From bamboo leaf to aerogel: Preparation of water glass as a precursor

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A B S T R A C T

In this study, water glass was synthesized from bamboo leaf as a precursor to produce silica aerogel. Bamboo leaf was combusted to produce bamboo leaf silica (BLS) and reacted with sodium hydroxide to form a water glass solution. The effects of the processing parameters such as the temperature, the time, and the agitation speed on the silica yield in water glass were studied. These processing parameters were optimized based on the regressed correlation to synthesize water glass. It was found that bamboo leaf contains approximately 20 wt.% of silica, which is higher than the silica content in rice husk. Characterizations of BLS confirmed that it has identical purity, amorphicity and chemical nature as rice husk silica. Optimization study also showed that BLS can be completely dissolved in NaOH in at least 2 h at 30 °C and an agitation speed of 20 rpm, depending on the combination of the parameters.

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1. Introduction

Silica aerogel is well known as the lightest solid that consists of amorphous 3-dimensional silica network with air occupying >96% of its volume [1]. Because of its high porosity, silica aerogel exhibits many attractive properties including high specific surface area (500–1200 m² g⁻¹) [2], low thermal conductivity (0.005–0.015 W m⁻¹ K⁻¹) [2,3], ultra-low dielectric constant (κ = 1.0–2.0) [4–6] and low refractive index (1–1.08) [2,7]. These special properties make aerogel a suitable material for thermal insulation (because of the low thermal conductivity), acoustic barriers (because it is highly porous), super capacitors (because of the low dielectric constant), catalytic support (because of the high specific surface area) and Cherenkov detector in high-energy physics (because of the low refractive index) [8].

Silica aerogel synthesis commonly involves either water glass or alkoxides as the precursor. The former was originally used by Samuel Kistler [9] to produce the first aerogel, whereas the latter is currently widely used because it requires fewer solvent exchange steps than the former. Water glass is conventionally manufactured by reacting sodium carbonate with silicon dioxide in the molten state. Because of the high temperature involved in this process, the market price of water glass makes it unattractive as a precursor. Furthermore, using alkoxides as a precursor also has drawbacks. In addition to being costly, alkoxides such as tetramethoxysilane (TMOS) and tetraethoxysilane (TEOS) are hazardous; in particular, TMOS can cause blindness [2].

Amorphous silica can be synthesized by sputtering [10–12] and bio-extraction [13–16]. Bamboo leaf was previously reported by other researchers [17,18] to contain 13–41 wt.% of silica depending on the bamboo species, the climate and the geographical influences. Extraction of silica from bamboo leaves using acids was previously attempted by other researchers [19]. Hence, in this work, water glass was prepared from bamboo leaves as a cheap source to compensate the cost of additional solvent exchange in the aerogel synthesis. Bamboo leaf is an agricultural waste that is commonly disposed in paper-pulp production. In Brazil, this waste contributes to 190 kT of waste per year and is normally burnt in open landfill [20], which directly causes airborne pollutants. In Asia, approximately 10 million tons of bamboo is harvested every year in China, India and Japan [21], which generates large quantities of bamboo leaf as waste. Thus using bamboo leaf as the precursor to synthesize aerogel can substitute the use of expensive raw materials, and helps to reduce environmental pollution. The synthesis of aerogel from bamboo leaf is not new because other researchers have previously attempted a similar approach by using rice husk [22–24] i.e., another agricultural waste that is known to have high silica content. Hence, rice husk was used throughout this work as a comparison to bamboo leaf.

2. Methods

2.1. Materials

The bamboo leaf used in this study belongs to the Bambusa heterostachya species, which is locally known as Buluh galah. The bamboo leaves were obtained from the forest park in the University of Malaya and the Forestry Research Institute of Malaysia (FRIM), Kuala Lumpur. The rice husk was obtained from the Padiberas Nasional (BERNAS) Berhad rice mill, Malaysia. Hydrochloric acid (HCl, 2 mol L⁻¹) and sodium hydroxide (NaOH, 2 mol L⁻¹) were purchased from R&M Chemicals (Malaysia).
2.2. Experimental procedure

Fig. 1 shows the workflow of this study, which includes synthesis, characterizations and optimization of the processing parameters in the water glass synthesis. Withered bamboo leaves (length > 20 cm) were initially washed with deionized water and dried in the oven at 90 °C for 72 h. Then, all dried leaves were cut into smaller pieces (approximately 8 cm) for easy leaching and combustion. Each sample (50 g) was combusted in air using muffle furnace at 15 °C min⁻¹ from room temperature to 650 °C.

This process was followed by isothermal heating at 650 °C for 4 h to extract the silica. The silica produced in the combustion are termed bamboo leaf silica (BLS) and rice husk silica (RHS). All samples were combusted at 650 °C to prevent crystallization of silica to form cristobalite and tridymite [16,25]. The weight percentages of BLS and RHS in biomass were calculated and reconfirmed using a thermogravimetric analysis (TGA, TA Instrument Q500). The TGA was performed in nitrogen atmosphere with three heating rates of 5, 10 and 20 °C min⁻¹; then isothermal heating was performed at 650 °C for 4 h. Finally, the samples were heated up to 1000 °C at 10 °C min⁻¹.

The purity of the BLS was determined using an energy dispersive X-ray analysis (EDX, INCA Energy 400) coupled with FESEM (FEI Quanta 200F). An X-ray diffractometer (XRD, PANalytical Empyrean) with a 2θ range of 10°–90° (step size 0.026°, Kα₁ = 1.5406 Å, Cu anode) was also used to detect any formation of combustion-induced crystallized silica in the BLS. Then, water glass was synthesized by reacting BLS with the sodium hydroxide (NaOH) solution. The silica yield in the formed water glass was determined using inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Perkin Elmer Optima 7000 DV); the silica yield (ξ) is defined as in Eq. (1):

\[
\text{Yield, } \xi = \frac{C_{\text{Si}} V_{\text{NaOH}}}{\phi m_{\text{BLS}}} \left(\frac{M_{\text{SiO}_2}}{M_{\text{Si}}}\right)
\]

where \(C_{\text{Si}}\) is the silica concentration in water glass, which is determined using ICP and measured in g L⁻¹; \(V_{\text{NaOH}}\) is the NaOH volume reacted with BLS, measured in L; \(\phi\) is the purity of BLS, which is determined using EDX and measured in wt.%; \(m_{\text{BLS}}\) is BLS mass in the reaction, measured in g; \(M_{\text{SiO}_2}\) is the molar mass of silica i.e., 60.084 g mol⁻¹; and \(M_{\text{Si}}\) is molar mass of silicon i.e., 28.086 g mol⁻¹.

To identify the processing parameters that affected the silica yield in water glass, the reactions of BLS with NaOH were repeated by varying the parameters for the range stated in Table 1. Then, the processing condition was optimized to achieve a high silica yield in water glass. The water glass with optimized silica yield (ξ) was characterized to study its elemental composition, density and pH.

3. Results

3.1. Bamboo leaf silica (BLS)

The distribution of silica in bamboo leaf can be clearly observed in the remaining ash after combustion, which is shown in Fig. 2b. The FESEM image in Fig. 2c shows that skeleton of the bamboo leaf ash remains intact after combustion.
Fig. 3 shows the TGA curve for the pyrolysis of bamboo leaves at various heating rates. The moisture content was removed at the initial stage of heating within the range of 30–100 °C. Pyrolysis began at approximately 200 °C, the major volatile organic compounds decomposed [26]. At low heating rates (5 and 10 °C min\(^{-1}\)), the samples were completely decomposed and yielded a constant ash content above 650 °C. A sharp bend was observed in the TGA curve at 20 °C min\(^{-1}\) because the reaction rapidly proceeds under high heating rate (20 °C min\(^{-1}\)). As a result, the sample was not completely decomposed and the reaction continued during the isothermal heating at 650 °C. After the isothermal heating, no significant weight loss is observed up to 1000 °C. The weight of the remaining ash content at 1000 °C is notably constant.

The EDX spectra of unleached raw biomass in Fig. 4 show that bamboo leaf has a lower silicon–carbon ratio than rice husk.

Based on the EDX elemental composition, the calculated silica contents of bamboo leaf and rice husk were 19.5 wt.% and 8.5 wt.% respectively. This value is lower than the previous, where the silica content in rice husk is typically 15–20 wt.% [27]. Although this difference is usually attributed to geographical variations, the author found that it is also because of the confusion between the silica content and the formed ash. Because ash contains silica and other impurities, the ash content is always larger than the silica content, as evidenced in Fig. 5 where the ash obtained from the unleached sample is highly impure. Hence, the silica content reported by other researchers is actually the ash content, where they assumed that ash only contained silica [28–30]. To illustrate this concept, the ash contents that were obtained from combustion and the TGA pyrolysis are tabulated in Table 2.

The ash content of rice husk in Table 2 matched the reported range of silica content. Assuming that BLS and RHS have identical purities, the silica content of bamboo leaf (29.8 wt.%) should be nearly double that of rice husk (14.7 wt.%). This hypothesis is confirmed by the EDX results of BLS and RHS obtained in combustion, as shown in Table 3.

Using the purity of both leached and unleached biomass, the silica content was calculated based on Eq. (2):

\[
\text{Silica content (wt\%)} = \frac{M_{\text{SiO}_2}}{M_{\text{Si}}} \times W_{\text{Si}} \times W_{\text{ash}} \times W_{\text{lch}}
\]

where \(M_{\text{SiO}_2}\) is the molar mass of silica, i.e., 60.084 g mol\(^{-1}\); \(M_{\text{Si}}\) is the molar mass of silicon, i.e., 28.086 g mol\(^{-1}\); \(W_{\text{Si}}\) is the weight percentage of silicon in ash, which is determined using EDX; \(W_{\text{ash}}\) is the weight percentage of ash after combustion; and \(W_{\text{lch}}\) is the weight percentage of

![Fig. 3. TGA curves of bamboo leaves pyrolyzed at various heating rates.](image1)

![Fig. 4. EDX spectra of unleached (a) bamboo leaf and (b) rice husks before combustion.](image2)

![Fig. 5. Purity of (a) unleached and (b) acid-leached BLS.](image3)

**Table 2**

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Bamboo leaf (wt%)</th>
<th>Rice husk (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustion</strong></td>
<td>29.73 ± 0.50</td>
<td>14.46 ± 0.43</td>
</tr>
<tr>
<td><strong>TGA pyrolysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 °C min(^{-1})</td>
<td>30.8</td>
<td>15.2</td>
</tr>
<tr>
<td>10 °C min(^{-1})</td>
<td>29.0</td>
<td>14.4</td>
</tr>
<tr>
<td>20 °C min(^{-1})</td>
<td>29.5</td>
<td>14.9</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>29.8</td>
<td>14.7</td>
</tr>
<tr>
<td><strong>Confidence interval</strong></td>
<td>28.8 – 30.7</td>
<td>14.3 – 15.2</td>
</tr>
<tr>
<td><strong>p-value</strong></td>
<td>0.42</td>
<td>0.70</td>
</tr>
</tbody>
</table>

\(^1\) Average of seven batches of biomass collected from different areas and times.

\(^{11}\)ANOVA at 95% level of confidence based on combustion and TGA at three different heating rates.
the biomass residue that remained after acid leaching. The calculated silica values are generally consistent with the results in Fig. 4, where bamboo leaf contains twice as much silica as rice husk.

Fig. 6 shows the XRD diffractograms of both bamboo leaf and rice husk, which exhibit featureless patterns with diffused peaks at 23°. As explained by other researchers [31], these diffused peaks are related to amorphous silica with some short-range primitive structures. This result confirms that the extracted BLS is amorphous and identical to RHS. In addition, small peaks were observed at 2θ of 32° and 35° for the unleached samples.

From the FT-IR spectra in Fig. 7, BLS and RHS have approximately identical chemical groups. The spectra included the peaks at 467, 799 and 1059 cm⁻¹ siloxane (Si–O–Si) group, which are related to the bending and stretching vibrations of the silica backbone [32,33]. Because there is a silanol group on the surface of silica, whose peak was observed at approximately 900 cm⁻¹ [33], it is confirmed that the synthesized BLS is identical to RHS and contains pure silica. The spectra also show that both BLS and RHS are highly transparent to infrared ray between 1250 and 3950 cm⁻¹, which corresponds to 2.5 and

### Table 3

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Bamboo leaf (wt%)</th>
<th>Rice husk (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unleached</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purity</td>
<td>71.5</td>
<td>70.3</td>
</tr>
<tr>
<td>Silica content</td>
<td>21.2</td>
<td>10.7</td>
</tr>
<tr>
<td><strong>Acid leached</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purity</td>
<td>81.3</td>
<td>86.6</td>
</tr>
<tr>
<td>Silica content</td>
<td>19.3</td>
<td>12.1</td>
</tr>
<tr>
<td><strong>Average silica content</strong></td>
<td>20.3</td>
<td>11.4</td>
</tr>
<tr>
<td>Confidence interval of silica content</td>
<td>17.4 – 23.1</td>
<td>9.3 – 13.5</td>
</tr>
</tbody>
</table>

†ANOVA at 95% level of confidence based on the leached and the unleached samples.
8 μm. This range is the well-known optical range where silica aerogel can transfer heat by the radiative mode. The largest difference between BLS and silica aerogel is the large absorption peaks at 1639 cm$^{-1}$ and 3431 cm$^{-1}$, which are attributed to the bending modes of the absorbed water [33]. These peaks are expected because silica aerogel without surface modification is well-known of its hygroscopic nature to strongly adsorb onto water molecules [34,35].

3.2. Synthesis of water glass from BLS

The effect of five selected processing parameters on the silica yield in water glass was studied, and the results are shown in Fig. 8. Among these parameters, the time, the temperature and the agitation speed generally have stronger influence on the silica yield than the NaOH concentration and the mass-to-volume ratio. The silica yield increased as the time (Fig. 8a–d), the temperature (Fig. 8a, e–g) or the agitation speed (Fig. 8d, g, i–j) increased. This relationship is expected because these three factors contribute to the increase in diffusion and reaction rate of BLS in the NaOH solution. The temperature generated the largest response on the silica yield when it was increased, followed by the agitation speed and the time. Hence, a silica yield of approximate unity can be achieved in a shorter time at elevated temperatures. Similarly, the silica yield can be increased when higher agitation speed or longer reaction time is applied, but the effect is less significant for high temperature. By comparison, the NaOH concentration and the mass-to-volume ratio have no significant effect on ξ. However, they

![Fig. 8. Effects of the processing parameters on the silica yield in water glass.](image-url)
exhibit some interaction as in Fig. 8h. The corresponding ANOVA regression model is summarized in Table 4. With the adjusted $R^2$ value of 0.97, the model is sufficiently explained using the five proposed processing parameters. Eq. (3) shows the model with the involved regressed coefficients of processing parameters.

$$\xi = \frac{1}{10,000} (90.7t + 268.7T - 43.7C - 48.9R + 47.9A - 5186)$$  (3)

Because the parameters $t, T$ and $A$ contribute positively to $\xi$, all the corresponding regressed coefficients are $> 0$. Although $\xi$ responds negatively to the increase of $C$ and $R$, their individual effects are relatively small compared to the other parameters. As shown in Table 1 where $2 \leq C \leq 6$ and $12 \leq R \leq 60$ in this study, their products with the regressed coefficients are on average one to two orders of magnitude smaller than the other effects. Hence, the negative effect of these two parameters only becomes significant when $t, T$ and $A$ are low. Moreover, the interaction between $C$ and $R$ and its effect on $\xi$ will be discussed in later section.

To minimize both energy and time consumption in the process, this study aimed to minimize the required time, temperature and agitation speed to achieve silica yield of $\xi = 1$. Reasonably, all three parameters cannot be simultaneously minimized because the mass transfer in the reaction can hardly be accomplished. Thus, only two of the three parameters are minimized, and the mass transfer is achieved by the remaining parameter in one of the following methods:

i. Forced convection created by only agitation ($A$); or

ii. Natural convection due to the temperature gradient and increase of diffusivity at higher temperature ($T$); or

iii. Diffusion that occurs with time ($t$).

The optimized results are shown in Fig. 9. To obtain water glass with the highest silica concentration, all optimizations were aimed to achieve the maximum mass-to-volume ratio of 60 g L$^{-1}$. As $\xi \rightarrow 1$, the silica concentration of water glass, $C_{SiO_2} \rightarrow R/M_{SiO_2} \approx 1M$ when $R = 60$ g L$^{-1}$ under the optimized conditions. In every case, the lowest possible temperature was set to 30 °C because the room temperature does not require any heating or cooling in the process. The result shows that the processing time can be reduced to 2 h if agitation and/or high temperature is applied. The reflux of the reactant mixture at higher temperature may further reduce the required time and agitation. However, such process must not be performed using

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Table 4

<table>
<thead>
<tr>
<th>Effect of processing parameters on the silica yield in water glass$^5$.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Processing parameters</strong></td>
</tr>
<tr>
<td><strong>p-value of</strong></td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Concentration of NaOH</td>
</tr>
<tr>
<td>Mass (BLS)/Volume (NaOH) ratio</td>
</tr>
<tr>
<td>Agitation speed</td>
</tr>
<tr>
<td>Adjusted $R^2$ of model</td>
</tr>
<tr>
<td>0.027</td>
</tr>
<tr>
<td>0.004</td>
</tr>
<tr>
<td>0.139</td>
</tr>
<tr>
<td>0.573</td>
</tr>
<tr>
<td>0.011</td>
</tr>
<tr>
<td>0.97</td>
</tr>
</tbody>
</table>

$^5$ANOVA at 95% level of confidence.
a glass container because the silica in glass can leach out due to the concentrated NaOH at high temperature.

3.3. Characterizations of water glass from BLS

Water glass was synthesized under the optimized condition in Fig. 9i, which can be performed at room temperature. Complete conversion of BLS under such condition was confirmed where $\xi = 1$, which produced water glass with a silica concentration of 1 mol L$^{-1}$ (3.5 wt.%, 1.12 g cm$^{-3}$) and pH >14. To determine the purity of the water glass, the water glass was dried and analyzed using EDX, and the result is shown in Fig. 10. It was verified that the water glass was pure and contained only sodium silicate. Water glass is usually graded by the molar ratio of SiO$_2$ : Na$_2$O, which is known as the modulus $R$. The modulus $R$ of this water glass, which was calculated based on the elemental composition in Fig. 10 is 0.85, which is lower than the range of 2.1–3.75 of the industrial grade. However, it is not uncommon that water glass that is synthesized from ashes has a low modulus $R$ [37]. Because a high mass ($m_{\text{ash}}$) to volume ($V_{\text{NaOH}}$) ratio is required to produce water glass with a high modulus $R$. Thus, the viscosity of the reactant mixture increased to form slurry, and it is difficult to obtain a uniform mass transfer.

4. Discussion

4.1. Characterizations of BLS

In Fig. 2b, no empty space was observed among the parallel veins of the bamboo leaf ash. Hence, it was inferred that silica were uniformly distributed in bamboo leaf, which is different from rice husk ash, where many empty spaces were observed in the skeleton of the flaky white solids that formed. Assuming that the ash contains mainly silica, it is reasonable to suspect that bamboo leaf contains a higher percentage of silica than rice husks. This hypothesis is confirmed using the EDX results of raw biomass in Fig. 4 and Table 3. From Table 2, the calculated $p$-values are both >0.05, which indicates that the ash content is affected neither by the methods of thermal decomposition nor the heating rates. Thus, the combustion of these biomasses in air is just as effective as pyrolysis in a nitrogen atmosphere. Thus, the synthesis of BLS can be achieved without the additional cost of using nitrogen in pyrolysis. In addition, the independence on the heating rates proved that thermal

![Fig. 9. Optimization of the processing conditions with minimum (i) $t$–$T$, (ii) $t$–$A$ and (iii) $T$–$A$.](image)

![Fig. 10. EDX spectrum of water glass that was synthesized from the BLS.](image)
decomposition under high heating rates did not induce anomalous reaction such as the formation of fixed carbon [38]. Because the TGA was performed up to 1000 °C after the isothermal heating at 650 °C, the equivalent ash contents obtained in both the combustion and the TGA methods indicate that organic materials are completely reacted at 650 °C with no further decomposition at high temperature.

In the presence of minerals such as potassium oxide and calcium oxide, the combustion of biomass can form fixed carbon, which reduces the purity of silica [38,39]. Thus, in Table 3, the purity of BLS increased after it was leached using HCl. Fig. 6b, d shows that the leached biomasses exhibited smoother spectra at both the diffused peaks and in all other regions than the unleached samples in Fig. 6a, c. The small peaks that were previously observed at 2θ of 32° and 35° in Fig. 6a, c were also eliminated in the leached samples. Therefore, it can be concluded that the amorphicity of the combusted BLS and RHS increased as a result of acid leaching.

4.2. Optimizations of the processing parameters to synthesize water glass

As observed in Fig. 8, the mass-to-volume ratio (R) and the NaOH concentration (C) are related. This relationship can be explained by the stoichiometry of the reaction between NaOH and BLS, which produces sodium metasilicate; under high pH, this compound will further convert to a more ionic species called sodium orthosilicate, as shown in Fig. 11.

Because the NaOH concentration was at least 2 mol L⁻¹, it is reasonable to assume that the BLS dissolved into NaOH to form sodium orthosilicate according to the following stoichiometry:

\[
\text{SiO}_2 + 4\text{NaOH} \rightarrow \text{Na}_4\text{SiO}_4 + 2\text{H}_2\text{O}
\]

Based on the stoichiometry, the molar ratio of \(\text{SiO}_2 : \text{NaOH}\) must be at least 1 : 4, i.e., \(n_{\text{SiO}_2}/n_{\text{NaOH}}<1/4\). This requirement implies that for a complete dissolution of BLS in NaOH, the ratio \(R/C\) must be < 15. In this work, the maximum mass-to-volume ratio and the minimum NaOH concentration are 60 g L⁻¹ and 2 mol L⁻¹, respectively. Hence, \(R/C > 15\) and NaOH became the limiting reactants in these experiments. This result implies that \(\xi\) is always less than unity under such conditions, as shown in Fig. 8. For example, \(\xi\) at 12 g L⁻¹, 2 mol L⁻¹ (\(R/C = 6\)) is 0.95 and decreased to 0.85 when \(R\) increased to 60 g L⁻¹ (\(R/C = 30\)). Because the NaOH concentration also increased to 6 mol L⁻¹, \(R/C = 10\) and \(\xi\) approached unity.

High silica yield was expected for notably low \(R/C\). However, the result is the opposite, where the lowest \(\xi\) is produced when the ratio \(R/C\) is small. This result implies that some unknown mechanism had suppressed the dissolution of silica when either a high NaOH concentration or a low BLS mass is used. It might be caused by the high concentration of \(OH^-\) ions, which led to the formation of electric double layers. These double layers prevented the \(OH^-\) ions from further reaching the remaining unreacted BLS. Thus, a complete conversion of BLS to water glass does not occur at both notably low and high \(R/C\) ratios. In this study, \(\xi \rightarrow 1\) in the range of \(10 < R/C < 15\). Because of this relationship between the NaOH concentration and the mass-to-volume ratio, their effect can be coupled to provide

\[
\xi = \frac{1}{10.000} (90.7t + 268.7T + 9.7RC + 47.9A - 5186)
\]

where \(10 < R/C < 15\).

5. Conclusions

The results verified that bamboo leaf has nearly twice as much silica as rice husk. The purity, the amorphicity and the chemical nature of BLS obtained in this work are similar to those obtained from rice husk. It is also confirmed that water glass with a silica concentration of 1 mol L⁻¹ (3.5 wt.% 1.12 g cm⁻³) and a modulus \(R\) of 0.85 can be synthesized from bamboo leaf. In the synthesis process, different parameters including the temperature, the time and the agitation speed had proved to have positive response to increase the silica yield in water glass. It was also discovered that the silica yield depends on the ratio of \(R/C\); to achieve a high silica yield, this ratio is in the range of \(10 < R/C < 15\). The statistical correlation obtained from the result may be used to estimate the silica yield and the silica concentration in water glass and to optimize the necessary condition in the process.

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