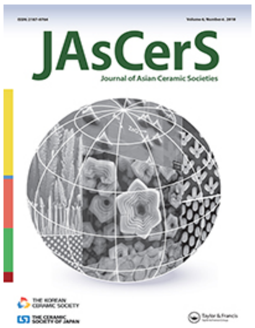

Journal of Asian Ceramic Societies

ISSN: (Print) 2187-0764 (Online) Journal homepage: https://www.tandfonline.com/loi/tace20

Rice husk/rice husk ash as an alternative source of silica in ceramics: A review

SK S. Hossain, Lakshya Mathur & P.K. Roy

To cite this article: SK S. Hossain, Lakshya Mathur & P.K. Roy (2018) Rice husk/rice husk ash as an alternative source of silica in ceramics: A review, Journal of Asian Ceramic Societies, 6:4, 299-313, DOI: 10.1080/21870764.2018.1539210

To link to this article: https://doi.org/10.1080/21870764.2018.1539210

Accepted author version posted online: 24 Oct 2018.
Published online: 08 Nov 2018.

JOURNAL OF ASIAN CERAMIC SOCIETIES
2018, VOL. 6, NO. 4, 299–313
https://doi.org/10.1080/21870764.2018.1539210

THE CERAMIC SOCIETY OF JAPAN · THE KOREAN CERAMIC SOCIETY · Taylor & Francis Taylor & Francis Group

REVIEW ARTICLE

OPEN ACCESS · Check for updates

Rice husk/rice husk ash as an alternative source of silica in ceramics: A review

SK S. Hossain, Lakshya Mathur and P.K. Roy

Department of Ceramic Engineering, IIT (BHU), Varanasi, India

ABSTRACT

Use of waste or by-products from different industries and the agricultural sector has received increasing attention in the scientific, technology, ecological, economic and social spheres in recent years. Rice husk (RH) is a by-product of rice milling and rice husk ash (RHA) is generated by combustion in a separate boiler. Both RH and RHA are abundantly accessible in rice growing countries such as China, India, Brazil, the USA, and Southeast Asia. RH has therefore been recycled by burning it for energy production. This generates RHA, which contains a huge quantity (85–95%) of amorphous silica. Over the past two decades, RHA has been used extensively in numerous fields for manufacturing of different silicates, zeolites, catalysts, nanocomposite, cement, lightweight construction materials, insulators, and adsorbents. This paper presents a comprehensive overview on the processing of nano-silica from RH/RHA. It tries at the same time, to present a critical review of the application of RHA as an ingredient for the production of various ceramic materials, e.g. refractory, glass, whiteware, oxide and non-oxide ceramics, silica aerogel and SiO_2/C composites. In summary, amorphous silica derived from RHA or RH provides a potential alternative to conventional silica sources (e.g. quartz) for the manufacture of value-added ceramics for practical applications.

ARTICLE HISTORY
Received 7 June 2018
Accepted 3 October 2018

KEYWORDS
Rice husk; rice husk ash; waste; ceramic; silica

1. Introduction

Today, the whole world is suffering from two types of problem, i.e. disappearance of virgin resources and the production of excess waste. From the perspectives of the economies, energy needs, and environments of developing as well as developed nation, the only way to eliminate these problems is to utilize these wastes in the main streams of production. In accordance with this realization, every production sector is looking to raise its income by using waste as a resource in its products. Similarly, the ceramics industry is also seeking to utilize waste in its productions. Much research has been conducted in last few decades to achieve this goal of the ceramics industry [1,2]. As a result, some waste has been identified as potential ingredients for use in the production of ceramics, e.g. fly ash [3,4], bottom ash [5], blast furnace slag [6], glass waste [7], petroleum waste [8], polished tile waste [9], paper-processing residues [10], waste marble powder [11], water treatment sludge [12] and oil production waste [13].

Ceramics are solid compounds of inorganic, non-metallic and metalloids atoms bonded primarily by a mixed type of bonding comprising of ionic and covalent bonds. Richerson et al. [14] defined ceramics as "most solid materials that aren't metal, plastic, or derived from plants or animals." Ceramics have some distinctive properties not offered by metals, including good chemical inertness, high-temperature stability, brittleness, a high melting point, and an electrical insulation capability. Due to these properties, ceramics offer a wide range of applications for modern society. In a broad sense, ceramics can be regarded as refractories, glass, tiles, sanitary ware, tableware, and ceramics for electrical applications [15]. In all these industries, silica (SiO_2) is the most important ingredient for production. Due to the massive use of silica in ceramic products, silica is believed to be the backbone of the ceramics industry [16]. Most manufacturers use silica sand, gravel, sandstone, granite, quartz, and quartzite as a silica source for the manufacture of ceramics [17]. All these sources of silica are found in nature. With the use of these raw materials, our problem remains the same, i.e. a loss of virgin raw materials. Therefore, the whole world is looking toward waste utilization to obtain silica. RHA is found to be the most promising waste to serve as a potential silica source.

Rice is the second most widely consumed food item globally, with rice paddy production registering about ~ 758 million metric tons in 2017, a number that will increase gradually due to the projected demand of the world population [18]. The statistics for rice paddy production in different countries according to production volume in 2017 is shown in Figure 1 [19]. China and India are the leading countries for rice paddy production, accounting for around 48.87 wt.% of the total volume of rice paddy production. Rice husk (RH) is a by-product of the industrial processing of rice and approximately 20 wt.% of bulk grain weight. The main constituents of

CONTACT SK S. Hossain saddamh.cer15@iitbhu.ac.in

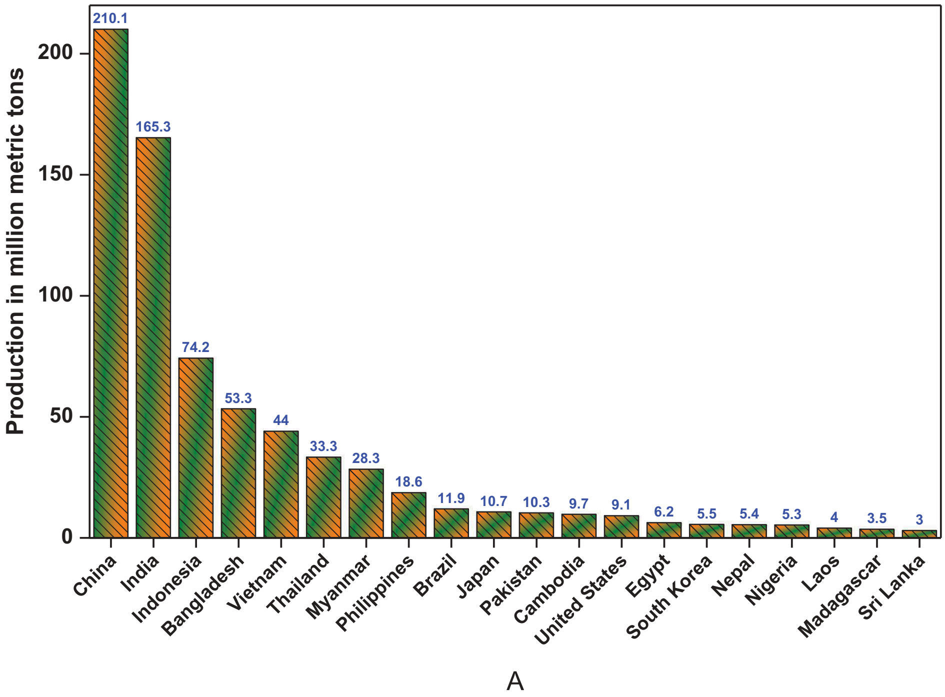

Figure 1. Statistic of rice paddy production of different country in 2017 [19].

RH are 70–80% organic substances such as cellulose, lignin, etc, and the remaining 20–30% comprise mineralogical components such as silica, alkalis and trace elements [20]. Due to its high calorific value (16,720 kJ/kg), most can be used as fuel in boilers for energy production through direct combustion or by gasification [21]. This burning generates new waste, designated as rice husk ash (RHA), which is roughly 25% of the initial husk weight and which causes environmental pollution as well as disposal problems [22]. Therefore, 1000 kg of paddy grain produces about 200 kg (20%) of RH, and when it is burned to generate energy, about 50 kg (25%) of RHA is generated, a volume containing around 45 kg (85–95 %) of amorphous silica. The properties of RHA depend on the ecological circumstances of its origin as well as the process applied for burning the husk [23]. It has a high silica content in the amorphous form, which has broad applicability in industries including ceramics, construction, chemicals and electronics among others [24]. Consequently, numerous investigations have been carried out to benefit from this aspect of RHA's applications.

Prasara-A and Gheewala [25] discussed sustainable use of RHA on a "triple bottom line" basis, i.e. economic, social and environmental. However, the technical viability or performance of RHA in different sectors is not covered by this study. Pode [26] extensively discussed RHA generation in different countries and its applications for advanced materials fabrication in several fields. Soltani et al. [27] spotlighted the applications of RH in different fields and discussed the uses of RH silica to synthesize some advanced non-oxide ceramics, silicon, and nano SiO_2, and their different fabrication processes as well as the process parameters. Liu et al. [28] elaborated the pozzolanic and adsorbent characteristics of RHA in a study. Shen (China) [29] reviewed current growth in the preparation of RH silica and its applications in environmental and energy functional materials. Shen et al. (Japan) [30] extensively discussed RH-derived porous silica and carbon and their application in the synthesis of zeolite materials, non-oxide ceramics, silica aerogels (SAs) and mesoporous or hierarchical carbon. As per our survey of the literature, no review articles were found that contain a wide discussion of "RHA as a replacement for silica in different areas of ceramics." This study presents a comprehensive summary of recent progress in the use of RHA as an alternative for silica in the manufacture of different ceramic materials, including both traditional and advanced ceramics.

2. Extraction of silica from RH/RHA

Silica is an important raw material for different industries including ceramics. It has a wide range of applications as a raw material in different fields of the ceramics industry. Quartz is a crystalline form of silica, which is mainly used in industry. Recently, the use of amorphous silica is gradually increasing due to some properties distinct from those of crystalline silica, i.e. the greater reactivity of amorphous silica. Fused silica, the main source of amorphous silica in industry, is expensive because it is an industrial product. RH/RHA can solve this difficulty, however due to its enormous active silica content and abundant availability. Therefore, several researchers are investigating economical, eco-friendly, easy ways of extracting high-purity silica from RH/RHA.

Broadly speaking, two types of synthesis methods were reported for extraction of silica, i.e. the chemical method and combustion method. The present review article considers only these extraction methods.

2.1 Combustion method

Direct combustion is the oldest and most widely used method of obtaining energy from biomasses or agriculture residues. This process is used in both domestic and industrial activities; it can be conducted in open fire stoves or different type of boilers, such as fluidized bed, stoker and suspension-fired boilers [31]. Oxygen present in the biomass acts as an oxidizing agent during the oxidation reaction of burning, which is an exothermic reaction. In the burning process, biomass is oxidized by the combustion, resulting in heat energy and a combustion product (ash). Heat produced in this burning is used to generate steam or reused later for drying operations through heat exchangers. The high-temperature and high-pressure steam drive the blades of a turbine that produces electricity.

90 wt.% of RH is used as a fuel to generate energy through a combustion process [32,33], moreover, due to the high energy potential of RH of around 15 to 18 MJ/Kg [34]. After combustion of RH, about ~ 20 wt. % of ash known as RHA is generated. RHA contains more than 85 wt.% of silica in its composition. The chemical composition of RHA, which was analyzed in different studies, is shown in Table 1 [35–37],. The composition variations of RHA depend mainly on the type of soil, weather conditions, agronomic handling and other parameters [37,38]. Typically, RHA containing silica is the amorphous form found in nature as verified by the XRD diagram, i.e. the absence of any crystalline peak, shown in Figure 2 [35].

Table 1. Chemical composition of RHA.

References	Bhardwaj et al. (35)	Gomes et al. [36]	Van et al. [37]
SiO_2	92.810	86.0	87.40
Na_2O	2.658	0.05	0.04
Al_2O_3	-	5.12	0.40
P_2O_5	1.071	0.48	-
K_2O	1.021	1.82	3.39
CaO	0.417	1.26	0.90
Fe_2O_3	0.312	1.12	0.30
MgO	0.212	0.48	0.60
SO_3	0.132	2.79	3.39
TiO_2	0.112	0.17	-
Others	1.255	0.71	3.58

Gomes et al. [36] discussed bubbling fluidized-bed combustion (BFBC) for RHA generation and the different parameters such as fluidization velocity, combustion temperature and elutriation behavior, which influence the characteristics of silica as well as its purity. A schematic diagram of RHA generation through BFBC is presented in Figure 3. The particle diameters are improved with increasing combustion temperature and fluidization velocity from 0.30 to 0.50 m/s. Bakar et al. [39] synthesized high-purity amorphous silica by combustion after acid treatment of RH. The purity of silica increased due to acid leaching of RH from 95% to around 99%. Subsequently, the specific surface area improved significantly with acid treatment. Sankar et al. [40] used the same process for the extraction of nano-silica powder from RH. They used acid treatment after the formation of RHA; however, it annealed again at 700ºC for 2 h. Another researcher also performed acid treatment of RH but in a controlled atmosphere, i.e. high pressure (2 kgf-cm^{-2}) and temperature (150°C) [41]. Gu et al. [42] discussed the kinetics of various pretreatments of RH before calcination deeply, i.e. water soaking, acid leaching and grinding. These pretreatment processes greatly influence the removal of metallic impurities and decomposition of organic matter in the

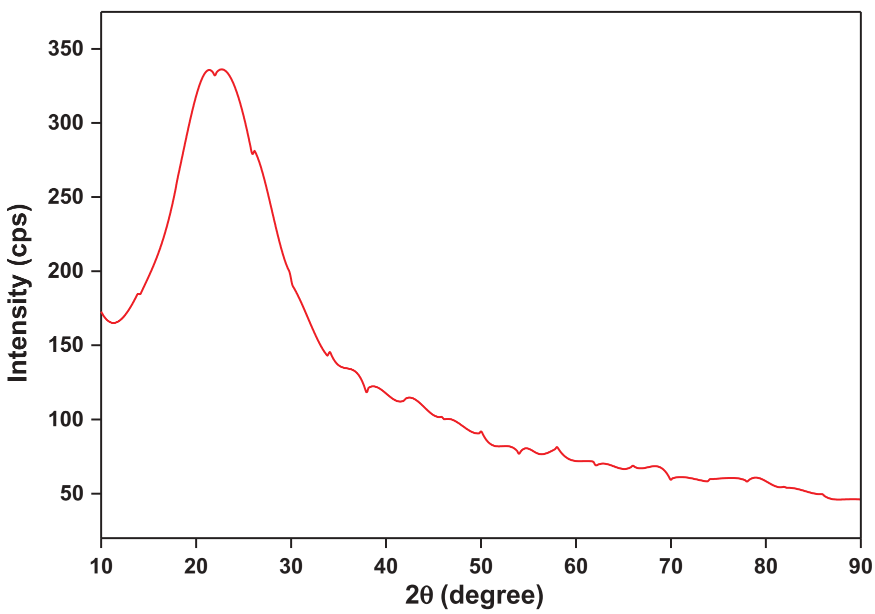

Figure 2. XRD image of RHA.

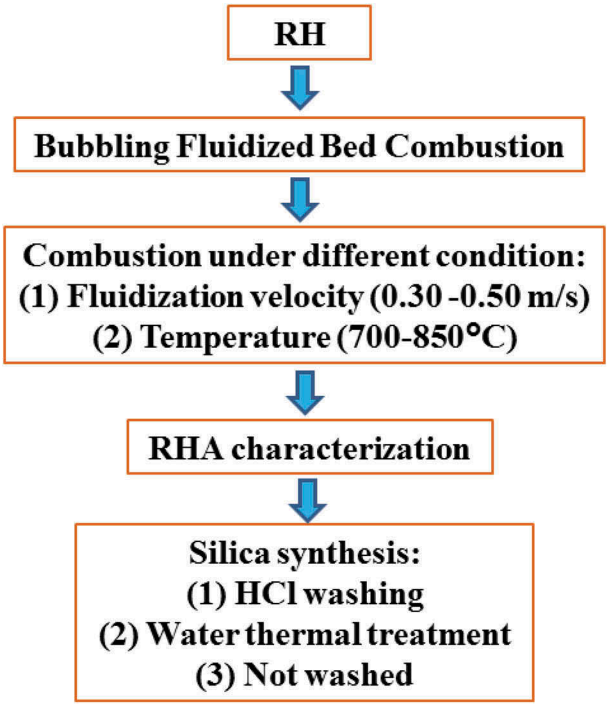

Figure 3. Experimental procedure flowchart of BFBC for RHA generation [36].

preparation of amorphous silica. The characteristics of powders (purity, surface area, and particle size) prepared by different researchers using different techniques are demonstrated in Table 2.

2.2 Chemical method

High-purity nano-silica has recently found wide-ranging applications in different fields such as pharmaceuticals, dyes, chromatography, drug delivery systems, electronic components, catalysts and adsorbent materials [43,44]. As a result, demand for high-purity silica is increasing. Combustion-derived RHA (without acid or alkali treatment) contain less than 95 wt.% of SiO_2, and the remaining part comprises different alkali oxides and impurities. With appropriate acid or alkali treatment of RH/RHA, however, the SiO_2 content can be increased in the system to more than 99 wt.%. Several researchers have therefore adopted different chemical routes to derive high-purity nano-silica.

Zulkifli et al. [45] extracted silica particles from RH by the alkali extraction method using the process shown in Figure 4. Initially, RHA was treated with HCl in a water bath at 75°C for 4 h to remove metallic impurities. Filtration was done by repeatedly washing it with DI water until the pH reached 7, and then drying it at 110°C for 12 h. The sample was reacted with NaOH to prepare sodium silicate solution with constant stirring for 1 h at 90°C. The sodium silicate solution was then reacted with ethanol, and water was added with constant stirring for 10 min. The whole mixture was titrated with 3 M H_3PO_4 till gel formation occurred. Centrifugation of the yellowish gel was conducted, and the product was washed with DI water to remove any excess sodium silicate and phosphate, followed by calcination to obtain silica particles. The following formulas can represent the overall chemical reaction:

$$SiO_2(s) + 2NaOH(l) \rightarrow Na_2SiO_3(l) + H_2O(l) \quad (1)$$

$$3Na_2SiO_3(l) + 2H_3PO_4(l) \rightarrow SiO_2(s) + 2Na_2PO_4(l) + 3H_2O(l) \quad (2)$$

Santana and Paranhos [46], and Zulfiqar et al. [47] extracted silica by the same method with some modifications. They extracted silica from RH in two steps: (i) conversion of RH into RHA; and (ii) formation of amorphous silica. They used concentrated H_2SO_4 and H_3PO_4 for precipitation of SiO_2 particles from silicate solution. The properties of the silica particles are tabulated in Table 2.

Song et al. [48] used the Taguchi method for extraction of silica from RH; it consists of two steps: the first comprising the formation of ash from RH, i.e. RHA, and the second corresponding to production of silica particle form this RHA, i.e. the Taguchi method. Flow charts of the two steps are shown in Figure 5(a) and (b), respectively. To complete the first step, the whole RH was washed and leached to remove impurities followed by screening with one 820 μm sieve. The sieved mass was then washed with deionized water with continuous stirring for 1 h and dried at 70°C to remove adhering dust. The dried mass was then leached with 1 M HCl for 2 h at 90°C. Now the whole sample was rinsed repetitively

Table 2. Properties of extracted silica by different method.

Process	BET surface area (m^2/g)	Particle size	SiO_2 (%)	Ref.
Fluidized bed combustion	Not mention	750 μm	86.00	Gomes et al. [36]
Acid treatment before combustion	208–218	0.50–0.70 μm	> 99	Bakar et al. [39]
Acid treatment after combustion	200–247	10–20 nm	Not mention	Sankar et al. [40]
Acid treatment (control atmosphere) before combustion	Not mention	181–294 nm	Not mention	Carmona et al. [41]
Alkali extraction	364	75–252 nm	Not mention	Zulkifli et al. [45]
Alkali extraction	173–294	Not mention	96.35–98.34	Costa and Paranhos [46]
Alkali extraction	200–339	63–170 nm	95.9	Zulfiqar et al. [47]
Alkali extraction	7.93–740.77	24–87 nm	95.68–99.89	Song et al. [48]
Hydrothermal	Not mention	10–50 nm	Not mention	Tolba et al. [50]
Hydrothermal	Not mention	15–35 nm	Not mention	Bathla et al. [51]
Carbonation	Not mention	Not mention	99.97	An et al. [52]

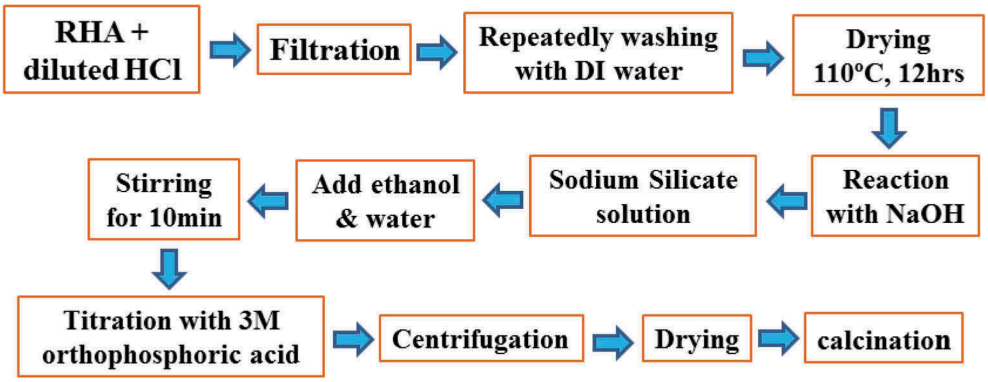

Figure 4. Extraction method of silica from RHA [45].

with DI water and calcined at 700°C for 2 h. This dried mass was marked as RHA. The second step, extraction of silica by the Taguchi method, is shown in Figure 5(b). RHA was used as an ingredient and mixed with 1.5 M NaOH and heat-treated at 90°C for 1 h. This sodium silicate solution was diluted to 1 M by adding DI water and titrated against 1 M HCl up to pH 7 to neutralize the solution. The sol was stirred until a gel was formed and then dried at 70°C for seven days for aging, followed by centrifugation at 10,000 rpm.

Liou and Yang [49] studied the different parameters of silica production from RHA through the alkali-extracted route. The acid and alkali concentrations, gelation pH, aging time and temperature were optimized for preparation of SiO_2 nanoparticles from RHA. The effects of different acids on the surface area and particle size of silica were also evaluated.

Tolba et al. [50] introduced a new technique of synthesizing nano-silica from RH, i.e. the hydrothermal route. A clean 2 g of RH was mixed with 10 mL of nitric acid and 10 mL of distilled water, and the mixture was placed in an autoclave for complete reaction at different temperatures, pressures and times. The resultant product was filtered and washed several times with distilled water to remove excessive acid and dried at 60°C to obtain white nano-silica. Bathla et al. [51] also used a different type of hydrothermal synthesis process to fabricate nano-silica from RH. First, organic acid leach RH was used to produce RHA at 700°C. Then the RHA was mixed with ferric nitrate $[Fe(NO_3)_3 \cdot 9H_2O]$ in a ratio of 1:6

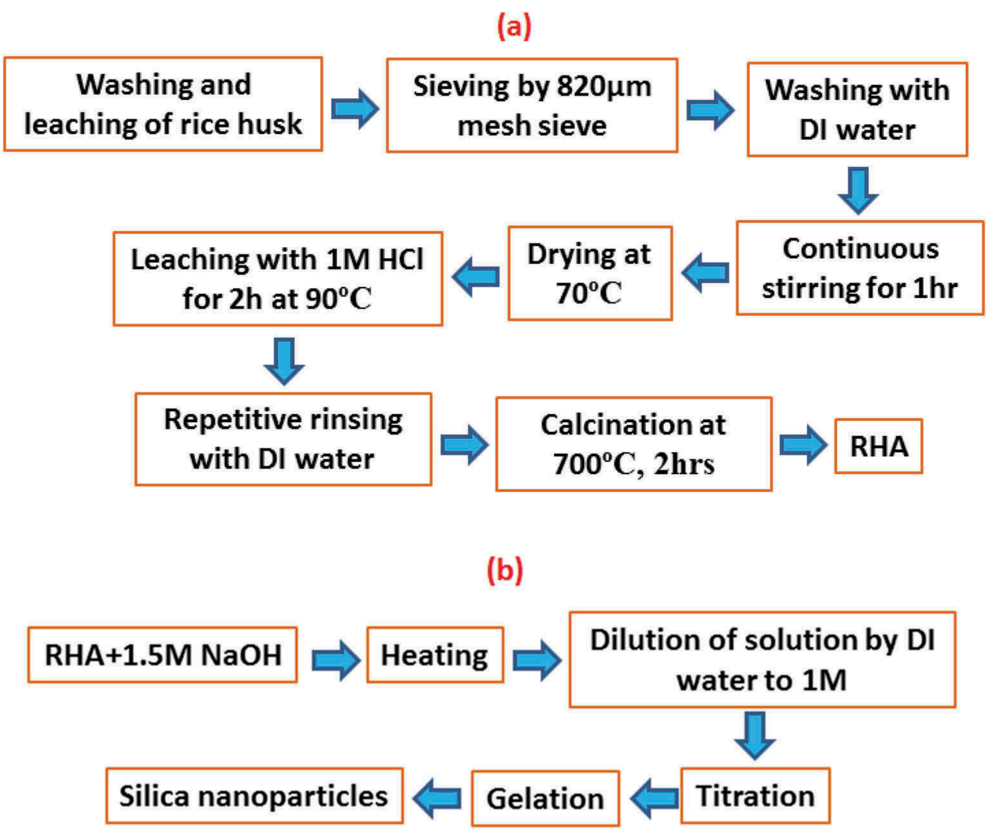

Figure 5. (a and b). Taguchi method for extraction of silica from rice husk [48].

and calcined at 420°C to obtain a composite powder. 2.5 gm of the composite powder was mixed with 25 mL of water and 40 mL of edamine [$C_2H_8NH_2$] and autoclaved for 5 days at 200°C. After completion of the reaction, centrifugation was used to separate the product from the solution, and the product was then washed several times with DI water. Fe_2O_3 was removed from the system by repeating the acid-leaching process, and white amorphous SiO_2 was finally obtained. Subsequently, An et al. [52] also developed a new route for preparation of silica from RHA via a carbonation process. Here, Na_2CO_3 was used as a reagent for SiO_2 extraction. However, this route is complicated due to the multiple processing steps, and efficiency is low at around ~ 72%.

Silica was extracted by different methods, which are included in Figure 6. In conclusion, it was found that silica extraction directly from RH is not economical or efficient (due to its high volume). For economical utilization, RH must first be used as a fuel for boilers, where it produces RHA as waste. Silica extraction from this waste can be done by two routes, which differ from each other in the purity of their end products. If RHA is used directly without any treatment, it gives 83–95% pure silica, while treatment of RHA with acid yields more than 95% pure silica. For high-purity silica, alkali extraction or other chemical methods which give greater than 99% pure nano-silica should be used.

3. Application of RH silica

In past few decades, many researchers have shown an interest in applying RH silica in several fields. The present article has attempted a review of their work with reference to ceramics. Application areas of RH silica in different ceramic fields are illustrated in Figure 7.

3.1 Refractories

Because RHA has low thermal conductivity (κ), it can be used as an ingredient in the manufacture of insulation refractories. The κ of refractory materials is ascribed to vibrating atoms caused by phonons (low temperature) and photon conductivity (high temperature) in crystalline materials. RHA containing silica is amorphous, however, which causes it to act as a non-heat conducting ingredient in refractories [53]. RHA insulation refractories are fabricated by mixing of different flux contents (as binder), plasticizers (due to the lack of plasticity of RHA) and pore-forming agents (to increase the porosity of final products) [23,35,54]. Air is entrapped in the pores of refractories, a characteristic which is attributed to lower values of κ, because entrapped air acts as a barrier to the flow of heat. These insulating refractories may be used as a second lining of furnaces or kilns in ferrous or non-ferrous industries. RHA is also used in ferrous industries for the casting of steel and for molten metal insulation in ladles and tundishes [55,56]. This insulation of molten metal prevents cracks in the structure of refractories that can occur due to temperature drops of 200°C when molten metal is transferred from a ladle to a tundish. The low thermal conductivity of RHA also leads to a gradual decrease in the temperature of steel, and moreover to its uniform solidification. In addition, several researchers are trying to use RHA in the production of advanced refractories, such as cordierite [57,58], forsterite [59] and mullite refractories [60].

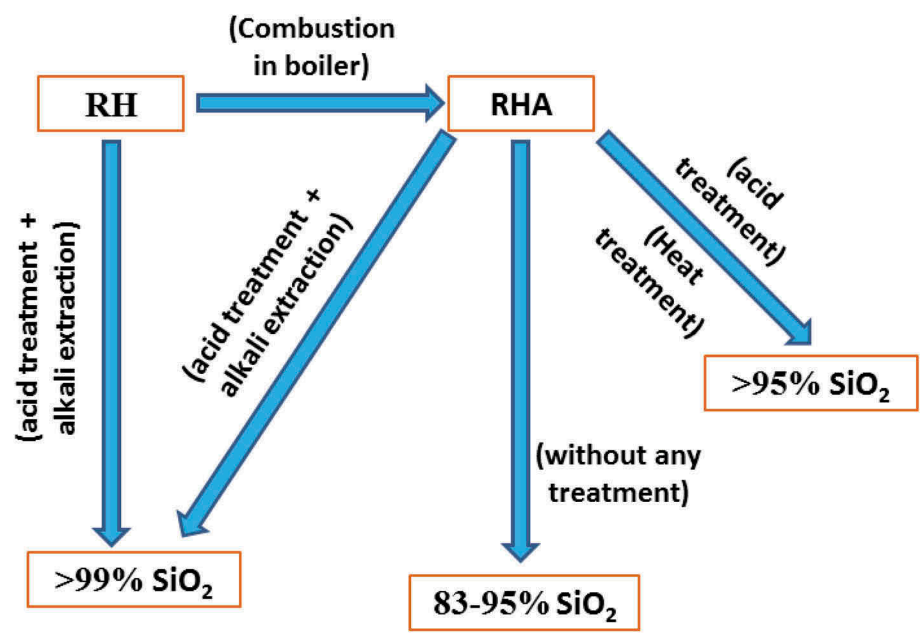

Figure 6. Conclusion of different methods.

Figure 7. Application of RH silica in ceramics.

3.2 Glass

Glass is a non-crystalline supercooled liquid. Generally, glass is amorphous; however, "glass ceramics" are a crystalline form of glass. Present-day glass is one of the most widely used materials for innumerable purposes, and the number is increasing tremendously. Silica (SiO_2) is the major ingredient for glass making, acting as a "network-former" in glass networks. Huge silica resources are therefore required for glass industries. For this reason, researchers are trying to find alternative sources of silica. RHA has tremendous potential to fulfill this requirement because it contains more than 90 wt.% of amorphous silica. Lee et al. [61] used RH silica to fabricate photoluminescent (PL) glass by two different routes, i.e. the mixing technique and the layering technique. For the mixing technique, PL pigment and molten glass were mixed directly; for the layering technique, however PL pigment was sandwiched between two layers of RH glass. This waste-derived glass is analogous to ordinary silica glasses, which should see their applications expand. Glass ceramics have some unique properties lacking in glass, such as mechanical, thermal, optical and electrical properties; these make them useful in other fields besides glass. Andreola et al. [62] and Sharma et al. [63] prepared glass ceramics using RHA as a silica source. Chen et al. [64] synthesized mesoporous bioactive glass (MBG) from RHA using the sol–gel method for application in drug delivery and bone regeneration. The obtained results exhibit excellent biocompatibility with no cytotoxicity in normal cells and MBG-folic acid with camptothecin (a water-insoluble anticancer drug) that destroys the cancer cells efficiently and selectively. It can be concluded that RHA-derived MBG can potentially be used in medical applications. Other researchers have therefore also prepared bio-glass from RHA by the sol–gel method [65].

3.3 Whiteware

Silva and Surangi [66] studied the effects of RHA addition for partial replacement of clay in the composition of clay roof tiles used for roofing buildings. Their study concludes that 10 wt.% RHA addition shows a ~ 45.97% increment in the breaking load, whereas density is reduced by ~ 3.04% and the thermal properties are also improved (indoor temperature decreases ~ 4°C). In whiteware bodies, the substitution of a conventional RHA silica source influences the vitrification temperature of the bodies, which is around 50–100°C [67,68]. Consequently, thermal expansion is reduced and mechanical strength improved at lower temperatures in mature bodies [69]. Bondioli et al. [70,71] analyzed the feasibility of using RHA in place of quartz in pigment and frit development. In the case of pigments, RHA was used to replace silica in Pr–$ZrSiO_4$ solid solution for synthesis of yellow-colored ceramic pigments. The obtained pigment shows the development of a stable, intense yellow color, which is similar to that of a composition containing pure quartz. Similarly, RHA is also applicable for frit manufacturing for use in tiles and glazes.

3.4 Oxide ceramics

3.4.1 Mullite

Mullite is an aluminosilicate refractory material with various attractive properties, such as low thermal expansion, a high melting point, high thermal stability, high thermal shock resistance and chemical stability [72,73]. Due to these properties, mullite is a potential material for use in traditional as well as advanced ceramics. It is the only stable crystalline phase in Al_2O_3–SiO_2 systems with the chemical formula $3Al_2O_3.2SiO_2$ [60]. The method of synthesis drastically affects mullite phase development, the mullitization temperature and its properties, because it controls the degree of mixing of raw materials. As mullite is a mixture of alumina and silica, so RHA can be a potential raw material for use as a silica source in its development. For this reason, many researchers have sought to use RHA as a raw material for mullite over the past few decades. The contribution of RHA to mullite development is a two-step process: the first step is extraction of silica from RHA and the second is application of the silica. To accomplish the first step, different methods have been used viz. alkali extraction, as discussed in section 2.2. The second step was accomplished by different methods. Sembiring et al. [74] used a gel-derived method for development of the mullite phase. They prepared silica sol by treating extracted silica with 5% KOH solution, followed by the addition of this sol to aluminium sol in an appropriate molar ratio of 3:2. HCl was added to the mixture slowly to produce gel, and the gel was then aged for 3 days followed by rinsing with distilled water to remove excess alkali and acid content. The rinsed mass was dried at 110°C for 12h and fired at 800, 950, 1050, 1150, 1250, and 1350°C. Serra et al. [60] used a reaction-sintering method for development of mullite. They mixed RHA and an alumina source in adequate amounts and ball-milled the mixture to achieve proper mixing of the raw materials. This mixed mass production was followed by palletization and sintering of the pellets at 1100–1600°C. Other researchers also used the reaction-sintering method moreover, for development of the mullite phase with RHA and other wastes [75]. In both approaches, i.e. the gel-derived and reaction-sintering methods, mullite phase formation increased with the firing temperature. With the gel-derived method, mullite was formed at 1350°C with a low amount of secondary phases compared to lower temperatures, i.e. 950–1250°C. Similarly, for the reaction-sintering method, secondary phases such as cristobalite and pure alumina phase were found for almost all temperatures but their intensities decreased with temperature. This can be attributed to incomplete reaction between silica and alumina at lower temperatures [60,74].

3.4.2 Cordierite

Cordierite is a magnesium aluminosilicate ($Mg_2Al_4Si_5O_{18}$) material with excellent thermal, electrical and chemical properties. It has a very low thermal expansion coefficient, i.e. < 4×10^{-6}/°C [76–79]. Cordierite also has a very low dielectric constant and high melting point; moreover, i.e. 1460°C. Due to these properties, researchers have found cordierite to be a potential material for use in gas turbines, industrial and lab-scale furnaces, and electronics packing materials, etc. Other uses for cordierite include integrated circuits due to its low dielectric constant [80,81]. As stated above, cordierite is a magnesium aluminosilicate system, and RHA can therefore be used as a silica source for cordierite. A few researchers have conducted studies in this area in the past two decades. Simbering et al. [57] used an alkali extraction method for extraction of silica from RHA followed by solid-state mixing of the raw materials for development of cordierite. For the later step, i.e. development of cordierite, they mixed all the raw materials in an alcohol medium in an appropriate ratio of MgO: Al_2O_3: SiO_2 i.e. 2:2:5. Mixing was conducted using a magnetic stirrer for 6 h in an alcohol medium. Upon completion of the mixing process, the mixed mass was filtered and dried at 110°C for 8 h to absorb residual alcohol. The dried mass was palletized using uniaxial hydraulic pressing and sintered at temperatures of 1050–1350°C. Similarly, Kurana et al. [78] used solid-state mixing of raw materials for development of the cordierite phase. They used RHA in place of kaolinite for development of cordierite. The milling was conducted in a planetary ball mill, however, and the medium was water. A sample was palletized at 1.96 MPa and sintered at 950-1350°C. The ramp rate for temperatures up to 1000°C was 5°C/min and 2.5°C/min for higher temperatures with a holding time of 1 h. Naskar et al. [82] used the sol–gel method for development of cordierite. They first prepared separate sols of silica and other ingredients and then mixed them. The mixtures were dried at 90°C, followed by calcination at 400–1400°C. In all three studies, formation of α–cordierite occurred at temperatures above 1200°C. μ-cordierite was formed at lower temperatures, i.e. below 1200°C, but the transition from μ-cordierite to α–cordierite occurred only at above 1200°C. The formation of μ-cordierite at lower temperatures indicates that a diffusion reaction between cristobalite and spinel ($MgAl_2O_4$) starts at this temperature [83]. Moreover, At high temperatures > 1200°C this μ-cordierite starts converting into α-cordierite, moreover, due to the formation of an Mg–O–Al–O–Si bond during phase transformation [57,82,83]. It can therefore be observed that active silica present in RHA promotes conversion of μ-cordierite to α–cordierite at low temperatures (1300°C) compared to other conventional sources (1400°C) due to its high surface area and fluxing properties. Besides this, application of RHA leads to a decrease in the activation energy required for crystallization of α–cordierite [78].

3.4.3 Lithium alumino-silicate

Lithium alumino-silicate (LAS) is a class of glass ceramics with extraordinary thermal and chemical properties. It has a negligible thermal expansion coefficient and high thermal and chemical durability [84,85]. It is very low thermal expansion makes it a suitable candidate for use in equipment requiring structural stability, i.e. no change in dimensions such as gas turbines. Its application fields also include telescope mirrors, cookware, cooktops, etc. In general, LAS has one of two types of crystalline form, i.e. β-eucryptite ($Li_2O.Al_2O_3.2SiO_2$) or β-spodumene ($Li_2O.Al_2O_3.4SiO_2$). Chatterjee and Naskar [86] studied the effects of various sources of silica on the properties of LAS by the sol–gel method. They prepared LAS successfully using RHA as one of the sources of silica.

3.4.4 Forsterite

Crystalline magnesium silicate, which is known as forsterite, has the chemical formula Mg_2SiO_4. It has a high melting point (1890°C), high chemical durability, good insulation properties, a low dielectric constant, low electrical conductivity and very low thermal conductivity, which make it a potential material for use in dielectric substrates [87], pigments [88], refractory materials [89], etc. Since forsterite is a part of the MgO-SiO_2 system, RHA can be used as a source of silica for its preparation. Mathur et al. [90] prepared nanocrystalline forsterite using RHA as a silica source by a solid-state method. In their study, they observed that some secondary phase of forsterite occurs at below 1000°C but that the pure forsterite phase is obtained at 1000°C. This formation of forsterite at 1000°C can be attributed to the diffusion of magnesia in the enstatite or clinoenstatite phases, which are formed at low temperatures.

3.4.5 Wollastonite

Wollastonite is a calcium silicate ($CaSiO_3$) mineral generally found in two polymorphic forms, i.e. α-wollastonite (pseudo-wollastonite) and β-wollastonite. It has low dielectric loss, high strength, low shrinkage, low volatile constituents, good bioactivity and biocompatibility [91]. Therefore, it has a wide range of applications, such as glasses, electrical insulators, paper, cement, paints, and biomaterials [92,93]. Ismail et al. [94] successfully derived β-wollastonite from RH straw as a source of silica and limestone as a source of lime (CaO). They investigated its bioactivity and biocompatibility for applications as biomaterials and dental implants. An alternative of the sol–gel method was used in their work. Both the ingredients were mixed at an appropriate ratio, i.e. a CaO:SiO_2 ratio of 45:55, followed by soaking in distilled water. The mixture was then autoclaved at 135°C for 8 h. Precipitated masses obtained from this step were then dried and sintered at 90°C and 950°C, respectively. Mansha et al. [95] developed acid-resistant calcium silicate with RHA as a source of silica. First, all the amorphous silica was extracted from RHA, and this was then allowed to react with CaO in an excess water medium. Heat treatment was conducted for the temperature range of 500°C to 1100°C. The Si/Ca molar ratio varied from 1.4 to 2.4. Molar ratios > 2.1 showed high acid resistivity compared to lower ratios. β-wollastonite was obtained at a molar ratio 1.8.

3.5 Non-oxide ceramics

3.5.1 Silicon carbide

Silicon carbide (*SiC*) is a promising non-oxide ceramic for numerous engineering applications, including reinforcement of ceramic and metal matrix composites, catalyst support materials, optic devices, electronic devices and grinding media, due to its unique characteristics such as high hardness and mechanical strength, wear and corrosion resistance, excellent thermal stability, wide band gap, chemical inertness and unique optical properties [96–98]. Conventional *SiC* powder is fabricated by the Acheson method based on carbothermal reduction of a quartz sand and coal mixture at high temperatures (~ 2400°C) [99]. The major problem with the carbothermal process is the high fabrication temperature, long reaction time and bulky grain size of *SiC*. Large particles reduce the sinterability of the product and require an extra milling process. The particle size of *SiC* powder can also be controlled by regulating the carbon and silica particle size in the mixture. Finding a more economical and simple fabrication approach is therefore a major challenge for synthesizing *SiC*. During the past few decades; RH acquired a great deal of attention as an ingredient for preparation of *SiC* (whiskers and particles). Cutler et al. [100,101] first used RH for the production of *SiC*. Many modifications have since been made for industrialization of this route through different studies. Recently, microwave heating is utilized to fabricate *SiC* [102–104]. Different catalyst activities for the formation of *SiC* have also been investigated in several studies [105]. Some metallic catalysts (Fe, Ni, Cr, Co and Pd) greatly influence the reaction rate between C and SiO_2 in the temperature range of 1200–1600°C, which is attributed to the high production rate with a desirable particle morphology. The RH route seems more promising, however due to low-temperature synthesis process and cheap ingredients. Almost all studies focus on fabrication of *SiC* from RH in two processing steps: (i) removal of volatile matter from RH (cooking) under a controlled atmosphere (400–800°C); and (ii) high-temperature heat treatment (> 1300°C) for formation of *SiC* by reacting between cooked RH containing carbon and silica [106]. The chemical reaction for the formation of *SiC* from RH can be expressed as follows [99]:

$$SiO_2(s) + C(s) \rightarrow SiO(g) + CO(g) \quad (3)$$

$$SiO(g) + 3CO(g) \rightarrow SiC(s) + 2CO_2(g) \quad (4)$$

$$SiO(g) + 2C(s) \rightarrow SiC(s) + CO(g) \quad (5)$$

$$CO_2(g) + C(s) \rightarrow 2CO(g) \quad (6)$$

Most recently, Li et al. [107] developed a new process for synthesizing *SiC* nanowires from RH silica with no catalysts or protective atmosphere. RHA and phenolic resin were mixed in a high-speed planetary mill with a stoichiometry of *SiC*. The mixed mass was then placed in a graphite crucible with a graphite cover, and the crucible was placed in an alumina container. The residual space in the alumina container was packed with graphite dust, and the container was locked with an alumina plate. This atmosphere stopped any oxidation of the mass. Calcination of the mixed mass was conducted at 1600°C for 3 h without a protective atmosphere. Afterwards, light-green β-*SiC* nanowires were acquired from the graphite crucible.

3.5.2 Silicon nitride

Silicon nitride (Si_3N_4) is a non-oxide high-temperature applicable ceramic material. It has some excellent characteristics such as high corrosion resistance, a low thermal expansion coefficient, high strength at high temperatures, higher thermal shock resistance than other ceramics and high creep resistance, which makes it a most promising structural ceramic for high temperatures [108,109]. Many processes have therefore been developed to produce Si_3N_4 powder. Carbothermal-nitridation of silica is the most common and economical method for preparation of Si_3N_4 powder [110]. High-purity fine silica and carbon, which are commercial available are required for this route. The uniform distribution and high reactivity of carbon and silica accelerate the nitridation reaction. The agricultural by-product RH consequently contains high reactive silica and carbon with good distribution. Thus, RH is a potential ingredient for Si_3N_4 manufacture [111]. Many researchers have therefore investigated carbothermal-nitridation of RH for Si_3N_4 synthesis [112–114]. Pavarajarn et al. [115] deeply investigated the mechanism of the carbothermal-nitridation reaction of RH for Si_3N_4 fiber and whisker fabrication. RH was first pyrolyzed in a horizontal tube furnace with a continuous flow of argon gas (36L/h) at 600°C for 3h. For the carbothermal-nitridation reaction, the pyrolyzed powder was placed on an alumina tray with a 2 mm depth of powder, and the tray was placed in the tube furnace. Heat treatment was conducted for 3 to 10 h in the temperature range of 1400–1470°C with a reaction gas mixture (90% N_2 + 10% H_2) atmosphere at a gas flow rate of 50 L/h. The differently shaped Si_3N_4 and unreacted powder were found in separate locations on the tray. Fibers were formed outside the cavity of the tray and blade-like whiskers formed on top of the unreacted powder. Whisker-shaped Si_3N_4 powder contains a single crystalline α form phase and the fibers contain a mixture of α and β phases. The reaction mechanism of this process is described by the following reaction formulas:

$$SiO(g) + 3C(s) + 2N_2(g) \rightarrow Si_3N_4(s) + 3CO(g)\ (xii) \quad (7)$$

$$SiO_2(s) + CO(g) \rightarrow SiO(g) + CO_2(g) \quad (8)$$

$$CO_2(g) + C(s) \rightarrow 2CO(g) \quad (9)$$

$$SiO_2(s) + H_2(g) \rightarrow SiO(g) + H_2O(g) \quad (10)$$

$$SiO_2(s) + 3CO(g) + 2N_2(g) \rightarrow Si_3N_4(s) + 3CO_2(g) \quad (11)$$

$$SiO(g) + 3C(s) + 2N_2(g) \rightarrow Si_3N_4(s) + 3CO(g) \quad (12)$$

3.6 Silica aerogel

SA is a synthetic nano-porous, ultra-light, structure-controllable, solid material, which possesses excellent characteristics such as super-low bulk density (0.03–0.5 g/cm^3), huge porosity (80–99%), a high specific surface area (500–1500 m^2/g), low thermal conductivity, catalysis and a low dielectric constant [116–118]. It has a wide range of technological applications, therefore such as in insulation materials for buildings, membranes, pollutant absorbents, microelectronics, catalytic supports, drug carriers and dielectric materials [119,120]. Many reports were found in which SA was successfully prepared from RHA through the sol–gel route [121–125]. In every case, SiO_2 was first extracted from RHA in the form of a sodium silicate (water glass) solution using a sodium hydroxide solution. The sodium ions were then removed by the cation exchange resin method [124,125] or by neutralizing the water glass solution using acid [121–123] to form silica hydrosol. A small quantity of tetraethyl orthosilicate (TEOS) was added to form a gel, and washing was conducted with water and ethanol. The pretreated gel was dried at atmospheric pressure [121–123] or supercritical drying [125] to attain SA. RHA-derived SA exhibits a porosity of about 80–85%, a pore volume of about 0.7–3 cm^3/g, a specific surface area of about 950–270 m^2/g and bulk density of about 0.3–0.7 g/cm^3.

3.7 C/SiO_2 composite

RH-derived C/SiO_2 composite material is the primary choice as an electrode (anode) material for next-generation high-performance lithium ion batteries (LIBs). This porous composite exhibits superior cycling stability, a good discharge specific capacity and a high rate capability for use in LIB anodes. A sustainable, facile and low-cost composite material, it may have huge potential to replace traditional graphite anodes in LIBs. Wang et al. [126] synthesized the C/SiO_2 composite from RH through a one-step heat-treatment process at 900°C in an inert atmosphere and used it as an LIB anode. It exhibits a good initial discharge capacity of 325 $mAh.g^{-1}$ and this value gradually increases with a number of cycles (485 $mAh.g^{-1}$ after 84 cycles) due to electrochemical activation of the composite. Another author prepared this composite from RH by a two-stage method [127]. The first step was carbonization, which occurred at 450°C under an N_2 gas flow. After that, the carbonized powdered precursor was calcined at 900°C under an argon/hydrogen mixed atmosphere. Cui et al. [128] fabricated the micro-porous C/SiO_2 composite by a conventional carbonization process with the addition of $ZnCl_2$ as an activating agent in the RH system. As an LIB anode, this porous composite shows 1105 $mAh.g^{-1}$ of discharge specific capacity with no degradation after 360 charge/discharge cycles at 0.1 Ag^{-1}. Watari et al. [129] synthesized a highly porous C/SiO_2 composite by heating RH pellets at 800–1150°C. The pellets were composed of RH powders with different particle sizes and different molding pressures. The results obtained from RH-derived C/SiO_2 composite possess a specific surface area of 450 m^2g^{-1}, a pore size of ~ 2 nm and porosity of around 87%.

4. Conclusions

Today, by-product and waste management for the development of new products has gained immense interest. In this framework, RH by-product and RHA waste are being considered as renewable and sustainable silica sources because they contain large quantities of amorphous silica. Thus, RHA has high potential as a replacement for conventional silica sources for the making of different ceramics such as refractories, glasses, whiteware, *SiC*, Si_3N_4, mullite, cordierite, wollastonite, SA, and C/SiO_2 composite. This review considers the numerous studies that have focused on the synthesis of silica from RH/RHA and its application for production of ceramics. Within the parameters of the objectives of this review, the following significant facts can be drawn:

- The purity, particle size and surface area of extracted silica depend on the extraction route, acid treatment and annealing temperature. The purity of silica obtained from different routes increases with increases in the number of chemical treatments.
- Utilization of RH for extraction of silica is not economically beneficial; however, its conversion to RHA adds a step of energy generation which contributes positively to economic viability.
- RHA can be used for preparation of insulating refractories due to its low thermal conductivity.
- As RHA is a huge source of amorphous silica, it has potential applications in glass formation. Silica acts as a "network former" in glass, with network formation easily achieved in the case of amorphous silica due to its high reactivity. This reason also makes it suitable for use in the preparation of SA.
- RHA can reduce the vitrification temperature of ceramic bodies a capability allowing its use in whiteware bodies up to a certain percent.
- The activation energy required for crystallization has been reduced by application of RHA, which assists in formation of mullite and cordierite.
- *SiC* conventionally is prepared by the Acheson method in which quartz and coal are mixed, followed by heat treatment at a very high temperature (2400ºC). The addition of RH decreases the formation temperature of *SiC*, however, since it already contains a homogeneous mixture of carbon and silica. Similarly, RH has tremendous potential for using as an ingredient for preparation of Si_3N_4 by the carbothemal-nitridation method, as it contains a homogeneous mixture of carbon and silica at the atomic level.

Highlights

(1) Extractions of amorphous silica from rice husk (RH) or rice husk ash (RHA).
(2) Overview about utilization of RH/RHA in ceramic industries for traditional as well as advanced ceramic product manufacturing.

To study the feasibility of RH silica to replace conventional source of silica.

Acknowledgments

The authors gratefully acknowledge all the faculty and staff of the Department of Ceramic Engineering, Indian Institute of Technology (BHU), Varanasi, India, and the Ministry of Human Resource Development (MHRD), Govt. of India, for providing appreciable support. Support provided by the reviewers and the editor of *Journal of Asian Ceramic Societies*, to enhance the quality of this work is also acknowledged.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

SK S. Hossain http://orcid.org/0000-0001-7910-4993
P.K. Roy http://orcid.org/0000-0001-9854-066X

References

[1] Vakalova TV, Pogrebenkov VM, Karionova NP. Solid-phase synthesis of wollastonite in natural and technogenic siliceous stock mixtures with varying levels of calcium carbonate component. Ceramics Int. 2016;42:16453–16462.
[2] Sm N, Hh E-M, Sabed M, et al. Highly porous scaffolds made of nanosized hydroxyapatite powder synthesized from eggshell. J Ceram Sci Technol. 2015;6:237–244.
[3] Zhu M, Ji R, Li Z, et al. Preparation of glass ceramic foams for thermal insulation applications from coal fly ash and waste glass. Constr Build Mater. 2016;112:398–405.
[4] Luo Y, Zheng S, Ma S, et al. Novel two-step process for synthesising β-SiC whiskers from coal fly ash and water glass. Ceramics Int. 2018. DOI:10.1016/j.ceramint.2018.03.082
[5] Carrasco-Hurtado B, Corpas-Iglesias FA, Cruz-Pérez N, et al. Addition of bottom ash from biomass in calcium silicate masonry units for use as construction material with thermal insulating properties. Constr Build Mater. 2014;52:155–165.
[6] Ozturk ZB, Gultekin E. Preparation of ceramic wall tiling derived from blast furnace slag. Ceramics Int. 2015;41:12020–12026.
[7] Hossain SS, Mathur L, Majhi MR, et al. Manufacturing of green building bricks: utilization of different wastes for construction purpose. J Mater Cycles Waste Manage. 2018. DOI:10.1007/s10163-018-0788-4
[8] Pinheiro BCA, Holanda JNF. Reuse of solid petroleum waste in the manufacture of porcelain stoneware tile. J Environ Manage. 2013;118:205–210.
[9] Ke S, Wang Y, Pan Z, et al. Recycling of polished tile waste as a main raw material in porcelain tiles. J Clean Prod. 2016;115:238–244.
[10] Sutcu M, Akkurt S. The use of recycled paper processing residues in making porous brick with reduced thermal conductivity. Ceram Int. 2009;35:2625–2631.
[11] Sutcu M, Alptekin H, Erdogmus E, et al. Characteristics of fired clay bricks with waste marble powder addition as building materials. Constr Build Mater. 2015;82:1–8.
[12] Geraldo RH, Fernandes LFR, Camarini G. Water treatment sludge and rice husk ash to sustainable geopolymer production. J Clean Prod. 2017;149:146–155.
[13] Bories C, Aouba L, Vedrenne E, et al. Fired clay bricks using agricultural biomass wastes: study and characterization. Constr Build Mater. 2015;91:158–163.
[14] Richerson DW. The magic of ceramics. Wiley-American Ceramic Society; 2nd edition, Canada; 2012 Sep 12.
[15] Rahaman MN. Ceramic processing and sintering. Second ed. New York: Marcel Dekker, Inc; 2003. p. 1–2.
[16] Carter CB, Mg N. Ceramic Materials Science and Engineering. Second ed. New York ; London: Springer; 2013. p. 19.
[17] Lavender MD. The Importance of Silica to the Modern World. Indoor Built Environ. 1999;8:89–93.
[18] Lokare KS, Rising from the Ashes: renewable Silica from Rice Husk Ash. [cited 2017 Sep 6]. Available from: http://www.biofuelsdigest.com/bdigest/2017/09/06/rising-from-the-ashes-renewable-silica-from-rice-husk-ash/
[19] [cited 2018 Oct 27]. Available from:https://www.statista.com/statistics/255937/leading-rice-producers-worldwide/
[20] Sarangi M, Bhattacharyya S, Behera RC. Effect of temperature on morphology and phase transformations of Nano crystalline silica obtained from rice husk. Phase Transitions. 2009;82(5):377–386.
[21] Della VP, Kuhn I, Hotza D. Rice husk ash as an alternate source for active silica production. Mater Lett. 2002;57:818–821.
[22] Kishore R, Bhikshma V, Prakash P. Study on strength characteristics of high strength rice husk ash concrete. Procedia Eng. 2011;14:2666–2672.
[23] Gonzalves MRF, Bergmann CP. Thermal insulators made with rice husk ashes: production and correlation between properties and microstructure. Constr Build Mater. 2007;21(12):2059–2065.
[24] El F, Hoffmann R, Rs H, et al. Applicability of rice husk ash. Quím Nova. 2005;28:1055–1060.
[25] Prasara-A J, Gheewala SH. Sustainable utilization of rice husk ash from power plants: A review. J Clean Prod. 2017;167:1020–1028.
[26] Pode R. Potential applications of rice husk ash waste from rice husk biomass power plant. Renewable Sustainable Energy Reviews. 2016;53:1468–1485.
[27] Soltani N, Bahrami A, Pech-Canul MI, et al. Review on the physicochemical treatments of rice husk for production of advanced materials. Chem Eng J. 2015;264:899–935.
[28] Liu X, Chen X, Yang L, et al. A review on recent advances in the comprehensive application of rice husk ash. Res Chem Intermed. 2016;42:893–913.
[29] Shen Y. Rice husk silica derived nano-materials for sustainable applications. Renewable Sustainable Energy Reviews. 2017;80:453–466.
[30] Shen Y, Zhao P, Shao Q. Porous silica and carbon derived materials from rice husk pyrolysis char. Microporous Mesoporous Mater. 2014;188:46–76.
[31] Witchakorn C, Bundit E-A. Sizing and Location of Electricity Power Generation from Rice Husk in Thailand. 19th World Energy Congress. 2004 Sep 5–9; Sydney, Australia .
[32] Delivand MK, Barz M, Gheewala SH, et al. Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand. Appl Energy. 2011;88:3651–3658.
[33] Demirbas A. Relationships between lignin contents and heating values of biomass. Energy Convers Manage. 2001;42:183–188.
[34] Yank A, Ngadi M, Kok R. Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. Biomass Bioenergy. 2016;84:22–30.
[35] Bhardwaj A, SK S H, Majhi MR. Preparation and characterization of clay bonded high strength silica refractory by utilizing agriculture waste. Bol Soc Esp Cerám Vidr. 2017;56:256–262.
[36] Gomesa GMF, Philipssenc C, Barda EK, et al. Rice husk bubbling fluidized bed combustion for amorphous silica synthesis. J Environ Chem Eng. 2016;4:2278–2290.

[37] Van VTA, Rößler C, Bui DD, et al. Pozzolanic reactivity of mesoporous amorphous rice husk ash in portlandite solution. Constr Build Mater. 2014;59:111–119.
[38] Alvarez J, Lopez G, Amutio M, et al. Bio-oil production from rice husk fast pyrolysis in a conical spouted bed reactor. Fuel. 2014;128:162–169.
[39] Bakar RA, Yahya R, Gan SN. Production of High Purity Amorphous Silica from Rice Husk. Procedia Chem. 2016;19:189–195.
[40] Sankara S, Sharma SK, Kaura N, et al. Biogenerated silica nanoparticles synthesized from sticky, red, and brown rice husk ashes by a chemical method. Ceramics Int. 2016;42:4875–4885.
[41] Carmona VB, Oliveira RM, Silva WTL, et al. Nanosilica from rice husk: extraction and characterization. Ind Crops Prod. 2013;43:291–296.
[42] Gu S, Zhou J, Luo Z, et al. Kinetic study on the preparation of silica from rice husk under various pretreatments. J Therm Anal Calorim. 2015;119:2159–2169.
[43] Hao L, Gong X, Xuan S, et al. Controllable fabrication and characterization of biocompatible core–shell particles and hollow capsules as drug carrier. Appl Surf Sci. 2006;252:8724–8733.
[44] Wantala K, Khongkasem E, Khlongkarnpanich N, et al. Optimization of As (V) adsorption on Fe-RH-MCM-41-immobilized GAC using Box-Behnken Design: effects of pH, loadings, and initial concentrations. Appl Geochem. 2012;27:1027–1034.
[45] Zulkifli NSC, Rahmann IAB, Mohamad D, et al. A green sol–gel route for the synthesis of structurally controlled silica particles from rice husk for dental composite filler. Ceramics Int. 2013;39:4559–4567.
[46] Costa JAS, Paranhos CM. Systematic evaluation of amorphous silica production from rice husk ashes. J Clean Prod. 2018;192:688–697.
[47] Zulfiqar U, Subhani T, Husain SW. Towards tunable size of silica particles from rice husk. J Non Cryst Solids. 2015;429:61–69.
[48] Songa S, Chob HB, Kim HT. Surfactant-free synthesis of high surface area silica nanoparticles derived from rice husks by employing the Taguchi approach. J Ind Eng Chem. 2018;61:281–287.
[49] Liou TH, Yang CC. Synthesis and surface characteristics of nanosilica produced from alkali-extracted rice husk ash. Mater Sci Eng B. 2011;176:521–529.
[50] Tolba GMK, Barakat NAM, Bastaweesy AM, et al. Effective and highly recyclable nanosilica produced from the rice husk for effective removal of organic dyes. J Ind Eng Chem. 2015;29:134–145.
[51] Bathla A, Narula C, Rp C, et al. Hydrothermal synthesis and characterization of silica nanowires using rice husk ash: an agricultural waste. J Mater Science: Mater Electronics. 2018;29:6225–6231.
[52] An D, Guo Y, Zhu Y, et al. A green route to preparation of silica powders with rice husk ash and waste gas. Chem Eng J. 2010;162:509–514.
[53] Pal AR, Bharati S, Krishna NVS, et al. The effect of sintering behaviour and phase transformations on strength and thermal conductivity of disposable tundish linings with varying compositions. Ceramics Int. 2012;38:3383–3389.
[54] Sobrosa FZ, Stochero NP, Marangon E, et al. Development of refractory ceramics from residual silica derived from rice husk ash. Ceramics Int. 2017;43:7142–7146.
[55] Ugheoke BI, Onche EO, Namessan ON, et al. Property optimization of kaolin-rice husk insulating fire-bricks. Leonardo Electron J Pract Technol. 2006;5:167–178.
[56] Ahmed YMZ, Ewaisem EM, Zaki ZI. Production of porous silica by the combustion of rice husk ash for tundish lining. J Univ Sci Technol Beijing. 2008;15 (3):307–313.
[57] Sembiring S, Simanjuntak W, Situmeang R, et al. Preparation of refractory cordierite using amorphous rice husk silica for thermal insulation purposes. Ceramics Int. 2016;42:8431–8437.
[58] Sembiring S, Simanjuntak W, Situmeang R, et al. Effect of alumina addition on the phase transformation and crystallisation properties of refractory cordierite prepared from amorphous rice husk silica. J Asian Ceramic Soc. 2017;5:186–192.
[59] SK S H, Mathur L, Singh P, et al. Preparation of forsterite refractory using highly abundant amorphous rice husk silica for thermal insulation. J Asian Ceramic Soc. 2017;5:82–87.
[60] Serra MF, Conconi MS, Gauna MR, et al. Mullite ($3Al_2O_3{\cdot}2SiO_2$) ceramics obtained by reaction sintering of ricehusk ash and alumina, phase evolution, sintering and microstructure. J Asian Ceramic Soc. 2016;4:61–67.
[61] Lee T, Othman R, Yeoh FY. Development of photoluminescent glass derived from rice husk. Biomass Bioenergy. 2013;59:380–392.
[62] Andreola F, Martınc MI, Ferrari AM, et al. Technological properties of glass-ceramic tiles obtained using rice husk ash as silica precursor. Ceramics Int. 2013;39:5427–5435.
[63] Sharma G, Arya SK, Singh K. Optical and thermal properties of glasses and glass-ceramics derived from agricultural wastes. Ceramics Int. 2018;44:947–952.
[64] Chen SY, Chou PF, Chan WK, et al. Preparation and characterization of mesoporous bioactive glass from agricultural waste rice husk for targeted anticancer drug delivery. Ceramics Int. 2017;43:2239–2245.
[65] Nayak JP, Kumar S, Bera J. Sol–gel synthesis of bioglass-ceramics using rice husk ash as a source for silica and its characterization. J Non Cryst Solids. 2010;356:1447–1451.
[66] Silva GHMJSD, Surangi MLC. Effect of waste rice husk ash on structural, thermal and run-off properties of clay roof tiles. Constr Build Mater. 2017;154:251–257.
[67] Prasad CS, Maiti KN, Venugopal R. Effect of rice husk ash in whiteware compositions. Ceramics Int. 2001;27:629–635.
[68] Jamo HU, Maharaz MN. Influence of Addition of Rice Husk Ash on Porcelain Composition. Sci World J. 2015;10(1):7–16.
[69] Prasada CS, Maiti KN, Venugopal R. Effect of substitution of quartz by rice husk ash and silica fume on the properties of whiteware compositions. Ceramics Int. 2003;29:907–914.
[70] Bondioli F, Andreola F, Barbieri L, et al. Effect of rice husk ash (RHA) in the synthesis of $(Pr,Zr)SiO_4$ ceramic pigment. J Eur Ceram Soc. 2007;27:2488–3483.
[71] Bondioli F, Barbieri L, Ferrari AM, et al. Characterization of Rice Husk Ash and Its Recycling as Quartz Substitute for the Production of Ceramic Glazes. J Am Ceram Soc. 2010;93(1):121–126.
[72] Kriven WK, Siah JF, Schmucker M, et al. High temperature microhardness of single crystal mullite. J Am Ceram Soc. 2004;87(5):970–972.

[73] Tumalla RR. Development of high performance interfill material for system chip technology. J Am Ceram Soc. 1991;74(2):895–899.

[74] Sembiringa S, Simanjuntakb W, Manurunga P, et al. Synthesis and characterisation of gel-derived mullite precursors from rice husk silica. Ceramics Int. 2014;40:7067–7072.

[75] Pype J, Michielsen B, Mullens S, et al. Impact of inorganic waste fines on structure of mullite microspheres by reaction sintering. J Eur Ceram Soc. 2018;38:2612–2620.

[76] Kobayashi Y, Sumi K, Kato E. Preparation of dense cordierite ceramics from magnesium compounds and kaolinite without additives. Ceram Int. 2000;26:373–739.

[77] Milberg ME, Blair HD. Thermal expansion of cordierite. J Am Ceram Soc. 1997;60:372373.

[78] Kurama S, Kurama H. The reaction kinetics of rice husk based cordierite ceramics. Ceram Int. 2008;34:269–272.

[79] Zhu K, Yang YD, Wu J, et al. Synthesis of cordierite with low thermal expansion coefficient. Adv Mater. 2010;105–106:802–804.

[80] Suzuki H, Ota K, Saito H. Yogyo-Kyokai-Shi (J. Ceram Soc Jpn. 1987;95:163.

[81] Pal D, Chakraborty AK, Sen S, et al. The synthesis, characterization and sintering of sol-gel derived cordierite ceramics for electronic applications. J Mater Sci. 1996;31:3995.

[82] Naskar MK, Chatterjee M. A novel process for the synthesis of cordierite ($Mg_2M_4Si_5O_{18}$) powder from rice husk ash and other sources of silica and their comparative study. J EurCeramSoc. 2004;24(13):3499–3508.

[83] Janackovič D, Jokanovič V, Gvozdenovič LK, et al. Synthesis and formation mechanism of sub micrometer spherical cordierite powder by ultrasonic spray pyrolysis. J Mater Sci. 1997;32:163–168.

[84] Lichtenstein AI, Jones RO, Gironcoli SD, et al. Anisotropic thermal expansion in silicates: A density functional study of β-eucryptite and related materials. Phys Rev B. 2000;62(17):11487–11493.

[85] Karmakar B, Kundu P, Jana S, et al. Crystallization kinetics and mechanism of low expansion lithium alumino silicate glassceramics by dilatometry. J Am Ceram Soc. 2002;85(10):2572–2574.

[86] Chatterjee M, Naskar MK. Sol–gel synthesis of lithium aluminum silicate powders: the effect of silica source. Ceramics Int. 2006;32:623–632.

[87] Sasikala TS, Suma MN, Mohanan P, et al. Forsterite based ceramic glass composites for substrate applications in microwave and millimeter wave communications. J Alloys Compd. 2008;461:555–559.

[88] Hadri ME, Ahamdane H, Raghni MAEI. Sol gel synthesis of forsterite, M-doped forsterite (M = Ni, Co) solid solutions and their use as ceramic pigments. J Eur Ceram Soc. 2015;35:765–777.

[89] Tw C, Yc D, Jp C. A study of synthetic forsterite refractory materials using waste serpentine cutting. Miner Eng. 2002;15:271–275.

[90] Mathur L, SK S H, Majhi MR, et al. Synthesis of nano-crystalline forsterite (Mg_2SiO_4) powder from biomass rice husk silica by solid-state route. Bol Soc Esp Cerám Vidr. 2018;57(3):112–118.

[91] Wan X, Chang C, Mao D, et al. Preparation and in vitro bioactivities of calcium silicate nanophase materials. Mater Sci Eng. 2005;C25:455–461.

[92] Vichaphund S, Kitiwan M, Atong D, et al. Microwave synthesis of wollastonite powder from eggshells. J Eur Ceram Soc. 2011;31:2435–2440.

[93] Ns N, Zz A. High-voltage electric insulators based on wollastonite. Glass and Ceramics. 2001;58:11–12.

[94] Ismail H, Shamsudin R, Hamid MAA, et al. Characteristics of β-wollastonite derived from rice straw ash and limestone. J Aust Ceramic Soc. 2016;52(2):163–174.

[95] Mansha M, Javed SH, Kazmi M, et al. Study of Rice Husk Ash as Potential Source of Acid Resistance Calcium Silicate. Adv Chem Eng Sci. 2011;1:147–153.

[96] Davidson A, Regener D. A comparison of aluminium-based metal-matrix composites reinforced with coated and uncoated particulate silicon carbide. Compos Sci Technol. 2000;60:865–869.

[97] Yang G, Cui H, Sun Y, et al. Simple Catalyst-Free Method to the Synthesis of-SiC Nanowires and Their Field Emission Properties. J Phys Chem C. 2009;113:15969–15973.

[98] Yang W, Araki H, Tang C, et al. Single-Crystal SiC Nanowires with a Thin Carbon Coating for Stronger and Tougher Ceramic Composites. Adv Mater. 2005;17:1519–1523.

[99] Narciso-Romero F, Rodriguez-Reinoso F. Synthesis of SiC from rice husks catalysed by iron, cobalt or nickel. J Mater Sci. 1996;31:779–784.

[100] Cutler IB, Lee JG, Shaikh N, et al. UTEC. 1974;73–157(A).

[101] Rahman I, Riley F. The control of morphology in silicon nitride powder prepared from rice husk. J Eur Ceram Soc. 1989;5:11–22.

[102] Li J, Shirai T, Fuji M. Rapid carbothermal synthesis of nanostructured silicon carbide particles and whiskers from rice husk by microwave heating method. Adv Powder Technol. 2013;24:838–843.

[103] Moshtaghioun B, Poyato R, Cumbrera F, et al. Rapid carbothermic synthesis of silicon carbide nano powders by using microwave heating. J Eur Ceram Soc. 2012;32:1787–1794.

[104] Tony VCS, Voon CH, Lee CC, et al. Effective Synthesis of Silicon Carbide Nanotubes by Microwave Heating of Blended Silicon Dioxide and Multi-Walled Carbon Nanotube. Mater Res. 2017;20(6):1658–1668.

[105] Krishnarao R. Effect of cobalt catalyst on the formation of SiC from rice husk silica–carbon black mixture. J Mater Sci. 1995;30:3645–3651.

[106] Zawrah M, Zayed M, Ali MR. Synthesis and characterization of SiC and SiC/Si_3N_4 composite nano powders from waste material. J Hazard Mater. 2012;227–228:250–256.

[107] Li W, Huang Q, Guo H, et al. Green synthesis and photoluminescence property of β-SiC nanowires from rice husk silica and phenolic resin. Ceramics Int. 2018;44:4500–4503.

[108] Herrmann M, Klemm H, Schubert C. Silicon nitride based hard materials. Handb Ceram Hard Mater. 2000;749–801. doi:10.1002/9783527618217.ch21

[109] Wang M, Xie M, Ferraioli L, et al. Light emission properties and mechanism of low-temperature prepared amorphous SiN films. I. Room-temperature band tail states photoluminescence. J Appl Phys. 2008;104:083504.

[110] Riley FL. Silicon Nitride and Related Materials. J Am Ceram Soc. 2000;83(2):245–265.

[111] Sun L, Gong K. Silicon-based materials from rice husks and their applications. Ind Eng Chem Res. 2001;40:5861–5877.
[112] Licko T, Figusch V, Puchyova J. Synthesis of silicon nitride by carbothermal reduction and nitriding of silica: control of kinetics and morphology. J Eur Ceram Soc. 1992;9:219–230.
[113] Real C, Alcala MD, Criado JM. Synthesis of Silicon Nitride from Carbothermal Reduction of Rice Husks by the Constant-Rate-Thermal-Analysis (CRTA) Method. J Am Cumm Soc. 2004;87(I):75–78.
[114] Padhi BK, Patnaik C. Development of Si_2N_2O, Si_3N_4, and SiC Ceramic Materials Using Rice Husk. Ceramics Int. 1995;21:213–220.
[115] Pavarajarn V, Precharyutasin R, Praserthdam P. Synthesis of Silicon Nitride Fibers by the Carbothermal Reduction and Nitridation of Rice Husk Ash. J Am Ceram Soc. 2010;93(4):973–979.
[116] Pan Y, He S, Cheng X, et al. A fast synthesis of silica aerogel powders-based on water glass via ambient drying. J Sol-Gel Sci Technol. 2017;82:594–601.
[117] Ślosarczyk A. Recent advances in research on the synthetic fiber based silica aerogel nanocomposites. Nanomaterials. 2017;7:44.
[118] Rajanna SK, Kumar D, Vinjamur M, et al. Silica aerogel microparticles from rice husk ash for drug delivery. Ind Eng Chem Res. 2015;54:949–956.
[119] Gurav JL, Rao AV, Nadargi DY, et al. Ambient pressure dried TEOS-based silica aerogels: good absorbents of organic liquids. J Mater Sci. 2010;45:503–510.
[120] Dorcheh AS, Abbasi MH. Silica aerogel; synthesis, properties and characterization. J Mater Process Technol. 2008;199:10–26.
[121] Nayak JP, Bera J. Preparation of Silica Aerogel by Ambient Pressure Drying Process using Rice Husk Ash as Raw Material. Trans Ind Ceram Soc. 2009;68 (2):91–94.
[122] Li T, Wang T. Preparation of silica aerogel from rice hull ash by drying at atmospheric pressure. Mater Chem Phys. 2008;112:398–401.
[123] Tadjarodi A, Haghverdi M, Mohammadi V. Preparation and characterization of nano-porous silica aerogel from rice husk ash by drying at atmospheric pressure. Materials Research Bulletin. 2012;47:2584–2589.
[124] Feng Q, Chen K, Ma D, et al. Synthesis of high specific surface area silica aerogel from rice husk ash via ambient pressure drying. Colloids Surf. 2018;A539:399–406.
[125] Cui S, Yu S, Lin B, et al. Preparation of SiO_2 aerogel from rice husk ash. RSC Adv. 2015;5:65818–65826.
[126] Wang L, Xue J, Gao B, et al. Rice Husk Derived Carbon-silica Composites as Anodes for Lithium Ion Batteries. RSC Adv. 2014;4:64744–64746.
[127] Ju Y, Tang JA, Zhu K, et al. SiOx/C composite from rice husks as an anode material for lithium-ion batteries. Electrochim Acta. 2016;191:41–416.
[128] Cui J, Cheng F, Lin J, et al. High surface area C/SiO_2 composites from rice husks as a high-performance anode for lithium ion batteries. Powder Technol. 2017;311:1–8.
[129] Watari T, Nakata A, Kiba Y, et al. Fabrication of porous SiO_2/C composite from rice husks. J Eur Ceram Soc. 2006;26:797–801.