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Article

Utilization of Rice Waste (*Oryza sativa* L) for The Production of Silica Gel with Var`iations in Mass Ratio of Raw Materials and Reactant Solutions

Aisyah Suci Ningsih, Endang Supraptiah, Idha Silviyati, Sri Murda Niati*, Ibnu Hajar, Marghis Nur Dila

Chemical Engineering Department, Politeknik Negeri Sriwijaya, Palembang, Sumatera Selatan -30139, Indonesia

Abstract

Rice is one of the major agricultural commodities that generates large amounts of biomass waste, particularly rice husks and rice straw. These by-products contain high silica content and have potential as raw materials for silica gel production. This study aimed to synthesize silica gel from rice husks and rice straw using the sol–gel method with different biomass ratios and acid activators. The ratios of rice husk to rice straw used were 100:0, 75:25, 50:50, 25:75, and 0:100 (w/w). The synthesis process was carried out using 3 M HCl and 3 M H_2SO_4 solutions as reactants. The obtained silica gel products were evaluated based on yield, moisture content, water adsorption capacity, and functional group characteristics using Fourier Transform Infrared (FTIR) spectroscopy. The results showed that the optimum silica gel was produced from a biomass ratio of 75 % rice husk and 25 % rice straw using H_2SO_4 as the reactant. The resulting silica gel exhibited a yield of 82.5 %, moisture content of 14.7 %, and water adsorption capacity of 0.0092 g/g. FTIR analysis confirmed the presence of silanol (Si–OH), siloxane (Si–O–Si), and siloxy functional groups, indicating successful silica gel formation. Overall, the synthesized silica gel demonstrated physicochemical properties consistent with standard silica gel characteristics and showed potential for application as an adsorbent material.

Keywords: *Silica gel, rice straw, rice husk*

* Corresponding author
Email addresses: sri.murda.niati@polsri.ac.id (Sri Murda Niati)

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Graphical Abstract

Introduction

Indonesia is one of the countries with extensive agricultural land distributed across major islands such as Java, Sumatra, and Sulawesi. The total agricultural land area in Indonesia reaches approximately 10.4 million hectares, with South Sumatra recorded as one of the provinces with the largest agricultural areas [1]. This condition supports Indonesia as one of the major rice-producing countries in the world. However, rice cultivation activities also generate large quantities of agricultural waste, including rice straw, rice husks, bran, and rice polish.

Agricultural waste derived from rice production has attracted considerable attention due to its potential for value-added applications. Among these by-products, rice husks and rice straw are rich in silica compounds and can be utilized as alternative raw materials for silica-based materials. Rice husks contain silica at concentrations ranging from approximately 90–98 %, while rice straw contains silica levels of around 82 % [2,3]. The high silica content makes these materials promising renewable resources for silica extraction and silica gel synthesis.

Silica gel is an amorphous silica material with high porosity and strong water adsorption capacitys [2]. Due to these characteristics, silica gel has been widely applied as an adsorbent, desiccant, catalyst support, anti-caking agent, cosmetic additive, and filler material in industrial products. One of the commonly used methods for silica gel synthesis is the sol–gel method because it is relatively simple, cost-effective, and capable of producing silica with high purity and controlled pore structure [3].

Previous studies have reported the utilization of rice husks or rice straw individually for silica production [3,4]. However, studies evaluating the combined use of rice husks and rice straw with different composition ratios for silica gel synthesis are still limited. Therefore, this study aimed to synthesize silica gel from rice husks and rice straw using the sol–gel method with different biomass ratios and

acid activators. The synthesized silica gel was characterized based on yield, moisture content, water adsorption capacity, and functional group analysis using Fourier Transform Infrared (FTIR) spectroscopy.

Furthermore, abundant rice waste has also been utilized as animal feed and bioenergy material. However, the utilization of rice straw as feed is limited due to its low nutritional value and high fiber content. Rice husks and bran are considered more suitable as concentrated feed because they contain higher energy content [4].

Several studies have also reported the conversion of rice waste into environmentally beneficial products. A community-based study in Padengo Village demonstrated that rice straw could be processed into compost using Effective Microorganism-4 (EM4) technology, which improved soil fertility while reducing agricultural waste accumulation [5]. In addition, rice husks have been utilized for biopellet production using tapioca flour as a binder, resulting in moisture contents of 6.6–8.4 %, ash contents of 6–16 %, and calorific values of approximately 4.064–4.135 J/g, indicating their potential as alternative biofuel materials [6]. Both rice straw and rice husks therefore represent promising renewable biomass resources for sustainable applications [7].

Silica (SiO_2) is an inorganic compound naturally found in materials such as sand, quartz, and silicate rocks. Naturally occurring silica generally possesses a crystalline structure with highly ordered atomic arrangements, whereas synthetic silica materials such as silica gel exhibit an amorphous structure without long-range crystallinity. Amorphous silica is commonly synthesized through methods such as the sol–gel process, which enables the formation of nano-sized particles with high surface area and reactivity [8]. Due to its porous structure and strong adsorption properties, silica gel has been widely used in industrial and laboratory applications as an adsorbent, desiccant, catalyst support, and moisture control material.

Silica gel ($SiO_2 \cdot xH_2O$) is characterized by solid glass-like particles with highly porous structures. It is commonly synthesized through the coagulation of sodium silicate sol derived from sodium silicate precursors. During the dehydration process, the gel structure transforms into rigid amorphous particles with high adsorption capability [9]. Silica gel can absorb moisture effectively without undergoing structural changes, making it highly suitable as a desiccant material [10]. The adsorption capability of silica gel is strongly influenced by the presence of silanol (Si–OH) and siloxane (Si–O–Si) functional groups on its surface [11].

Previous studies have investigated the influence of acid catalysts on the synthesis of silica materials from rice husk ash. Hayati et al. reported the use of hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and phosphoric acid (H_3PO_4) at concentrations of 3 M during the sol–gel synthesis process to promote silica hydrolysis and condensation reactions [12]. In addition, silica gel synthesized from rice husks using HCl solution showed promising physicochemical properties, including a surface area of 130.867 m^2/g, total pore volume of 0.1420 cc/g, and average pore diameter of 4.34 nm [12]. These findings indicate that rice husk-derived silica has strong potential as a raw material for silica gel production.

Compared with previous studies, the novelty of this research lies in the utilization of mixed rice husk and rice straw biomass as silica sources for silica gel synthesis. The incorporation of rice straw was considered because rice straw also contains high silica

content, approximately 83 %. Therefore, this study aimed to investigate the synthesis of silica gel from mixtures of rice husks and rice straw using strong acid solutions, namely HCl and H_2SO_4, through the sol–gel method to produce environmentally friendly silica gel materials with potential industrial applications.

Materials and Methods

Materials

The materials used in this study were rice straw and rice husks collected from local rice fields in Indonesia. The chemical reagents used included sodium hydroxide (NaOH, Merck, Germany), hydrochloric acid (HCl 37 %, Merck, Germany), sulfuric acid (H_2SO_4 96 %, Merck, Germany), and distilled water. All chemicals used were of analytical grade without further purification.

The equipment used in this study included a furnace (Nabertherm, Germany), analytical balance (Ohaus Pioneer™, USA), hot plate magnetic stirrer (IKA® C-MAG HS 7, Germany), laboratory oven (Memmert, Germany), desiccator (Pyrex®, USA), mortar and pestle, aluminum foil, pH paper (Merck, Germany), filter paper (Whatman No. 42, UK), stainless steel sieve (100 mesh), and standard laboratory glassware including beakers, volumetric flasks, measuring cylinders, Erlenmeyer flasks, and glass rods. Functional group characterization of the synthesized silica gel was performed using Fourier-Transform Infrared Spectroscopy (FTIR) (Shimadzu IRPrestige-21, Japan).

Experimental Design

The independent variables in this study were the type of acid reagent solution and the composition ratio of rice husk and rice straw used as raw materials for silica gel synthesis. The composition ratios of rice husk to rice straw were 100:0, 75:25, 50:50, 25:75, and 0:100 (w/w). The fixed variables were heating temperature and heating duration during the synthesis process. The dependent variables observed were silica gel yield, moisture content, and water adsorption capacity.

Preparation of Rice Husk and Rice Straw Ash

Rice husks and rice straw were washed thoroughly using distilled water to remove adhering impurities and dirt, followed by sun drying until constant weight was achieved. The dried rice husks were then oven-dried at 110 °C for 2 h, while the rice straw was dried at 200 °C for 10 min.

Subsequently, the rice husks and rice straw were immersed separately in 200 mL of 1 M HCl solution and heated at 75 °C for 1 h to remove metallic impurities and reduce mineral contaminants. The suspension was filtered using Whatman No. 42 filter paper, and the solid residue was washed repeatedly with distilled water until neutral pH was reached.

The cleaned rice husks and rice straw were then calcined in a furnace (Nabertherm, Germany) at 700 °C for 2 h to produce rice husk ash and rice straw ash. After cooling to room temperature, the resulting ash was ground using a mortar and pestle and sieved through a 100-mesh sieve to obtain homogeneous ash particles.

Silica Gel Synthesis

Rice husk ash and rice straw ash were mixed according to the predetermined composition ratios, and 40 g of the mixed ash was dissolved in 200 mL of 2.5 M NaOH solution. The mixture was heated at 100 °C for 2 h on a hot plate magnetic stirrer (IKA®, Germany) under continuous stirring and covered with aluminum foil to minimize evaporation.

After heating, the mixture was filtered using Whatman No. 42 filter paper to separate insoluble residues, and the sodium silicate filtrate was collected. The filtrate was then titrated using either 3 M HCl or 3 M H_2SO_4 solution under continuous stirring until pH 7 was achieved, resulting in hydrogel formation through the sol–gel process.

The formed hydrogel was aged at room temperature for 24 h to complete the gelation process. The hydrogel was subsequently washed repeatedly with distilled water to remove residual ions and impurities. The washed hydrogel was filtered and dried in an oven (Memmert, Germany) at 80 °C for 2 h to obtain silica gel powder.

Product Analysis Method, Moisture Content Test (SNI 3751-2009)

Heat the porcelain dish at 130 °C in an oven for 1 hour. Cool the porcelain dish in a desiccator for 30 minutes and weigh it. Weigh 1 g of silica (W) and place it on the porcelain dish, then bake it in an oven at 130 °C for 1 hour. Cool the porcelain dish containing silica in a desiccator for 30 minutes, then weigh the sample (W1). Once a constant weight is obtained, calculate the moisture content using the formula 1 (SNI 3751-2009) [13].

$$\text{Moisture Content} = \frac{W+W_1}{W} \times 100\ \% \qquad (1)$$

where W = Initial sample weight (g); W1 = Weight of sample after heating (g).

Product Analysis Method, Absorption Test

1 g of silica and prepare 100 ml of distilled water. Store the silica gel in a desiccator with the distilled water, then leave it for 1 day until the mass of the silica gel does not change. Weigh the mass of the silica gel after it has been stored in the desiccator. Calculate the change in silica gel mass before and after storage, and determine the adsorption capacity of the silica gel by comparing the amount of water absorbed per gram of silica gel (Formula 2) [14].

$$q\ (\%) = (W_t - W_0)/ W_0\ \ 100\ \% \qquad (2)$$

where q is the water adsorption capacity (%), W_0 is the initial dry weight of silica gel (g), and W_t is the weight of silica gel after adsorption equilibrium (g).

Functional Group Characteristics (FTIR)

Infrared spectroscopy is used to identify functional groups present in silica gel. Each functional group in silica gel has characteristic absorption at specific wavenumbers, enabling qualitative identification using infrared spectroscopy. This characterization is expected to be used for qualitative indication of the success of silica gel synthesis [15,16]. FTIR analysis results are presented in the form of a spectrum graph, where the X-axis represents the absorption spectrum plotted against wavenumber, and the Y-axis represents the percentage of transmittance [17]. The silica gel production process is shown in Figure 1. The silica gel testing process is shown in Figure 2.

Figure 1. Overview process; (a) Drying of rice husks and straw; (b) Furnace output of rice husks and straw; (c) Furnace feedstock; (d) Ground rice husk and straw ash; (e) Suspension filtration process; (f) Heating

the mixture of ash and HCl solution; (g) Preparation of sodium silicate solution; (h) Sol-gel process with H_2O and $CuSO_4$; (i) Filtered and washed hydrogel.

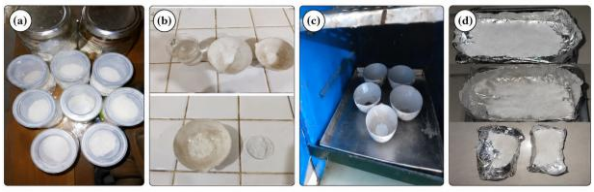

Figure 2. Photograph of samples. (a) Silica gel sample; (b) Silica gel absorption test; (c) Silica gel moisture content test; (d) Silica gel usage test

Result and Discussion

Effect of Reagent Type and Biomass Composition on Silica Gel Characteristics

The synthesis of silica gel from mixtures of rice husk (RH) and rice straw (RS) produced materials with varying yields, moisture contents, water adsorption capacities, and silica functional group characteristics (Table 1). Since each treatment was performed without replication, the data were interpreted descriptively to identify trends associated with biomass composition and acid reagent type.

The results indicate that both RH proportion and acid reagent influenced the physicochemical properties of the synthesized silica gel. Generally, increasing the RH content improved silica recovery and adsorption performance, reflecting the higher silica content of rice husk relative to rice straw. For HCl-treated samples, the highest yield was obtained from the 100:0 RH:RS ratio (52.0%), while the lowest yield was observed in the 0:100 treatment (5.75%). Water adsorption capacity showed a similar pattern, decreasing from 0.0084 g g^{-1} at the 75:25 ratio to 0.0052 g g^{-1} in the rice-straw-only sample. These results suggest that increasing the proportion of rice straw reduced silica recovery and adsorption capacity due to its lower silica content and greater abundance of non-siliceous constituents.

Table 1. Results of Rice Husk and Rice Straw Silica Gel Synthesis

Sample Code	Type of solution Reagent	Mass Ratio SP : JP (%)	Yield (%)	Moisture Content (%)		Water Adsorption (g/g)	
				Result	SNI Standard	Result	SNI Standard
A1	HCl	100:0	52	14.1	≤15	0.0080	≥0.0075
A2	HCl	75:25	37	14.6	≤15	0.0084	≥0.0075
A3	HCl	50:50	21.5	10.8	≤15	0.0068	≥0.0075
A4	HCl	25:75	13	7	≤15	0.0056	≥0.0075
A5	HCl	0:100	5.75	2.9	≤15	0.0052	≥0.0075
B1	H_2SO_4	100:0	78.25	14.6	≤15	0.0076	≥0.0075
B2	H_2SO_4	75:25	82.5	14.7	≤15	0.0092	≥0.0075
B3	H_2SO_4	50:50	61.25	11.8	≤15	0.0080	≥0.0075
B4	H_2SO_4	25:75	29.25	11.6	≤15	0.0064	≥0.0075
B5	H_2SO_4	0:100	13.5	7.5	≤15	0.0063	≥0.0075

Description: SP : JP Mass Ratio (%) → SP = Rice Husk, JP = Rice Straw

Compared with HCl, H_2SO_4 consistently produced silica gel with superior performance across all biomass ratios. The optimum formulation was achieved at an RH ratio of 75:25 using 3 M H_2SO_4, yielding 82.5% silica gel with the highest water

adsorption capacity (0.0092 g g^{-1}) while maintaining an acceptable moisture content (14.7%). Notably, this adsorption capacity exceeded the minimum requirement specified in SNI 06-2477-1991 (0.0075 g g^{-1}), indicating good adsorbent quality.

The superior performance of the H_2SO_4-treated samples indicates that sulfuric acid was more effective than hydrochloric acid in promoting silica gel formation during the sol–gel process. Across comparable biomass compositions, H_2SO_4 treatment generally resulted in higher yields and water adsorption capacities, suggesting enhanced silica precipitation and a more developed gel structure. The maximum yield (82.5%) was achieved at a rice husk-to-rice straw ratio of 75:25, whereas the highest yield obtained using HCl was 37%. Thus, H_2SO_4 increased silica recovery by approximately 123%, demonstrating the substantial effect of acid reagent selection on synthesis efficiency. These findings highlight the importance of both precursor composition and acid catalyst type in optimizing silica gel production from agricultural residues.

Table 2. Results of Analysis of Silica Gel Function Groups in Rice Husk and Rice Straw

Types of Vibration	Wave Number (cm^{-1})	
	Sample A2	**Sample B2**
Span -OH from Si-OH	3391.13	3386.11
Bending -OH from Si-OH	1640.34	1638.9
Asymmetry range Si-O from Si-O-Si	1060.8	1042.16
Symmetry range Si-O from Si-OH	953.93	878.62
Asymmetry range Si-O-Si	793.99	788.97
Curve Si-O-Si	454.73	432.5

A = HCl Solution Variation, B = H2SO4 Solution Variation, Material Mass Ratio 75%:25%

Moisture content analysis showed that all synthesized silica gel samples contained less than 15% moisture, indicating acceptable water content for silica gel materials. Low residual moisture is advantageous because excessive water may adversely affect adsorption performance and storage stability.

The adsorption capacity of silica gel is strongly influenced by its pore structure and the density of surface silanol (Si–OH) groups, which contribute to water adsorption through hydrogen-bond interactions. The higher adsorption capacities observed in several treatments therefore suggest the formation of a more developed porous network with a greater number of accessible active sites. Notably, the silica gel synthesized using H_2SO_4 at a rice husk-to-rice straw ratio of 75:25 achieved the highest yield and adsorption capacity, indicating that this formulation provided the most favorable conditions for silica gel formation.

Overall, the results highlight the feasibility of utilizing rice husks and rice straw as renewable silica sources for value-added silica gel production. The observed differences among treatments further confirm that both feedstock composition and acid reagent type are key factors governing silica recovery and adsorption properties. These findings support the potential application of agricultural waste-derived silica gel as an environmentally sustainable adsorbent material.

Tabel 3. Silica Gel Usage Test Results

Day Observation	Sample Mass A2 (g)	Sample Mass B2 (g)
1	1.0	1.0
2	1.13	1.26
3	1.15	1.33
4	1.19	1.38
5	1.22	1.41
6	1.28	1.48
7	1.37	1.52

Description: A = Variation in HCl Solution, B = Variation in H2SO4 Solution, Material Mass Ratio 75 % : 25 %.

Yield Results

Yield is a comparison of the weight of the precipitate obtained with the amount of silicate ash used. The yield value produced will be related to the amount of bioactive content contained therein [18]. The relationship between the composition of rice husk and rice straw mixtures and the silica gel yield can be seen in Figure 3.

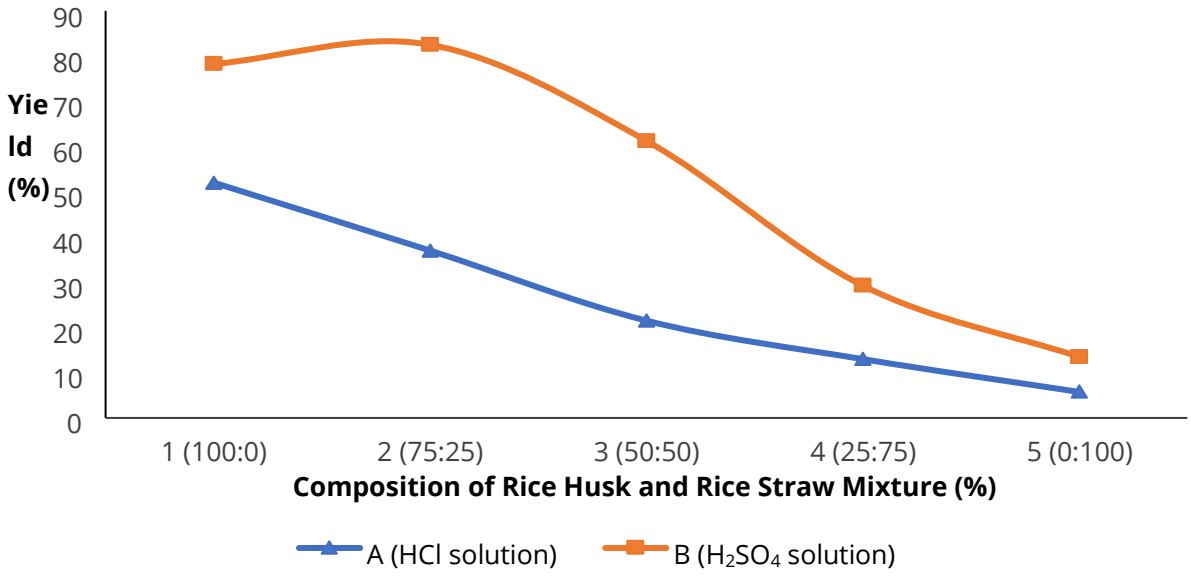

Figure 3. Graph showing the effect of the composition of rice husk and rice straw mixtures

As shown in Figure 3, the highest silica gel yield was obtained from sample B2 (75% rice husk:25% rice straw) synthesized using H_2SO_4, reaching 82.5%, whereas the lowest yield was recorded for sample A5 (0% rice husk:100% rice straw) synthesized using HCl, with a yield of only 5.75%. These results indicate that both biomass composition and acid type strongly influenced silica recovery during the sol–gel process.

An increase in rice husk proportion generally resulted in higher silica gel yields. This trend can be attributed to the inherently higher silica content of rice husks compared with rice straw, enabling more efficient sodium silicate formation and subsequent silica precipitation. In contrast, increasing the proportion of rice

straw reduced silica recovery, likely due to its lower silica concentration and higher content of non-siliceous organic components.

The use of H_2SO_4 consistently produced higher yields than HCl across comparable biomass ratios. Notably, the optimum formulation (B2) exhibited a yield approximately 123% higher than the best-performing HCl-treated sample (A2, 37%). The superior performance of H_2SO_4 may be associated with its stronger acidic character and diprotic nature, which promotes more efficient protonation of silicate species and facilitates silica condensation during gel formation. Consequently, silica precipitation from sodium silicate solution becomes more complete, resulting in greater silica recovery and improved gel formation. These findings are consistent with previous studies reporting that sulfuric acid enhances silica formation efficiency during sol–gel synthesis from rice-derived silica sources [12].

Moisture Content Test

TMoisture content analysis was performed to evaluate the hygroscopic properties of the synthesized silica gel. This parameter reflects the amount of water retained within the silica structure and is closely related to the abundance of surface silanol groups and the porous characteristics of the material. In this study, moisture content was determined from the weight loss of silica gel after heating at 130 °C for 1 h, representing the removal of physically adsorbed water. The results of the moisture content analysis are presented in Figure 4. Overall, all synthesized silica gel samples exhibited moisture contents below the maximum limit specified by the silica gel quality standard (≤15%), indicating acceptable physicochemical quality for adsorbent applications.

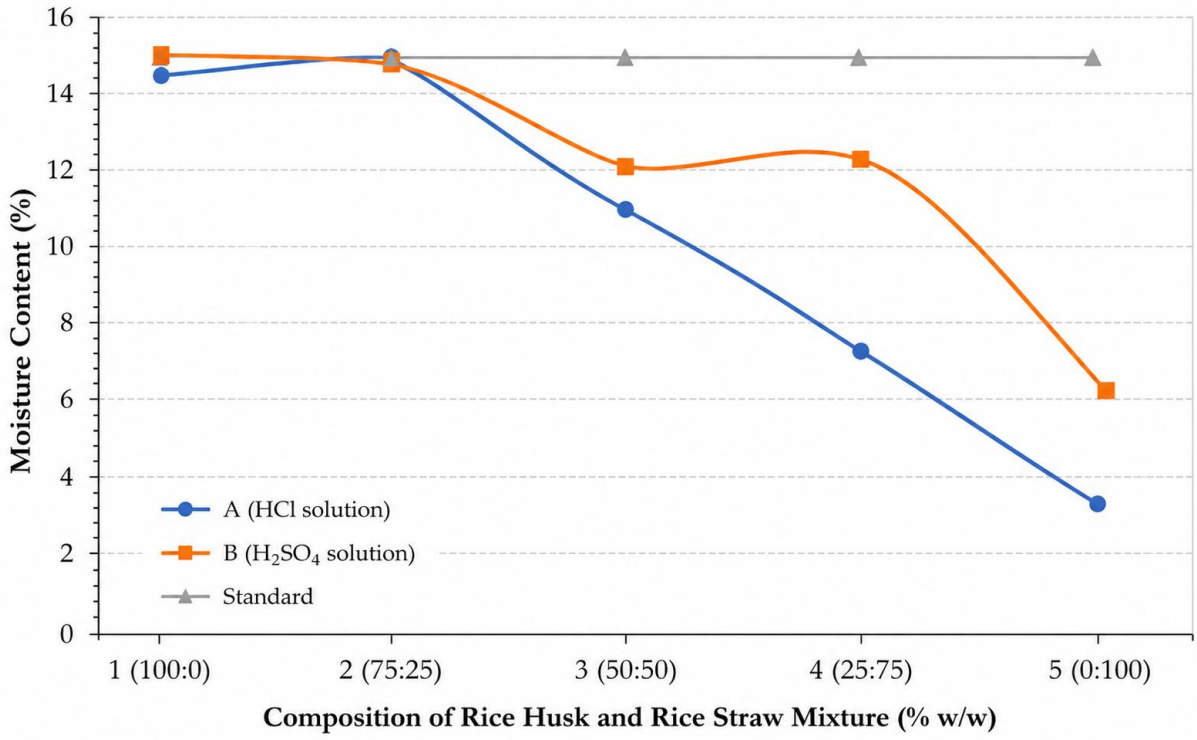

Figure 4. Graph showing the effect of the composition of rice husk and rice straw mixtures on moisture content

Based on the graph in Figure 4, it can be seen that the highest moisture content was found in sample B2, which was 14.7 % with a composition of 100 % rice husks using H_2SO_4 solution, and the lowest moisture content was found in sample A5, which was 2.9 % with a composition of 100 % rice straw using HCl solution. Factors that can affect the moisture content percentage include raw materials and acid solutions. In addition, moisture content can also be influenced by the amount of water vapor in the air and the duration of the cooling process [19]. Differences in material percentages can affect the moisture content value obtained. The higher the rice husk content, the higher the moisture content value [20]. This is because rice husks have a high silica content, while straw has a lower silica content. The higher the silanol (Si-OH) content in silica, the greater the ability of silica gel to bind water molecules due to the increased hydrogen bonds.

Additionally, strong acid solutions cause an increase in moisture content. This is because sulfuric acid has a higher acidity than hydrochloric acid. The increase in the acidity of the synthesized silica gel is estimated to originate from the increase in the number of silanol groups caused by the increased H^+ ions used in the production of silica gel [22]. Sulfuric acid has $2H^+$, while HCl only has H^+ ions.

The higher the acidity value, the greater the number of silanol (Si-OH) groups present in the silica gel, thereby increasing its ability to donate protons [9]. Based on the results of the percentage of air content, all treatments on the samples have met the requirements of SNI silica gel [20], which states that the maximum water content value of silica gel is 15%, so that the water content in the silica gel samples meets the quality requirements with the optimal water content being in sample B2.

Water Adsorption Capacity of Synthesized Silica Gel

One application of silica gel adsorption capacity that was tested to determine the quality of the adsorbent was its absorption capacity for H_2O, since adsorbents are generally used as absorbent materials (adsorption). Adsorption in silica gel is an absorption process that occurs when a fluid/liquid binds to a solid and eventually forms a thin layer or film on its surface [9]. Water adsorption capacity is defined as the maximum ability of silica gel to adsorb water from saturated vapor. The results of water absorption on silica gel from rice husks and straw can be seen in Figure 5.

Based on Figure 5, the highest water adsorption capacity was observed in sample B2, which was synthesized using a mixture of 75 % rice husk and 25 % rice straw with H_2SO_4 solution, reaching 0.0092 g/g. In contrast, the lowest adsorption capacity was found in sample A5, consisting of 100 % rice straw synthesized using HCl solution, with an adsorption value of 0.0052 g/g.

The water adsorption capability of silica gel is influenced by several factors, including silica content, acid reagent type, pore structure, and the chemical composition of the synthesized silica material [23]. Higher silica content generally contributes to better adsorption performance because silica-rich materials possess larger surface areas and more active adsorption sites [9]. Rice husks contain higher silica content compared with rice straw; therefore, silica gel synthesized with higher rice husk composition tended to exhibit superior adsorption properties.

The type of acid reagent also significantly affected the adsorption performance of the synthesized silica gel. Silica gel prepared

using H_2SO_4 solution showed higher water adsorption capacity than samples synthesized using HCl. This phenomenon may be attributed to the stronger acidity and higher proton contribution of H_2SO_4, which contains two dissociable H^+ ions, whereas HCl only contributes one H^+ ion. Higher acidity during the sol–gel process can enhance silica hydrolysis and condensation reactions, promoting the formation of larger numbers of silanol (Si–OH) groups on the silica surface [9]. These silanol groups play an important role in water adsorption because they can interact strongly with water molecules through hydrogen bonding.

The presence of abundant silanol groups increases the hydrophilic nature of silica gel, thereby improving its adsorption capacity. In addition, better pore formation during gelation may contribute to increased surface area and adsorption efficiency. The results indicate that the combination of high rice husk composition and H_2SO_4 reagent produced silica gel with more favorable physicochemical characteristics for adsorption applications.

According to the Indonesian National Standard (SNI No. 06-2477:1991), silica gel should have a minimum water adsorption capacity of 0.0075 g/g [21]. Based on the obtained results, several synthesized silica gel samples met or exceeded this standard, particularly sample B2 with an adsorption capacity of 0.0092 g/g. This value was also higher than that of commercial silica gel, which exhibited an adsorption capacity of approximately 0.0085 g/g.

Conversely, samples synthesized using HCl with higher proportions of rice straw (A3–A5) showed relatively lower adsorption capacities, in some cases below the commercial silica gel standard. The lower adsorption performance may be associated with reduced silica purity and less optimal pore formation due to the higher organic and cellulose content of rice straw [22].

Overall, the results demonstrate that silica gel synthesized using H_2SO_4 and a rice husk to rice straw ratio of 75:25 exhibited the optimum water adsorption performance. These findings indicate that agricultural biomass waste can be effectively utilized as an environmentally friendly raw material for silica gel production with competitive adsorption properties.

Identification of Functional Groups of Synthesized Silica Gel

Functional group identification of the synthesized silica gel was carried out using Fourier Transform Infrared (FTIR) spectroscopy. FTIR analysis is commonly used to identify characteristic functional groups in silica materials based on their absorption bands at specific wavenumbers. The active functional groups present on the surface of silica gel mainly consist of silanol (Si–OH) and siloxane (Si–O–Si) groups, which play important roles in adsorption processes and surface interactions. Therefore, FTIR characterization was performed to confirm the successful formation of silica gel synthesized from mixtures of rice husks and rice straw. The FTIR spectra of silica gel synthesized from a mixture of 75 % rice husk and 25 % rice straw using HCl solution (sample A2) and H_2SO_4 solution (sample B2) are presented in Figures 6 and 7, respectively.

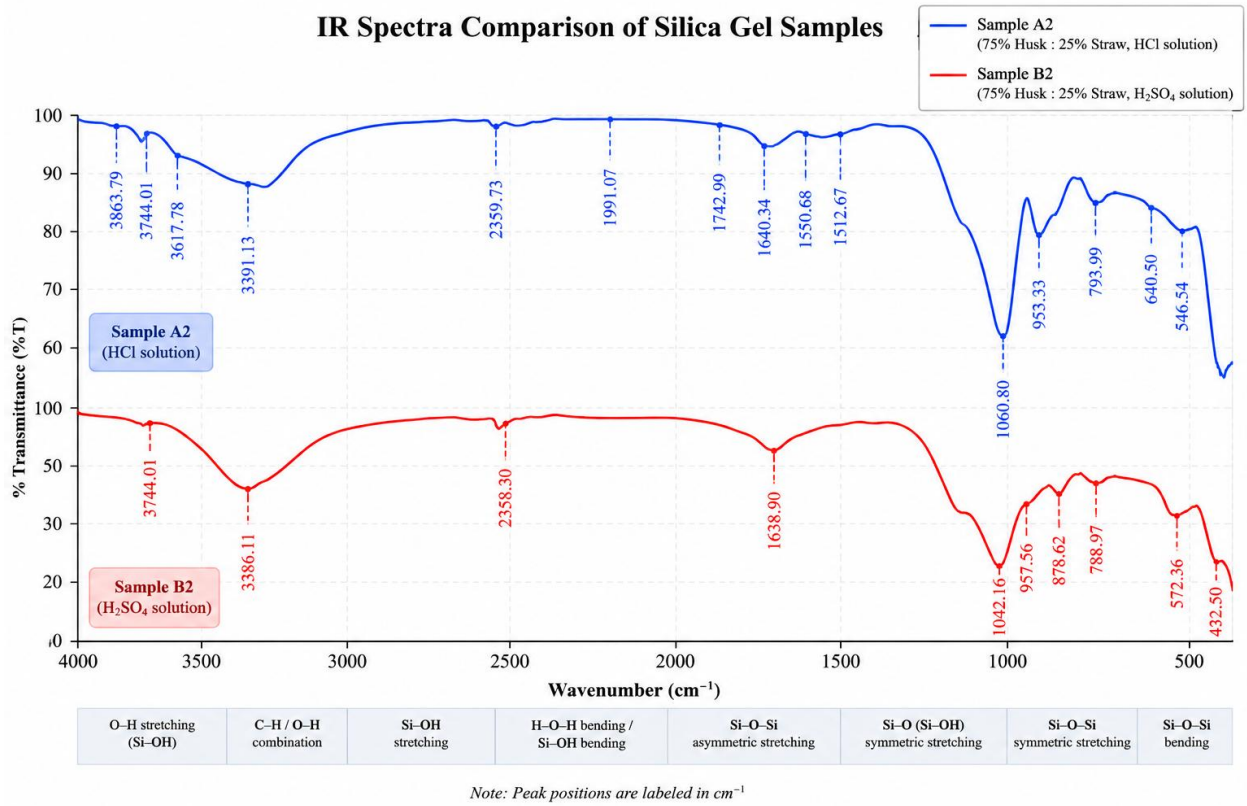

Figure 6. IR Spectrum Overlay of Silica Gel Synthesis Results for Sample A2 and B2

Based on the FTIR spectrum of sample A2 (Figure 6), a broad absorption band was observed at 3391.13 cm^{-1}, corresponding to the stretching vibration of hydroxyl (–OH) groups associated with silanol (Si–OH). The presence of hydroxyl groups was further confirmed by the absorption peak at 1640.34 cm^{-1}, which represents the bending vibration of adsorbed water or Si–OH groups. The absorption band at 793.99 cm^{-1} indicates the symmetric stretching vibration of the siloxane (Si–O–Si) group, while the absorption at 454.73 cm^{-1} corresponds to the bending vibration of the Si–O–Si bond. In addition, the absorption peak at 953.93 cm^{-1} was assigned to the symmetric stretching vibration of Si–O from silanol groups, whereas the strong absorption band at 1060.80 cm^{-1} indicates the asymmetric stretching vibration of Si–O–Si bonds.

Similarly, the FTIR spectrum of sample B2 (Figure 7) showed a broad absorption band at 3386.11 cm^{-1}, indicating the stretching vibration of hydroxyl groups from Si–OH. The bending vibration of the hydroxyl group was observed at 1638.90 cm^{-1}. The absorption band at 788.97 cm^{-1} corresponds to the stretching vibration of siloxane (Si–O–Si), while the absorption at 432.50 cm^{-1} represents the bending vibration of the Si–O–Si group. Furthermore, the absorption peak at 878.62 cm^{-1} indicates the symmetric stretching vibration of Si–O from silanol groups, and the absorption band at 1042.16 cm^{-1} corresponds to the asymmetric stretching vibration of Si–O–Si bonds.

In general, the FTIR spectra of all synthesized silica gel samples exhibited characteristic absorption bands of silica materials. The identified functional groups included silanol (Si–OH), siloxane (Si–O–Si),

and siloxy (Si–O) groups, which are typical functional groups of amorphous silica gel. The presence of these functional groups confirms that silica gel was successfully synthesized from rice husk and rice straw biomass through the sol–gel process using both HCl and H_2SO_4 solutions.

The abundance of silanol and siloxane groups also indicates the potential adsorption capability of the synthesized silica gel, since these functional groups act as active adsorption sites for water molecules and other polar compounds. Therefore, the FTIR results support the adsorption analysis results, where silica gel synthesized using H_2SO_4 and a rice husk to rice straw ratio of 75:25 demonstrated superior adsorption performance.

Usability Testing of Synthesized Silica Gel

The usability test was conducted to evaluate the effectiveness of the synthesized silica gel as a moisture-absorbing material. This test was performed by observing changes in mass and physical appearance of the silica gel samples before and after storage in a wardrobe environment for seven days. The results of the usability test are presented in Figure 8.

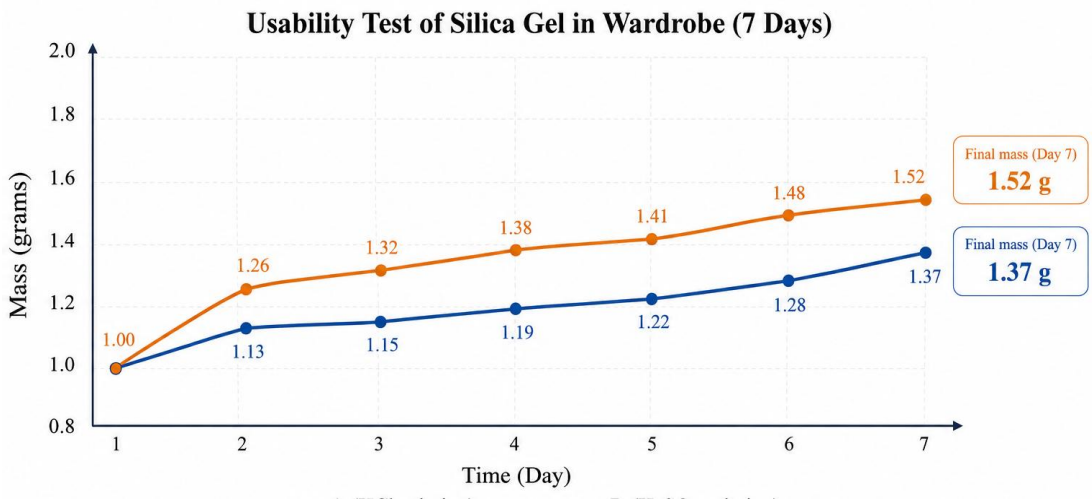

Figure 8. Graph of Silica Gel Usage Test for 7 Days

Based on Figure 8, both silica gel samples initially had a mass of 1.0 g on the first day of testing. After seven days, the silica gel synthesized using HCl solution showed an increase in mass to 1.37 g, while the silica gel synthesized using H_2SO_4 solution increased to 1.52 g. The increase in mass observed in both samples indicates that the synthesized silica gel successfully absorbed moisture from the surrounding environment inside the wardrobe.

The higher mass increase observed in the silica gel synthesized using H_2SO_4 suggests that this sample possessed better moisture adsorption capability compared with the silica gel synthesized using HCl [24]. This result is consistent with the previous adsorption analysis, which demonstrated that silica gel prepared using H_2SO_4 exhibited superior adsorption performance due to the presence of larger numbers of active silanol groups and potentially better pore development.

In addition to mass changes, visual observations also showed changes in the physical appearance of the silica gel samples after the usability test. Initially, the silica gel appeared as dry white granules. However, after seven days of exposure, the silica gel became slightly clumped and

exhibited a pale coloration. The clumping phenomenon occurred due to moisture absorption by the silica gel, causing the particles to agglomerate. Meanwhile, the slight color change may have been influenced by absorbed moisture and environmental impurities during storage.

The observed increases in mass and changes in physical appearance indicate that the synthesized silica gel effectively functioned as a moisture-absorbing material. These findings demonstrate the potential application of silica gel synthesized from rice husk and rice straw biomass as an environmentally friendly desiccant material for humidity control and moisture adsorption applications

Conclusions

Based on the results of the research that has been done, it can be concluded that silica gel with a mixture composition of 75 % rice husk and 25 % rice straw has the most optimal silica gel synthesis results, where rice husk has a higher silica content than rice straw. The use of H_2SO_4 solution in the manufacture of silica gel has the most optimal yield, water content, and water adsorption results compared to the manufacture of silica gel with HCl solution, with values of 82.5 %, 14.7 %, and 9.2 ml/g, respectively. Based on the results of the characteristics using FTIR, the synthesized silica gel has the characteristics of the general silica gel functional groups, which are silanol functional groups (Si-OH), siloxy functional groups (Si-O), and siloxane functional groups (Si-O-Si) with the results of silica gel using H_2SO_4 solution having better absorption.

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Author Contributions

Marghis Nurlaila contributed to validation, visualization, and data interpretation. **Idha Silviyati** contributed to formal analysis, investigation, and data collection. **Endang Supraptiah** contributed to software, data curation, and writing of the original draft. **Aisyah Suci Ningsih** contributed to conceptualization, methodology, and project administration. **Sri Murda Niati** contributed to supervision, resources, and writing—review and editing. All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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