example, evaluated acid-leached rice husk calcined between 500 and 900 °C for 2 h and demonstrated the production of amorphous silica, with relatively limited improvement in silica production above approximately 600 °C. Therefore, in this study, the acid-leached rice husk was calcined at 600°C for 2 hours. After the furnace cooled, the resulting rice husk ash (RHA) was carefully collected and sieved.

2.3 Sodium Silicate Preparation

Sodium silicate ($\text{Na}_2\text{O}:\text{SiO}_2$), also known as water glass, was produced by dissolving RHA in sodium hydroxide (NaOH) solution. Thirty (30) g of RHA was added to 200 mL of 1 M NaOH solution,

and the mixture was heated on a hot plate under constant stirring at 120°C for 3.5 hours. The mixture was then cooled to room temperature and filtered using Whatman No. 1 filter paper (110–125 mm diameter, particle retention ~11 µm) to obtain a clear sodium silicate solution.

2.4 Silica Aerogel Synthesis, Surface Modification, and Drying

Silica aerogel was produced from the sodium silicate solution by first adjusting its pH to between 4 and 5 through the dropwise addition of acetic acid under gentle stirring, stopping just before gel formation began. Gelation was carried out by dropping the acidified sol into a beaker containing hexane as the top layer and 5% aqueous ammonia as the bottom layer; the resulting gel beads were left for 10 minutes to strengthen before being transferred to warm water for further ageing. The aged beads were then soaked in ethanol for 24 hours to exchange the pore water with ethanol, and this solvent-exchange step was repeated for a further 24 hours to ensure complete exchange.

Surface Modification of aerogel beads was carried out to introduce or improve its hydrophobicity. It was achieved using a silylating agent where in this study Trimethylchlorosilane (TMCS) together with ethanol and n-hexane using in the following proportion: 25% ethanol, 25% TMCS and 50% n-hexane by volume (ratio of ethanol: TMCS: n-hexane = 1:1:2). The gel beads were soaked in each silylating mixture with gentle mixing for 3.5 hours in sealed containers at ambient pressure. After silylation, the beads were washed three times with n-hexane to remove residual TMCS and finally dried on a hot plate at 80°C for 1 hour, yielding the finished silica aerogel at ambient pressure (i.e., without supercritical drying). The overall process, from raw rice husk to the surface-modified, dried silica aerogel, is summarized in Figure 1.

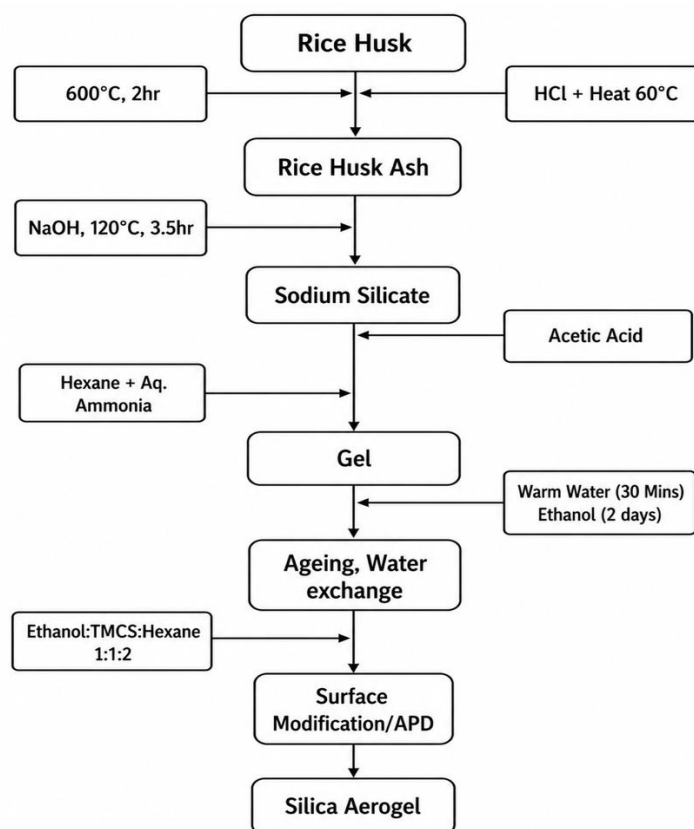


Figure 1: Process flow for the development of hydrophobic silica aerogel from rice husk.

2.5 Characterization of Silica Aerogel

Surface area was determined using the Brunauer–Emmett–Teller (BET) multipoint method, and pore size and pore volume were determined using the Barrett–Joyner–Halenda (BJH) method, both on a NOVA touch 4LX instrument. Prior to analysis, the aerogel was degassed at 200°C for 4 hours, and nitrogen adsorption-desorption isotherms were obtained at 77.3 K. Moreover, functional groups present

in the aerogel were identified by Fourier-transform infrared spectroscopy (FTIR) using a Perkin Elmer Frontier FTIR spectrometer (mid-IR: 8300–350 cm^{-1} ; far-IR: 700–30 cm^{-1} ; best resolution 0.4 cm^{-1}), scanning the wavenumber range 650–4000 cm^{-1} .

Hydrophobicity was assessed from the water contact angle of a droplet placed on the horizontally positioned aerogel surface, measured with a DataPhysics OCA 15EC–Series instrument and its high-resolution camera; this property has been reported to increase with the amount of silylating agent used and the soaking time in the silylating mixture (Khedkar et al., 2019). Also, bulk density was determined by weighing an empty 50 cm^3 glass flask, filling it with aerogel particles (tapping seven times until no further volume reduction occurred), and reweighing it. Bulk density (g/cm^3) was calculated as the ratio of aerogel mass to flask volume (Equation 1). Porosity was then calculated from the bulk density using Equation 2, assuming a standard amorphous silica density of 2.2 g/cm^3 .

$$\text{Density} = (M_1 - M_0)/V_a \quad (1)$$

where M_0 = mass of the empty flask (g); M_1 = mass of flask and aerogel (g); V_a = volume of the flask (cm^3).

$$\text{Porosity} = (1 - \rho_a/\rho_{st}) \times 100 \quad (2)$$

where ρ_a = density of the developed aerogel (g/cm^3); ρ_{st} = standard density of amorphous silica (g/cm^3).

Finally, surface morphology was examined using a JEOL JSM-IT300LV scanning electron microscope (SEM) at magnifications corresponding to 10, 20, 30, and 100 μm resolutions.

3. RESULTS AND DISCUSSION

3.1 Visual Transformation During Synthesis

The visual appearance of the intermediate products obtained during synthesis (Figure 2) supports successful conversion of rice husk into silica aerogel at each processing stage. The rice husk ash (RHA) obtained after calcination appeared as a fine white powder, indicating effective combustion of the husk and near-complete removal of carbonaceous matter. Recent reviews identify rice husk as an abundant agro-industrial by-product with a composition well suited to conversion into silica and other advanced materials (Hamidu et al., 2025), and rice husk ash has been widely reported to contain a high proportion of amorphous SiO_2 usable as a low-cost aerogel precursor (Deng et al., 2025).

The sodium silicate solution obtained after alkaline digestion of the RHA was golden-brown and slightly transparent, consistent with dissolution of silica into the alkaline medium, although the colour may partly reflect trace impurities carried over from the RHA. The use of RHA-derived sodium silicate, rather than commercial silicate or alkoxide precursors, is significant because it provides a cheaper, more sustainable route to aerogel synthesis (Ochoa-Munoz et al., 2025); similarly, waste-derived sodium silicate has been highlighted as a pathway to more scalable, less energy-intensive aerogel production (Borzova et al., 2024).

Upon acidification, white gel particles formed, confirming conversion of soluble silicate species into a hydrated silica gel network via hydrolysis and condensation. This wet-gel stage is critical, as the final aerogel structure depends on preserving the gel network through ageing, solvent exchange, surface modification, and drying; rice husk ash-derived sodium silicate has similarly been reported to convert into hydrogels and then alcogels via solvent exchange prior to ambient pressure drying (Halim et al., 2021). After drying, the finished aerogel appeared as fragile, extremely light, irregular particles, consistent with the low-density, highly porous nature expected of silica aerogels and confirming successful synthesis via the ambient-pressure-drying route (Deng et al., 2025; Halim et al., 2021; Ochoa-Munoz et al., 2025).



Figure 2: Visual transformation during silica aerogel synthesis: (a) rice husk ash; (b) sodium silicate solution; (c) gel particles in ethanol for exchange of pore water with ethanol; (d) Dried silica aerogel particles.

3.2 Textural Properties (BET, BJH, and t-Plot Analysis)

Nitrogen adsorption-desorption analysis was used to evaluate the textural properties of the synthesized aerogel, including BET specific surface area, BJH pore size and pore volume, and t-plot microporosity and external surface area, since these parameters are central to evaluating silica aerogels as environmental adsorbents (Goryunova et al., 2023).

The nitrogen adsorption-desorption isotherm (Figure 3) showed a gradual increase in adsorbed volume at low-to-intermediate relative pressure followed by a sharp rise at high relative pressure, typical of a mesoporous material in which multilayer adsorption and capillary condensation dominate. The separation between the adsorption and desorption branches indicates hysteresis, commonly associated with mesopore filling/emptying (Thommes et al., 2015), while the sharp rise at high relative pressure suggests the presence of larger mesopores and interparticle voids.

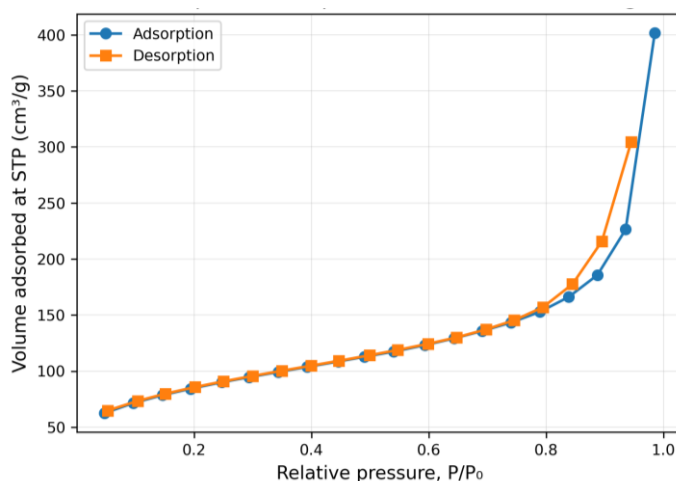


Figure 3: Nitrogen adsorption-desorption isotherm of the silica aerogel.

BET analysis (Figure 4) gave a specific surface area of 303.60 m²/g with a correlation coefficient of $r = 0.999915$ and a BET C constant of 124.16, indicating strong linearity in the fitting range and favourable interaction between nitrogen molecules and the aerogel surface. This value is

comparable with recent rice husk-derived silica aerogel studies reporting surface areas of 312 and 298 m²/g (Akhter, Soomro, and Inglezakis 2023) and TEOS-doped/non-TEOS-doped aerogels of 296.18 and 267.06 m²/g (Soylu et al., 2025), placing the present material within the range expected for mesoporous silica aerogels, notwithstanding known sensitivity of surface area to precursor chemistry, ageing, solvent exchange, and drying method.

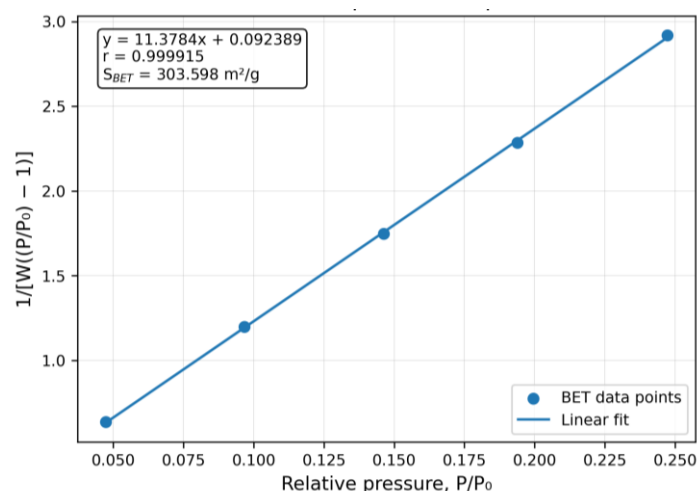


Figure 4: BET multipoint linear plot used to calculate specific surface area.

The t-plot analysis gave an external surface area of 303.60 m²/g, essentially identical to the BET value, indicating that the measured surface area is associated mainly with mesopores and external surface rather than micropores.

From the BJH analysis (Figure 5), the adsorption and desorption branches gave pore radii of 1.687 and 1.701 nm respectively, corresponding to pore diameters of approximately 3.37 and 3.40 nm. Under the IUPAC pore classification (pores < 2 nm: micropores; 2–50 nm: mesopores; > 50 nm: macropores) (Thommes et al., 2015), the aerogel is therefore classified as mesoporous, a structure expected to provide favourable diffusion pathways for adsorbate access to internal sites.

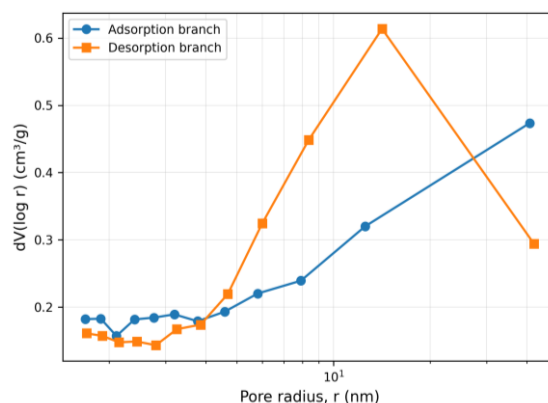


Figure 5: BJH pore size distribution based on adsorption and desorption branches.

The BJH pore volume (Figure 6) was 0.520 cm³/g from the adsorption branch and 0.525 cm³/g from the desorption branch, confirming an appreciable void network for adsorbate accommodation; the corresponding BJH surface areas were 111.55 and 121.82 m²/g, lower than the BET value because BJH analysis captures only pore-size-related surface area from capillary condensation, whereas BET reflects total specific surface area from multilayer nitrogen adsorption. This pore volume is somewhat lower than the 0.85 and 0.75 cm³/g reported for some rice husk-derived silica aerogels (Akhter et al., 2023), a difference attributable to variation in synthesis route, precursor source, gel ageing, solvent exchange, surface modification, and drying conditions across studies.

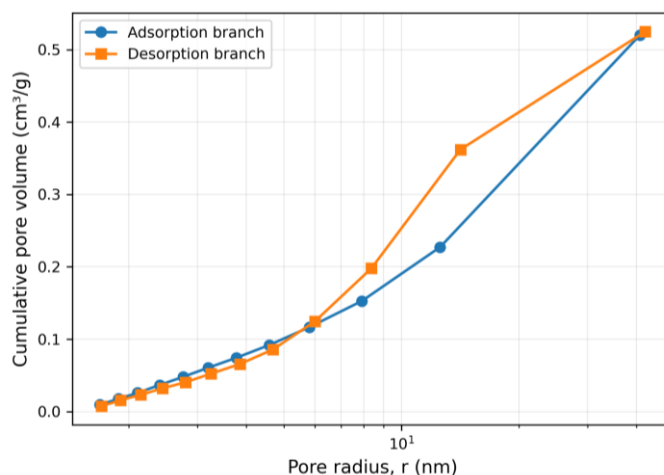


Figure 6: BJH cumulative pore volume of the silica aerogel.

The t-plot analysis (Figure 7) gave a micropore volume of 0 cm³/g and micropore area of 0.000 m²/g, confirming that the material is not micropore-dominated and that its surface area arises mainly from mesopores and external surfaces, consistent with the BJH pore-diameter results.

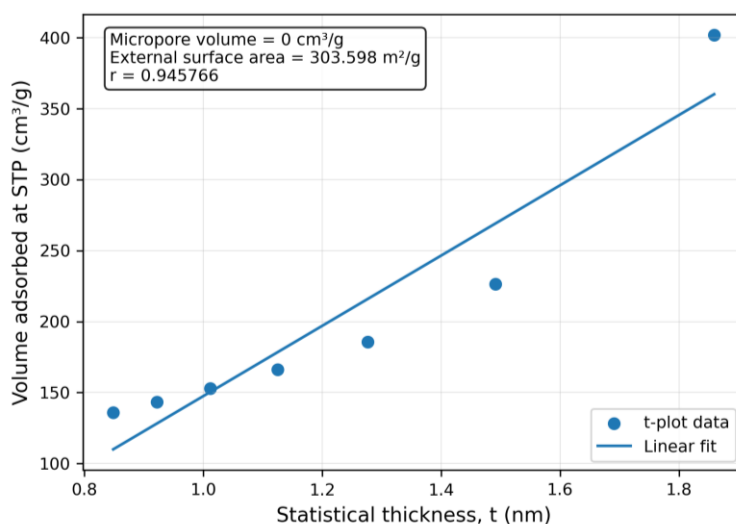


Figure 7. t-plot showing the absence of measurable micropore volume.

Collectively, the BET, BJH, and t-plot results indicate a mesoporous silica aerogel with a moderately high surface area (303.60 m²/g), pore diameter of 3.37–3.40 nm, and pore volume of 0.520–0.525 cm³/g — properties favourable for adsorption, since high surface area provides adsorption sites, mesoporosity supports accessibility and mass transfer, and pore volume accommodates adsorbate molecules, consistent with the general characterization of silica aerogels as highly porous adsorbents for environmental applications (Goryunova et al., 2023).

3.3 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectra of the synthesized aerogel (Figure 8) showed a broad band near 3359.03 cm⁻¹ attributed to O-H stretching from surface silanol groups and adsorbed water, and a band at 1627 cm⁻¹ corresponding to O-H bending. A weak band near 2964.14 cm⁻¹ suggested residual aliphatic C-H groups from the precursor or surface-modification step. A strong absorption at approximately 1065.82 cm⁻¹ was assigned to asymmetric Si-O-Si stretching, confirming formation of the silica network, while the band near 945.66 cm⁻¹ was associated with Si-OH stretching, indicating surface silanol groups. Additional bands at 848.6, 758.95, and 668.83 cm⁻¹ were attributed to symmetric stretching, bending, or related silica-network/surface-group vibrations. Overall, the spectrum confirms successful formation of a silica aerogel bearing siloxane and silanol functional groups that may contribute to adsorption via surface interaction with contaminants (Ma et al., 2025; Minju et al., 2021; Ransing et al., 2023).

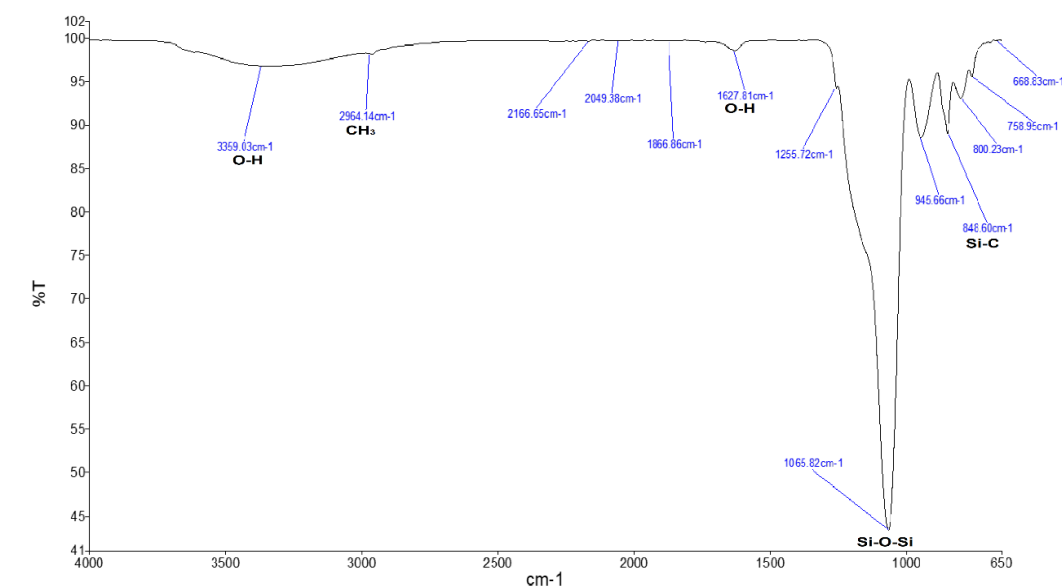


Figure 8: FTIR spectrum of the synthesized silica aerogel.

3.4 Hydrophobicity

Water contact-angle analysis on duplicate aerogel samples (Figure 9) gave contact angles of 156.7°/157.0° and 154.4°/154.7° (means of 156.85° and 154.55°), yielding an overall mean of 155.70° ± 1.34°. The small difference of approximately 2° between the duplicate samples is considered minor and may be attributed to local variations in surface roughness, pore distribution, and the uniformity of TMCS coverage across the aerogel surface. Because contact-angle measurement is highly sensitive to the exact location at which the water droplet is deposited, small differences in surface texture and chemical heterogeneity can influence the measured value. Additional experimental factors, including droplet volume, sample levelling, baseline selection, and image-fitting during contact-angle determination, may also contribute to slight variations. Nevertheless, both duplicate samples consistently exhibited contact angles well above 150°, indicating good reproducibility of the surface modification and confirming the superhydrophobic character of the prepared silica aerogel (Akbari et al., 2025; Tian et al., 2015).

Since surfaces with contact angles above 150° are generally classified as superhydrophobic (Wu et al., 2024), the TMCS-modified aerogel is confirmed to be superhydrophobic. This high contact angle likely reflects the combined effect of low surface energy from the silylating treatment and the porous micro/nano-rough structure of the aerogel, which together limit contact between water droplets and the solid surface. Comparable superhydrophobic contact angles have been reported for rice husk-derived silica aerogel (up to 159.5°) and silica-polyimide aerogel blankets (≈ 153°) (Deng et al., 2025; Liu et al., 2021), suggesting that the surface modification applied in this study was effective and may enhance the aerogel's interaction with hydrophobic organic contaminants during adsorption.

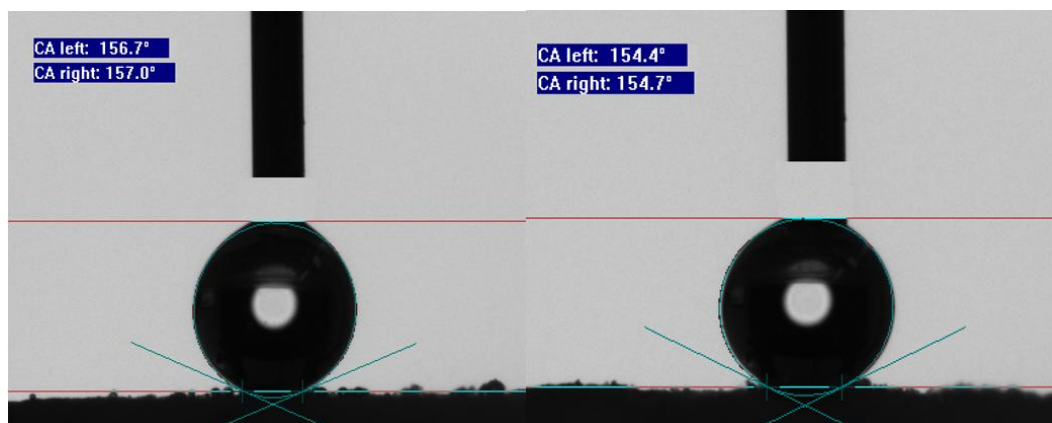


Figure 9: Water contact angles of the silica aerogel.

3.5 Density and Porosity

The bulk density and porosity of the developed aerogel were calculated as 0.18 g/cm³ and approximately 92%, respectively. The low bulk density confirms the lightweight nature of the aerogel and indicates that its porous network was largely retained after ambient pressure drying, while the high porosity shows that roughly 92% of the aerogel volume is void space, with only about 8% occupied by the solid silica framework. This is consistent with the characteristic low-density, highly porous structure of silica aerogels generally (Payanda Konuk et al., 2023), and the porosity value obtained here is comparable to porosities exceeding 90% reported for other rice husk-derived silica aerogels (Ochoa-Munoz et al., 2025). The developed material can therefore be considered highly porous and structurally suited to adsorption, as its open pore network should support mass transfer and access to internal adsorption sites.

3.6 Surface Morphology (SEM)

SEM micrographs at 10, 20, 30, and 100 μ m resolutions (Figure 10) revealed an irregular, rough, agglomerated structure with visible interparticle voids across all magnifications. Lower magnification showed larger porous clusters, while higher magnification revealed finer silica particles and rough micro-domains forming the aerogel network, confirming that the synthesized material is a porous aerogel-like structure rather than a dense silica solid. The agglomerated morphology may partly reflect capillary stress during ambient pressure drying, which can induce shrinkage and local structural rearrangement; nonetheless, the persistence of visible pores and rough texture indicates that the porous framework was substantially retained. Similar porous, mesoporous morphology has been reported for other rice husk ash-derived silica aerogels prepared by sol-gel synthesis and ambient pressure drying (Akhter, Soomro, Jamali, et al. 2023; Deng et al., 2025; Ochoa-Munoz et al., 2025). The rough, porous surface observed here is favourable for adsorption, as it provides accessible surface sites and diffusion pathways for contaminant molecules, supporting the suitability of this rice husk-derived silica aerogel as an adsorbent for water treatment.

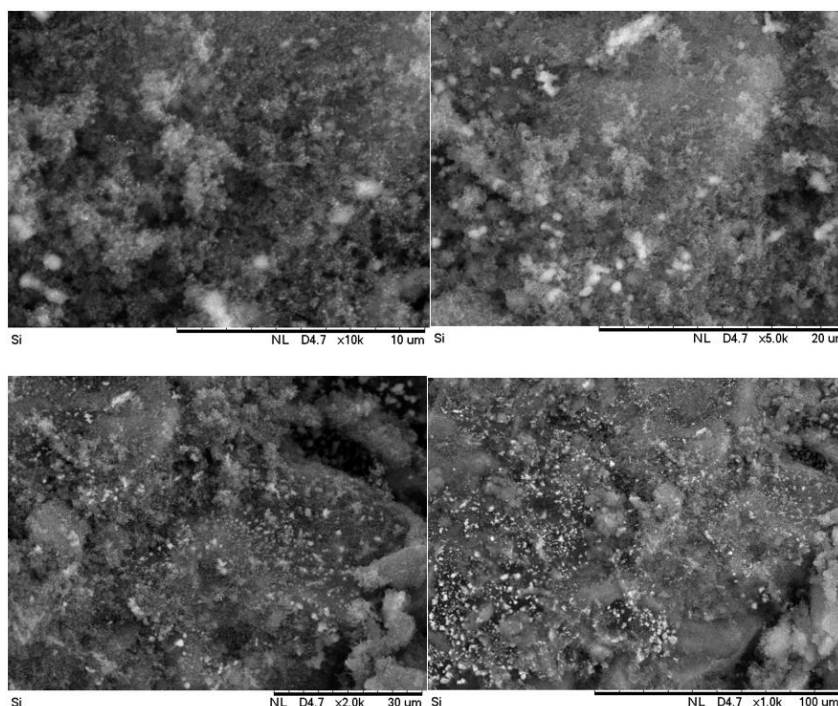


Figure 10: SEM images of the silica aerogel at 10, 20, 30, and 100 μ m resolutions.

Table 2: Summary of textural, chemical, and physical properties of the synthesized silica aerogel

Property	Result
BET specific surface area	303.60 m ² /g (r = 0.999915; BET C = 124.16)
External surface area (t-plot)	303.60 m ² /g
BJH pore radius (adsorption / desorption)	1.687 nm / 1.701 nm ($\approx$ 3.37–3.40 nm diameter)
BJH pore volume (adsorption / desorption)	0.520 cm ³ /g / 0.525 cm ³ /g
Water contact angle (mean $\pm$ SD)	155.70° $\pm$ 1.34° (superhydrophobic)
Bulk density	0.18 g/cm ³
Porosity	$\approx$ 92%

4. CONCLUSION

Hydrophobic silica aerogel was successfully synthesized from rice husk via acid leaching, calcination, alkaline extraction to sodium silicate, acid-catalyzed sol-gel synthesis, ethanol solvent exchange, TMCS surface modification, and ambient pressure drying. The resulting material exhibited a mesoporous structure with a BET specific surface area of 303.60 m²/g, pore diameter of 3.37–3.40 nm, and pore volume of 0.52 cm³/g, alongside negligible microporosity. FTIR confirmed the presence of Si-O-Si and Si-OH functional groups characteristic of a silica network. Water contact-angle measurements (155.70° $\pm$ 1.34°) confirmed superhydrophobic behaviour, while low bulk density (0.18 g/cm³) and high porosity ($\approx$ 92%) confirmed the characteristic lightweight, open-pore structure of silica aerogels. SEM further revealed a rough, porous, agglomerated surface morphology consistent with these bulk properties. Taken together, these results demonstrate that rice husk, an abundant, low-cost, and environmentally sustainable agricultural by-product, can be converted into a hydrophobic, mesoporous silica aerogel with textural and surface properties consistent with materials reported to be effective for adsorption applications and recommend future adsorption studies

REFERENCES

- Akhter, F., Soomro, S. A., & Inglezakis, V. J. (2023a). Green, organic, and facile synthesis of mesoporous silica aerogels for highly efficient Pb(II) removal from synthetic wastewater: Isotherm and kinetic studies. *Biomass Conversion and Biorefinery*. Advance online publication. <https://doi.org/10.1007/s13399-023-04060-9>
- Akhter, F., Soomro, S. A., Jamali, A. R., & Inglezakis, V. J. (2023b). Structural, morphological and physiochemical analysis of SiC₈H₂₀O₄/C₂H₅O/C₇H₁₆ modified mesoporous silica aerogels. *Physical Chemistry Research*, 11(1), 1–8. <https://doi.org/10.22036/PCR.2022.332609.2044>
- Azat, S., Sartova, Z., Bekseitova, K., & Askaruly, K. (2019). Extraction of high-purity silica from rice husk via hydrochloric acid leaching treatment. *Turkish Journal of Chemistry*, 43(5), 1258–1269. <https://doi.org/10.3906/kim-1903-53>
- Bakar, R. A., Yahya, R., & Gan, S. N. (2016). Production of high purity amorphous silica from rice husk. *Procedia Chemistry*, 19, 189–195. <https://doi.org/10.1016/j.proche.2016.03.092>
- Borzova, M., Schollbach, K., Gauvin, F., & Brouwers, H. J. H. (2024). Sustainable ambient pressure-dried silica aerogel from waste glass. *Current Research in Green and Sustainable Chemistry*, 9, Article 100425. <https://doi.org/10.1016/j.crgsc.2024.100425>
- Deng, Y., Sha, Z., Wang, X., Duan, K., Xue, W., Beadham, I., Xiao, X., & Zhang, C. (2025). Exploration of key factors in the preparation of highly hydrophobic silica aerogel from rice

- p>husk ash assisted by machine learning.
- Gels*
- , 11(1), Article 74.
- <https://doi.org/10.3390/gels11010074>
- Goryunova, K., Gahramanli, Y., & Gurbanova, R. (2023). Adsorption properties of silica aerogel-based materials. *RSC Advances*, 13, 18207–18216. <https://doi.org/10.1039/D3RA02462H>
- Halim, Z. A. A., Yajid, M. A. M., & Hamdan, H. (2021). Effects of solvent exchange period and heat treatment on physical and chemical properties of rice husk derived silica aerogels. *Silicon*, 13, 251–257. <https://doi.org/10.1007/s12633-020-00421-5>
- Hamidu, I., Afotey, B., Kwakye-Awuah, B., & Anang, D. A. (2025). Synthesis of silica and silicon from rice husk feedstock: A review. *Heliyon*, 11(4), Article e42491. <https://doi.org/10.1016/j.heliyon.2025.e42491>
- Khedkar, M. V., Somvanshi, S. B., Humbe, A. V., & Jadhav, K. M. (2019). Surface modified sodium silicate based superhydrophobic silica aerogels prepared via ambient pressure drying process. *Journal of Non-Crystalline Solids*, 511, 140–146. <https://doi.org/10.1016/j.jnoncrysol.2019.02.004>
- Liu, R., Wang, J., Liao, J., & Zhang, X. (2021). Robust silica-polyimide aerogel blanket for water-proof and flame-retardant self-floating artificial island. *Frontiers in Materials*, 8, Article 659655. <https://doi.org/10.3389/fmats.2021.659655>
- Ma, H., Wang, B., Zhang, Y., & Zheng, L. (2025). Mechanically reinforced silica aerogels via thermally induced phase separation of poly(ethylene-co-vinyl alcohol). *Gels*, 11(11), Article 870. <https://doi.org/10.3390/gels11110870>
- Minju, N., Nair, B. N., & Savithri, S. (2021). Sodium silicate-derived aerogels: Effect of processing parameters on their applications. *RSC Advances*, 11, 15301–15322. <https://doi.org/10.1039/D0RA09793D>
- Ochoa-Muñoz, Y. H., Guerrero-Calderón, R. S., Mejía de Gutiérrez, R., & Torres-León, J. A. (2025). Rice husk-derived silica aerogels for efficient removal of amoxicillin and erythromycin from water. *Surfaces and Interfaces*, 78, Article 108089. <https://doi.org/10.1016/j.surfin.2025.108089>
- Payanda Konuk, O., Alsuhibe, A. A. A. M., Yousefzadeh, H., Ülker, Z., Bozbağ, S. E., García-González, C. A., Smirnova, I., & Erkey, C. (2023). The effect of synthesis conditions and process parameters on aerogel properties. *Frontiers in Chemistry*, 11, Article 1294520. <https://doi.org/10.3389/fchem.2023.1294520>
- Rahmani, A., Nazemi, F., Barjasteh Askari, F., & Davoudi, M. (2018). Preparation, characterization, and application of silica aerogel for adsorption of phenol: An in-depth isotherm study. *Health Scope*, In Press. <https://doi.org/10.5812/jhealthscope.15115>
- Ransing, A. A., Dhavale, R. P., Parale, V. G., Bangi, U. K. H., Choi, H., Lee, W., Kim, J., Wang, Q., Phadtare, V. D., Kim, T., Jung, W. K., & Park, H.-H. (2023). One-pot sol-gel synthesis of highly insulative hybrid P(AAm-co-AAc)-silica aerogels with improved mechanical and thermal properties. *Gels*, 9(8), Article 651. <https://doi.org/10.3390/gels9080651>
- Soylu, T. M., Özel, C., Karakuzu İkizler, B., Özarslan, A. C., Terzioğlu, P., Başaran Elalmış, Y., & Yücel, S. (2025). Mesoporous silica aerogels for sunflower oil refining and investigation of their adsorption performance. *Journal of Sol-Gel Science and Technology*, 115, 327–348. <https://doi.org/10.1007/s10971-024-06395-9>
- Štandeker, S., Novak, Z., & Knez, Ž. (2007). Adsorption of toxic organic compounds from water with hydrophobic silica aerogels. *Journal of Colloid and Interface Science*, 310(2), 362–368. <https://doi.org/10.1016/j.jcis.2007.02.021>
- Štandeker, S., Veronovski, A., Novak, Z., & Knez, Ž. (2011). Silica aerogels modified with mercapto functional groups used for Cu(II) and Hg(II) removal from aqueous solutions. *Desalination*, 269(1–3), 223–230. <https://doi.org/10.1016/j.desal.2010.10.064>
- Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface

- area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(9–10), 1051–1069. <https://doi.org/10.1515/pac-2014-1117>
- Wang, D., McLaughlin, E., Pfeffer, R., & Lin, Y. S. (2011). Adsorption of organic compounds in vapor, liquid, and aqueous solution phases on hydrophobic aerogels. *Industrial & Engineering Chemistry Research*, 50(21), 12177–12185. <https://doi.org/10.1021/ie201301n>
- Wang, D., McLaughlin, E., Pfeffer, R., & Lin, Y. S. (2012). Adsorption of oils from pure liquid and oil-water emulsion on hydrophobic silica aerogels. *Separation and Purification Technology*, 99, 28–35. <https://doi.org/10.1016/j.seppur.2012.08.001>
- Wu, P., Qi, Y., Wang, Y., Wang, X., Zhang, Y., & Li, X. (2024). Advances in self-healing silica-based superhydrophobic coatings. *Surfaces and Interfaces*, 51, Article 104800. <https://doi.org/10.1016/j.surfin.2024.104800>
- Akbari, R., Ambrosio, F., Berry, J. D., & Antonini, C. (2025). Wetting characterisation on complex surfaces by an automatic open-source tool: DropenVideo. *Journal of Colloid and Interface Science*, 678, 1075–1086. <https://doi.org/10.1016/j.jcis.2024.08.159>
- Tian, T., Tao, H., Xiao, J., Xu, X., & An, J. (2015). A low cost and facile preparation of hydrophobic silica films and powders by a solution-based process. *Journal of Wuhan University of Technology–Materials Science Edition*, 30, 489–493. <https://doi.org/10.1007/s11595-015-1177-7>