

From earth to space: Utilizing agrowaste and sand as earthen materials to develop sustainable silica aerogels for aerospace applications

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Abstract:

Silica aerogel is widely recognized for its extremely low density, high porosity, remarkable optical transparency, and outstanding thermal and acoustic insulation properties—qualities that make it highly suitable for aerospace applications. Despite these advantages, traditional synthesis techniques often depend on costly and hazardous precursors. In this study, we investigate rice husk, an abundant agricultural waste, and beach sand, a naturally occurring geological material in Nigeria, as alternative silica sources. Using sol–gel processing combined with supercritical CO₂ drying, we successfully synthesized and characterized nanostructured silica aerogels. The findings reveal that these aerogels (rice husk and beach sand based, respectively) exhibit a low density (0.53 and 0.68 g/cm³), large surface area (1214 and 635 m²/g), reduced speed of sound (~ 50 m/s in both aerogels), low thermal conductivity (0.16 and 0.17 W/mk), high transmittance (90 % in both aerogels within the visible range of the electromagnetic spectrum) as their physical properties comparable to those produced from conventional precursors, presenting a more sustainable and cost-effective route for the development of advanced materials in aerospace engineering.

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1. Introduction

Aerogels are unique nanostructured materials derived from the sol–gel process, characterized by their exceptionally high porosity. They were first developed in the early 1930s by Kistler, who aimed to create a porous material for fuel storage. By drying silica gels prepared from water glass under supercritical conditions, using solvent exchange to replace the pore liquid (methanol) without collapsing the gel skeleton, he successfully produced silica aerogels (Woignier, *et al.*, 2015; Wesam, *et al.*, 2016). This pioneering work laid the foundation for decades of research, and it was not until the 1980s, when aerogels were applied in Cherenkov detectors, that their full potential began to gain attention. Since then, aerogels have captured the interest of scientists across disciplines, leading to their integration into diverse applications (Arlon and Michael, 1983).

The appeal of aerogels lies in their remarkable physicochemical properties. With an exceptionally high surface area, ultra-low bulk density, extremely low thermal conductivity, low sound velocity, and low refractive index, they serve as thermal and acoustic superinsulators, catalysts and catalyst supports, storage containers for liquid rocket propellants, collectors of cosmic dust, membranes, optical fiber precursors, and in many other

industrial applications. Among the various types, nanosilica aerogels, composed of silicon dioxide, stand out for their extraordinary combination of properties, including low density, low dielectric constant, high optical transparency, and large surface area (Nadiir, *et al.*, 2013).

Traditionally, silica gels have been synthesized from expensive and potentially hazardous sol–gel precursors such as tetramethyl orthosilicate (TMOS), tetraethyl orthosilicate (TEOS), and polyethoxydisiloxane (PEDS). However, the high cost and health concerns associated with these chemicals have encouraged researchers to explore safer, cheaper, and more sustainable alternatives. Recent studies have turned to natural silica-rich resources like rice husk (an agricultural byproduct) and beach sand (a geological material) as promising substitutes (Omatola, *et al.*, 2023).

The choice of rice husk is particularly appealing. With Nigeria and other nations expanding rice production as part of agricultural diversification efforts, husk disposal poses both environmental and health challenges. When burned, rice husk generates about 20% ash, which is rich in silica (80–98%), but open burning often results in air pollution and waste management problems (Omatola and Onojah, 2009; Saleh, *et al.*, 2019; Rana and Das, 2020). Repurposing rice husk as a silica source not only reduces

waste but also adds value to an otherwise underutilized byproduct. Similarly, beach sand, abundant in many regions affected by desert encroachment and the drying of lakes and rivers, offers another accessible silica source for large-scale applications.

Silica occurs naturally in many well-known forms, including quartz, sand, and glass (Azzahra, *et al.*, 2020), and is one of the most abundant elements in the Earth's crust (Permatasari, *et al.*, 2016). It also exists in biological systems, as plants and animals can incorporate silica into their structures. For instance, rice plants absorb silica from soil, storing it in their husks, while sand represents its geological counterpart. By leveraging these natural and renewable sources, researchers can produce nanosilica aerogels in a cost-effective and environmentally sustainable way, without compromising performance (Meftah, *et al.*, 2023).

Silica aerogel has recorded useful applications (Ram and Monika 2012) in:

- a. High - energy physics Cherenkov radiation (electromagnetic radiation emitted by particles that move faster than light within the same material) detectors to capture high velocity particles,
- b. Shock wave studies at high pressures because of their ability to reduce the high velocity of propagating disturbance of the wave,
- c. Inertial confinement fusion (ICF),
- d. Radio-luminescent and
- e. Micrometeorites.

Silica gel is highly valued for its excellent energy-absorbing capacity, which makes it an effective protective material in safety devices. Beyond this, it also serves as a versatile source for synthetic adsorbents, carriers, medical additives, and fillers in composite materials, where it delivers outstanding performance at the nanoscale (Van, *et al.*, 2013).

In recent years, attention has shifted toward utilizing rice husk and beach sand as alternative natural sources of silica. These materials can be processed to extract sodium silicate, which in turn serves as a precursor for synthesizing nanosilica aerogels with properties comparable to those produced from conventional orthosilicates. This marks a significant departure from the use of expensive and potentially hazardous orthosilicate-based precursors. In the Nigerian context, rice husk, an abundant agricultural byproduct, and beach sand, readily available in large quantities, hold great promise as local raw materials that can drive industrialization.

Silica, most commonly found as sand, is abundant in nature and widely distributed. It is also biologically incorporated by plants and animals from soil and water into their structures. Chemically, silica consists of silicon dioxide (SiO_2), formed from the two most abundant elements in the Earth's crust: oxygen and silicon. Given this abundance, there is growing interest in developing nanosilica gels from local, safe, affordable, and sustainable sources such as rice husk and sand. In addition to their accessibility, the conversion of rice husk, often treated as waste and indiscriminately disposed of, into nanosilica gel offers both environmental benefits and economic value. This work therefore serves a dual purpose: demonstrating

the potential of Nigeria's natural resources for advanced material synthesis and contributing new knowledge, particularly on the underexplored use of beach sand for aerogel production.

The significance of this study also lies in its alignment with local content initiatives, which seek to reduce dependence on costly imports while promoting indigenous innovation. By characterizing nanosilica gels derived from rice husk ash and Nigerian beach sand, this research provides important data that could support their adoption in high-tech applications, including aerospace systems.

Globally, silica aerogels continue to attract intense research interest due to their unique properties and versatility. In aerospace technology in particular, they have been employed by NASA in several missions as hypervelocity particle collectors and advanced thermal insulators. Despite this, Nadiir, *et al.* (2013) observed that literature on their broader aerospace applications remains limited. They proposed the development of "Maerogel," a silica aerogel specifically designed for aeronautic use, highlighting the need for continued exploration of this fascinating material.

1.1 Evolutionary trends in silica aerogel production

Aerogels are often called "blue smoke" or "frozen smoke" because of their cloudy, almost ghost-like appearance as shown Figure 1. Essentially, they are gels in which the liquid content has been replaced with air, giving them extremely low density and unique nanostructural features, hence their recognition as an invention of nanotechnology (Nadiir, *et al.*, 2013).

The story of silica aerogel began in 1931, when Steven S. Kistler at the College of the Pacific in Stockton, California, synthesized it through the acidic condensation of sodium silicate (water glass). He went on to study its physical properties, particularly structure, density, and thermal conductivity, under different pressures and gases such as air, carbon dioxide, and chlorofluorocarbons (Kistler, 1935). His work established silica aerogel as the solid with the lowest thermal conductivity at atmospheric pressure.

Kistler soon realized that making an air-filled gel required more than simply drying a wet gel. His first attempt, involving the conversion of water in the gel to a supercritical fluid, failed because the silica dissolved. In 1932, however, he succeeded: he washed the gel to remove salts, replaced the water with alcohol, and then converted the alcohol into a supercritical fluid, which was safely vented. The result was a solid aerogel that was light, porous, and transparent (Arlon and Michael, 1983). Encouraged by this breakthrough, Kistler later produced aerogels from a wide variety of sources, including alumina, nickel tartrate, cellulose, gelatin, agar, egg albumen, rubber, and several metal oxides.

In the 1950s, Kistler joined Monsanto Corporation, which began marketing aerogels as additives in toothpaste and cosmetics. However, production stopped in the 1960s after cheaper fused-silica methods using silicon

tetrachloride became available. Interest in aerogels declined because Kistler's process was costly, tedious, and time-consuming.

The next major milestone came in 1968, when the French government turned to Stanislaus Teichner at Université Claude Bernard Lyon to help address challenges in storing oxygen and rocket fuels using porous materials. Recognizing the limitations of Kistler's method, Teichner applied sol-gel technology to synthesize high-quality silica aerogels more efficiently. This innovation solved many of the earlier challenges and sparked renewed interest in aerogel research and development.

By the 1980s, particle physicists discovered that silica aerogels were excellent for producing and detecting Cherenkov radiation. Large detectors were built in Hamburg, Germany (DESY), and at the University of Lund in Sweden using the TMOS method. However, an accident occurred when methanol leaked during supercritical extraction, causing an explosion (Arlon and Michael, 1983). In 1983, Arlon Hunt and the Microstructure Materials Group at Berkeley Laboratory introduced a safer alternative by replacing toxic TMOS with TEOS and methanol with liquid carbon dioxide, avoiding damage to both the gel and equipment.

In 1996, BASF in Germany advanced this further by developing silica aerogels from sodium silicate with carbon dioxide drying, which they marketed as "Basogel" (Nadiir, et al., 2013). Around the same time, Larry Hrubesh and colleagues at Lawrence Livermore National Laboratory achieved aerogels with record-low densities (0.003 g/cm^3), while Brinker, Smith, and others at the University of New Mexico developed surface-modification techniques that made it possible to produce nanoporous aerogels at lower cost.

Silica itself occurs naturally in several crystalline forms, including quartz, tridymite, and cristobalite, as well as less common phases such as keatite, coesite, and melanophlogite (Rana and Das, 2020; Azzahra, et al., 2020). Over time, researchers have learned to synthesize nanosilica gels from a variety of natural resources—such as rice husk ash, sand, sugarcane bagasse ash, boiler ash, and even volcanic mud—using different techniques. These include spray flame pyrolysis, ethanol-based sol-gel processing, ultrasonication with surfactants, sol-gel with calcination, wet-chemical and dry methods, hydrothermal or co-precipitation approaches, alkali fusion, and mineral carbonation in high-pressure autoclaves (Azzahra, et al., 2013).

1.2 Use of rice husk as silica source

Rice husk ash (RHA) is one of the richest natural sources of silica, containing between 87–97% silica. This makes it an economical and sustainable raw material for producing sodium silicate, which can then be used to synthesize nanosilica. Several studies have explored different techniques to achieve this.

Kamath and Proctor (1998) prepared silica gel from RHA by treating it with 1 M sulfuric acid at pH 7. After aging, washing, and drying, they obtained a slightly basic gel with 65% moisture content, a surface area of $258 \text{ m}^2/\text{g}$,

a pore diameter of 12.1 nm, and particle sizes ranging from 5–40 nm. Jal et al. (2004) followed a precipitation method to synthesize nanosilica, reporting a surface area of $560 \text{ m}^2/\text{g}$, density of 2.2 g/cm^3 , and a particle size of about 50 nm. Infrared analysis confirmed the presence of hydrogen-bonded silanol and siloxane groups.

The cost advantage of RHA-derived silica over traditional precursors such as tetraethyl orthosilicate (TEOS) has been emphasized in several works. Ram and Monika (2012) noted that TEOS not only makes silica synthesis expensive but also poses health hazards, while rice husk, as an agricultural byproduct, provides a safe and abundant alternative. Similarly, Noushad, et al. (2014) synthesized silica nanoparticles using alkaline extraction followed by acidic precipitation, while Ghorbani, et al. (2015) and Abu, et al. (2016) employed thermochemical extraction techniques.

Terkula, et al. (2017) obtained nanosilica from rice husks calcined at $700 \text{ }^\circ\text{C}$. Their XRD analysis revealed an amorphous structure with no sharp peaks, while SEM showed fine aggregated globules of silica. Other studies, including those by, Vaibhav, et al. (2015), and Mor, et al. (2017), confirmed that nanosilica can be produced from RHA with varying degrees of crystallinity and purity, depending on the extraction method. For example, Mor, et al. (2017) reported that nanosilica produced at lower temperatures was amorphous and nearly 99% pure, but that large-scale commercial production would require heating up to $1300 \text{ }^\circ\text{C}$, an energy- and cost-intensive process.

Jembere (2018) prepared amorphous nanosilica gel from RHA via precipitation, finding impurities such as K, Ca, Na, and Al, with silica (SiO_2) making up about 84.47% of the composition. Rana and Das (2020) further highlighted the superiority of RHA over quartz as a precursor, citing its cost-effectiveness, energy efficiency, and high silica content (90.5%). They suggested applications in synthetic chemistry, thin-film coatings, adhesives, and optoelectronic devices. More recently, Sabah, et al. (2020) successfully produced nanosilica using only precipitation, while Sajid, et al. (2022) reported crystalline nanosilica synthesized from RHA calcined at $1000 \text{ }^\circ\text{C}$. Their analysis revealed crystallite sizes of about 60 nm, lattice strain of 2.84×10^{-3} , and FTIR peaks confirming silanol, water molecules, and Si–O–Si bonds.

The progress made in transforming rice husk into silica aerogels has also led to significant technological innovation. Building on the sol-gel route combined with supercritical CO_2 drying, Halimaton filed a U.S. patent in 2004 (granted in 2007, No. 20070276051A1). The patented aerogel, known commercially as Maerogel (short for Malaysia-made Aerogel), marked one of the first large-scale industrial applications of rice husk-derived aerogels (Nadiir, et al., 2013).

1.3 Use of sand as silica source

Research on extracting sodium silicate from beach sand remains limited, likely because of the very high temperatures required to melt sand. Nurulizzah (2010) at Universiti Teknologi Petronas reported the synthesis and

characterization of nanosilica from local siliceous sand, achieving a particle size of about 96 nm as confirmed by SEM analysis. Similarly, Pallavi, et al. (2012) noted that melting quartz sand with sodium carbonate (Na_2CO_3) requires temperatures as high as 1300 °C, yielding only about 60% silica (SiO_2)—a highly energy-intensive process. Ahmed, et al. (2013) explored another route, using silica sand as the raw inorganic material for producing silicon oxide nanoparticles through high-energy milling technology. Ali et al. (2014) synthesized silica gel from sand sourced in southern Tunisia by mixing it with sodium carbonate and heating it to 1060 °C. This process produced silica with a relatively high purity, ranging from 88.8–97.5%.

Khoshman, et al. (2015) investigated thin films grown from Jordanian silica sand. Their EDX analysis confirmed a near-stoichiometric composition of SiO_2 (73.42% Si and 25.83% O). They also highlighted silica's excellent thermal stability, which underpins its common use as a thermal insulator. Further, Munasir, et al. (2015) synthesized silicon oxide nanopowders containing quartz and cristobalite phases from silica sands using both dry and hydrothermal methods. In their process, silica sand powders were mixed with sodium hydroxide to extract sodium silicate. They found the hydrothermal method to be superior, producing 98% pure silica oxide with spherical particles averaging 30 nm in size, characterized by silanol (Si–O), siloxane (Si–O–Si), and OH groups on the surface. Terkula et al. (2017) reiterated that sodium silicate, typically derived by melting quartz sand with sodium carbonate at ~1300 °C, is the key precursor for silica production. However, they emphasized that this route yields only about 60% silica while consuming vast amounts of energy.

2. Materials and method

The nanosilica aerogels used in this study were synthesized from rice husk ash and pulverized beach sand via the sol–gel route, following the method reported by Omatola, et al. (2023). The detailed procedure is outlined below.

2.1 Collection and decontamination of rice husk and beach sand

Rice husks were obtained from a local rice mill, thoroughly washed with running tap water to remove soil and soluble impurities, and then oven-dried at 70 °C for one hour. Beach sand was collected from a riverbank, washed in the same manner, and dried under identical conditions. Both samples were subsequently boiled in

dilute HCl for three hours at 100 °C to achieve demineralization / leaching. Afterward, they were repeatedly rinsed with deionized water and oven-dried under the same conditions as above.

2.2 Production of rice husk ash and pulverized beach sand

The pre - treated rice husks and beach sand were separately calcined in a muffle furnace. The rice husks were heated at 1000 °C, while the beach sand was subjected to 1300 °C, yielding fine silica powders with enhanced reactivity.

2.3 Digestion and precipitation

Twenty grams of each silica powder was digested in 1 M aqueous NaOH at 70 °C for one hour. Using the sol–gel process, the filtrate of the dissolved silica was neutralized with H_2SO_4 to form a hydrogel. The hydrogels were thoroughly rinsed with deionized water, then repeatedly soaked and washed in ethanol to remove residual salts. To strengthen the gel network, the samples were aged in n-hexane to obtain an alcogel.

2.3.1 Supercritical drying

The strengthened gels were dried using an assembled carbon dioxide supercritical dryer specially fabricated for this work. The alcogels obtained were placed in the autoclave part of the dryer and heated to the temperature 31 °C and pressure of 80 bar after the pumping the liquefied CO_2 . The process comprised four stages: elution, diffusion, heating, and evaporation. During elution, liquefied CO_2 displaced the solvent within the solvogel's pores without damaging its structural framework, and the mixture was left for 48 hours. In the heating stage, the CO_2 was brought to its critical point (31 °C, 80 bar). The diffusion stage allowed the supercritical CO_2 to penetrate the gel structure and extract the solvent without crossing the liquid–vapor phase boundary, thereby eliminating surface tension and preventing pore collapse. Finally, in the evaporation stage, the CO_2 was slowly vented, leaving behind a dry, air-filled porous structure—hence the term aerogel.

2.4 Characterizations of the nanosilica gels

The silica aerogels obtained were characterized using a range of instrumental techniques to determine their purity, structural features, particle sizes, as well as their thermal and optical properties.

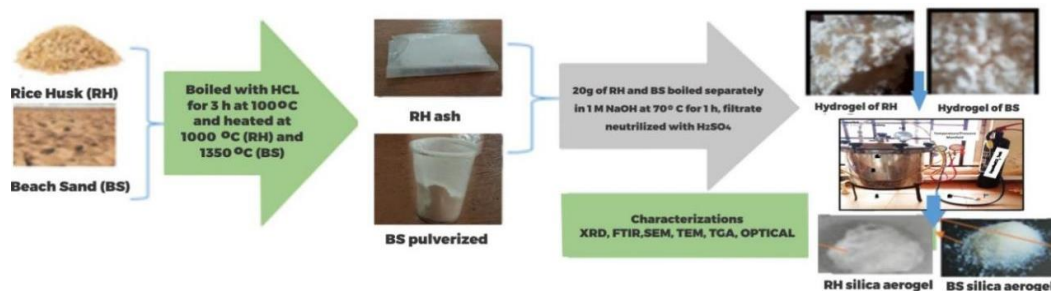


Figure 1: Schematic representation for the synthesis of silica aerogel

2.5 Computational analysis

The density, surface area, refractive index, and dielectric constant were calculated using the equations outlined below. Specifically, the density of silica aerogel was determined using Equation 1, based on the simplified Clausius–Mosotti relation (Dorcheh, et al., 2008), which links the refractive index (n), obtained from the refractometer, to the density (ρ).

$$\rho = \frac{n - 1}{0.19} \quad (1)$$

The surface area (SA) was calculated using Equation 2 (Omatola et al., 2023). This equation relates the density (ρ) of the silica aerogel to its surface area (m²/g) and particle size (d, in nanometres), with the latter determined using a transmission electron microscope (TEM).

$$SA = \frac{6000}{\rho d} \quad (2)$$

Refractivity (R) represents the extent to which a medium bends or deviates a ray of light as it passes through its surface. It is calculated using equation 3, as shown below:

$$R = n - 1 \quad (3)$$

where n is the refractive index of the silica aerogel.

Among porous materials, silica aerogel stands out for its exceptionally low refractivity (Burchell, et al., 2001). The dielectric constant (ε_r), which describes how the material responds to an applied electric field (ε_r), is defined using equation 4 and 5 (Fox, 2010):

$$\epsilon_r = n^2 - k^2 \quad (4)$$

$$k = \frac{\alpha}{4\pi} \lambda \quad (5)$$

Where k is extinction coefficient, λ is wavelength and α is absorption coefficient defined in equation 6:

$$\alpha = \frac{\ln \frac{1}{T}}{d} \quad (6)$$

Where T is transmittance measured using the uv - visible spectrophotometer

The speed of sound, v as a critical parameter in the test of mechanical properties of silica aerogel is determined according to equation 7 (Bi, et al., 2022):

$$V = 48.9 + 0.797\rho + 0.00129\rho^2 \quad (7)$$

The speed obtained from equation 7 is by extension useful in the analysis of the time effect of a force of impact called impulse, Ft according to equation 8, representing Newton's second law of motion:

$$F = \frac{m(v - u)}{t}$$

or Ft = m(v - u) = change in momentum (8)

Where F represents force, t is time, m is mass, v and u for final and initial velocity, respectively.

The Poisson's ratio, ν is given by equation 9 (Lei et al., 2013). It is another mechanical property of a solid material that quantifies its lateral strain response to a longitudinal tensile loading whose values range from 0.2 to 0.5.

$$\nu = 0.3236\rho^{-0.107} \quad (9)$$

3. Results and discussion

The results revealed that the synthesized aerogels possess low density, large surface area, particle sizes below 100 nm, low thermal conductivity, excellent thermal stability, and high optical transmittance across the visible to near-infrared regions of the electromagnetic spectrum. These physical properties obtained using standard characterization techniques, are in close agreement with the findings of Nadiir, et al. (2013), as summarized in Table 1.

Table 1: Comparison of the physical properties of conventional silica aerogel, Maerogel, and BS/ RH aerogels

Property	Conventional aerogel (Nadiir, et al., 2013)	Maerogel (Nadiir, et al., 2013)	BS aerogel	RH aerogel
Density (g/cm ³)	Less than 0.35	0.03	0.53	0.68
Surface area (m ² /g)	600 - 1000	700 - 900	1214	635
Mean pore diameter (nm)	20	20.8	20	20
Poisson's ratio	0.20	0.20	0.17	0.16
Sound velocity (m/s)	100	100	~ 50	~ 50
Young modulus (N/m ²)	10 ⁶ - 10 ⁷	10 ⁶ - 10 ⁷	-	-
Crystallite size (nm)	NS	NS	59.30	63.00
Particle diameter (nm)	2 - 5	5	9.32	13.90
Thermal conductivity (W/mK)	0.015	0.02	0.16	0.17
Optical transmittance	-	-	90% at λ = 500 - 900 nm	90% at λ 600 - 800 nm
Refractive index	1.0 - 1.05	1.0 - 1.05	1.06	1.13
Refractivity (%)	≈ 5	≈ 5	6	13
Dielectric constant	~ 1.1	~ 1.1	~ 1.4	~ 1.3
Maximum absorption wavelength (λ _m) with the ultraviolet region	-	-	225 nm	243 nm

3.1 Density and surface area

In this study, silica aerogels synthesized from rice husk and beach sand, both naturally rich sources of silica, exhibited ultra-low densities of 0.53 and 0.68 g/cm³,

respectively, which align well with values reported in literature. These exceptionally low densities guarantee a high porosity and large surface area suitable for advanced applications, including their uses as structural fillers in

spacecraft, fuel storage media, and efficient particle capture in space (Sonu, et al., 2023). The nanosized dimension (9.32 and 13.90 nm for both aerogels) obtained using the transmission electron microscope (Omatola et al., 2023) and the ultralow density account for the obtained large surface areas (1214 and 635 m²/g) computed from equation 2, desirable in the design and construction of storage medium for aerospace exploration.

3.2 Optical transparency and low refractive indices

Figure 2 (a) and (b) depicts the optical absorbance by the beach sand and rice husk based aerogel, respectively. While Figure 3 (a) and (b) illustrates optical transparency of the beach sand and rice husk derived aerogel, respectively.

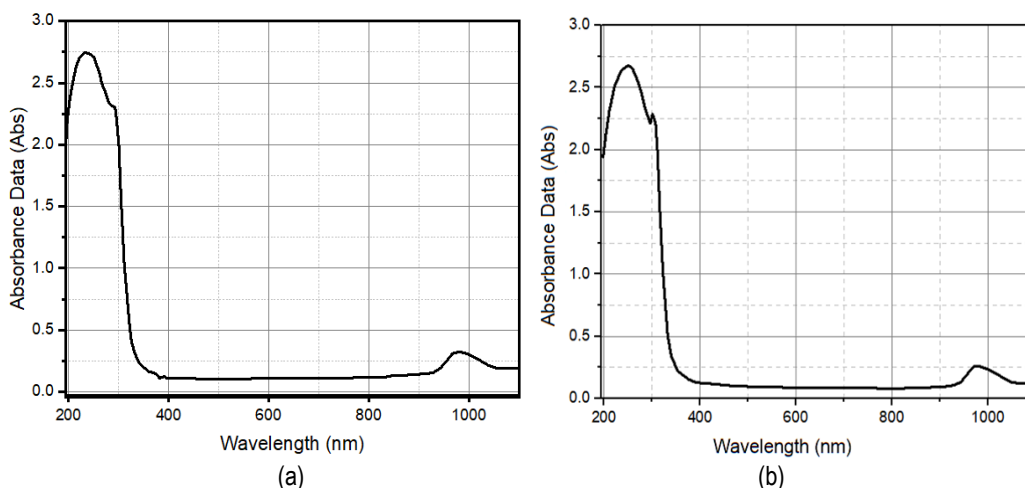


Figure 2: Absorbance versus wavelength for (a) Beach sand Aerogel (b) Rice husk aerogel

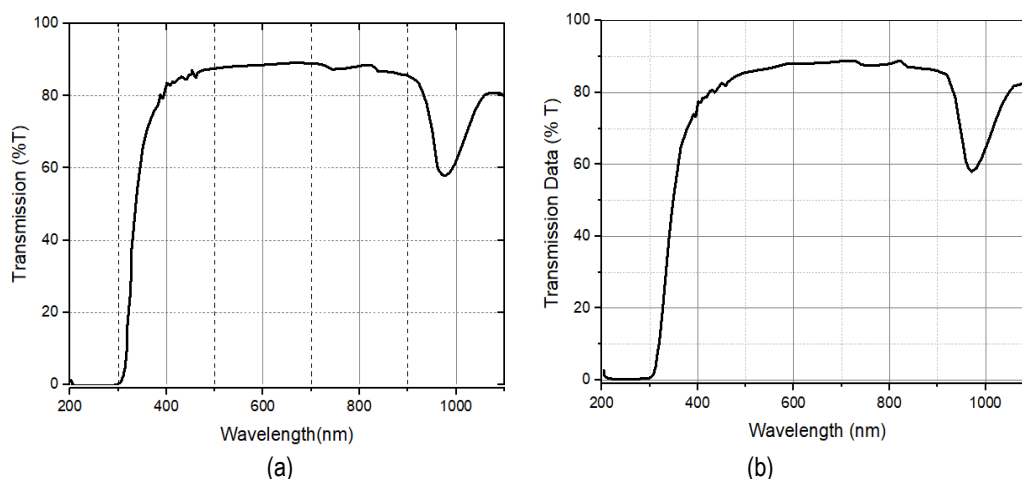


Figure 3: Transmittance against wavelength for (a) beach sand aerogel (b) Rice husk aerogel

Figure 2 illustrates the absorbance against wavelength of the electromagnetic spectrum, particularly from the ultraviolet (uv), visible - near - infrared(NIR) regions. There exists a maximum absorbance by the aerogels in the uv range and extremely minimal absorbances within the visible - NIR regions, thus suggesting the suitability of the produced aerogels as uv attenuators or as radiation shields. However, the aerogels exhibited a high degree of optical transparency as depicted in Figure 3, making them valuable for applications such as hypervelocity particle capture in aerospace exploration. Their ability to transmit light with minimal scattering and low diffusion, owing to their fine particle orientation, can facilitate the detection of cosmic debris (Nadiir, et al., 2013) and supports use in optical waveguides, daylighting devices, and optoelectronic screens (Burchell, et al., 2001;

Torres-Torres, et al., 2015). This property has already been exploited in space missions such as the Tanpopo mission, where silica aerogels were successfully used to capture micrometeorites, interplanetary dust, and even potential biological molecules, highlighting their promise for astrobiological research.

Another key optical property of silica aerogels is their refractive index. The values measured in this study are very close to that of air (~1.0), indicating minimal reflective losses. This unique feature will position them as excellent candidates for Cherenkov detectors, which require media with refractive indices approaching unity (Sumiyoshi, et al., 1998). Beyond aerospace detection systems, the low refractive index of silica aerogels is also being explored in planetary research. For instance, Wordsworth, et al. (2019) reported that silica aerogels can transmit sufficient visible

light to support photosynthesis, while simultaneously blocking harmful ultraviolet radiation and raising surface temperatures above water's melting point, an attribute that could one day make habitation on Mars more feasible.

3.3 Thermal insulation

The silica aerogels produced here have shown a very low thermal conductivity even at increasing temperature according to the results obtained using the Hot - Disk Constants Analyzer. Silica aerogel is renowned for its exceptionally low thermal conductivity, which has earned it the reputation of being a 'super-insulating' and fire-retardant material. Unlike sand or water, which is traditionally used to extinguish fires but is heavy and difficult to transport, silica aerogel offers a lightweight alternative with significant economic advantages since it can be derived from sand. Its combination of low density and superior insulation properties makes it particularly attractive for use in thermal protection systems, such as insulating pipes, wires, and electronic components within the fire zones of aero-engines. Compared to conventional metal sheets, it provides both weight reduction and enhanced safety. Being inorganic and non-flammable, silica aerogel can withstand continuous operation between $-273\text{ }^{\circ}\text{C}$ and $650\text{ }^{\circ}\text{C}$ and has a very high melting point. Unlike many existing organic fire-proof coatings, it does not release toxic fumes when exposed to high heat (Nadiir, et al., 2013).

The National Aeronautics and Space Administration (NASA) recognized these advantages as early as 1997, when silica aerogel was incorporated into the Mars Pathfinder mission. It was packed into composite boxes, known as Warm Electronics Boxes (WEBs), to protect sensitive instruments such as the Alpha Particle X-Ray Spectrometer (APXS). These boxes ensured that the instruments stayed within their operational range of $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$, despite Mars' extreme cold. The success of this application led to further use of silica aerogel in the 2003 Mars Exploration Rovers, Spirit and Opportunity. In these missions, aerogel worked alongside radioisotope heater units (RHUs) to buffer temperature swings of nearly $100\text{ }^{\circ}\text{C}$ between Martian day ($+20\text{ }^{\circ}\text{C}$) and night ($-90\text{ }^{\circ}\text{C}$). Originally intended to last just three months, Spirit continued operating until March 2010, covering 7.7 km in total, while Opportunity functioned even longer.

These achievements will continue to demonstrate the extraordinary durability of silica aerogel in harsh environments. Its ultralight structure not only resists extreme temperature fluctuations but also provides long-lasting thermal insulation, making it indispensable for aerospace applications (Eisen, et al., 1998; Hickey, 1997; Mars Rover, 2013).

3.4 Sound insulation

Silica aerogel can slow down the propagation of sound waves to as low as $50 - 100\text{ m/s}$, making it an effective noise silencer. This property arises from its very low Young's modulus (Nadiir, et al., 2013). By the reduction in the speed of sound to 50 m/s within the structure of the produced silica aerogels further affirm them

as a kinetic energy absorber, and hence help to minimize force impacts when being used to construct safety devices. This kinetic energy absorbing property can earn its use as mechanical impact absorber in airbus via the elongation of the time effect of the force - called impulse, a consequence of Newton's second law of motion. The reduction in the speed of a penetrating object into the aerogel will make the force of impact to reduce drastically, hence rendering the silica aerogel as a safety material. This trait is employed in the design of aerospace safety features in crumple zones to absorb and distribute impact forces over a longer duration of time thereby reducing peak forces exerted on components and humans.

4. Conclusion

This study has demonstrated that silica aerogels derived from beach sand and rice husk as earthen materials combine lightweight structure, high surface area, and by extension high porosity, and multifunctional performance. Both materials exhibited strong ultraviolet absorption, high transmittance in the visible-NIR range, and refractive indices close to air, underscoring their potential in UV shielding, solar energy systems, and optoelectronic devices. Their exceptionally low thermal conductivity and acoustic damping properties further highlight their suitability for thermal protection, fire-retardant coatings, and impact absorption applications. Importantly, producing these aerogels from abundant natural resources offers a sustainable and low-cost alternative to conventional silica aerogels, opening opportunities for broader use in aerospace, energy, and advanced material technologies.

Recommendations

- Explore doping and composite development to improve strength, stability, and optical performance.
- Develop low-cost, large-scale synthesis methods for industrial applications.
- Conduct long-term tests under humidity, thermal cycling, and radiation exposure.
- Evaluate performance in solar cells, UV-protective coatings, thermal insulation, and impact-absorbing systems.

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