Preparation of Silica Granules from Geothermal Sludge for Adsorption of Methylene Blue

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**Abstract.** Geothermal power plants generate large volumes of silica-rich sludge (often >85% SiO₂) as an industrial by-product, yet this resource remains underexploited due to contaminating metal oxides. In this work, we transform geothermal sludge into silica–alginate adsorbent granules and evaluate their capacity to remove methylene blue (MB) from water. Optimized acid leaching (2 M HCl, 90 °C, 5 h) increased silica purity from 85% to 93.9% and achieved a high recovery rate (94.9%). The purified silica was used to synthesize silica material via Pluronic P123 templating and subsequent incorporation into Ca²⁺-crosslinked sodium alginate beads. Structural analysis (FTIR) confirmed formation of an Si–O–Si siloxane network in the calcined material. In batch adsorption tests with MB, the optimized dry granules (prepared using 0.017 mol P123) achieved 64.15% dye removal and a capacity of 2.48 mg/g (under 50 mg/L initial MB). The granules exhibited fast uptake (majority of adsorption within 30–40 min). These quantitative results demonstrate that silica derived from geothermal waste can be effectively re-used as a porous adsorbent, supporting sustainable water treatment.

Keywords: Geothermal Sludge, Silica Granule, Dye Adsorption, Clean Water

# INTRODUCTION

Geothermal energy production generates large quantities of solid waste, known as geothermal sludge, which is rich in silica (SiO₂) with contents often exceeding 85% by weight [1]. However, the silica-rich sludge also contains significant metal oxides (Fe₂O₃, Al₂O₃, CaO, etc.) that inhibit direct use of the material, necessitating purification. Acid leaching, particularly with HCl, is effective at dissolving these impurities while retaining the silica framework [2]. Hydrochloric acid (HCl) has been widely reported as a favourable leaching agent due to its ability to selectively remove metal oxides without significantly degrading the silica framework. Once purified, the silica can be reassembled into structured adsorbents. In particular, surfactant templating methods (e.g. using Pluronic P123) can produce ordered silica with high surface area and controlled pore size[3,**4]. This method enables control over structural properties such as channel size, surface area, and thermal stability, making it effective for adsorption and separation applications.**

Despite these advantages of porous silica, fine silica powders suffer practical limitations: they are mechanically weak, hard to separate from water, and prone to agglomeration (loss of surface area) in aqueous systems. To overcome this, silica–polymer composite beads are often used [5,6]. Embedding silica into a biopolymer (here, sodium alginate) yields mechanically robust beads that are easy to handle and reuse [7]. Alginate (a natural anionic polysaccharide) forms stable gel beads when cross-linked by Ca²⁺, and its carboxylate groups provide additional binding sites for metal ions or cationic organics. Silica–alginate composites have shown promise in adsorbing cationic dye, like methylene blue from wastewater [8-10]. Compared to powder forms, the resulting granules offer superior mechanical stability, easier recovery, and better performance consistency in aqueous environments. A synthetic dye known for its high stability, toxicity, and resistance to biodegradation [9]. Methylene Blue (MB) is commonly used in the textile and dyeing industry and is often found in industrial wastewater, where its removal is essential to prevent environmental harm, so developing efficient adsorbents is of significant environmental relevance [10,11].

This study addresses that gap by systematically optimizing HCl leaching and P123 templating of geothermal-sourced silica, followed by alginate granulation. We then evaluate the resulting silica–alginate beads for MB adsorption, aiming to relate synthesis conditions to adsorbent performance. In this way, the work contributes to sustainable utilization of waste and pollutant remediation by transforming an industrial waste into a reusable adsorbent.

# materials and methods

# Materials

Geothermal sludge was collected from an Indonesian geothermal plant. Analytical-grade HCl (37%, Sigma-Aldrich), NaOH (Sigma-Aldrich), Pluronic P123 (Sigma-Aldrich), sodium alginate, calcium nitrate, and deionized water were used without further purification.

# Synthesis of Silica from Geothermal Sludge

The sludge powder was first sieved (120 mesh) to ensure uniform particle size. Sixty grams of sieved sludge was then leached with 375 mL of 2 M HCl at 90 °C under stirring with 300 rpm for 5 hours. These conditions (acid concentration, temperature, and time) were selected based on preliminary tests and literature indicating effective impurity removal without excessive consumption of acid (3). After leaching, the mixture was cooled, filtered, and the solid residue was thoroughly washed with water until neutral pH. The purified silica was dried at 100 °C for 3 h. The resulting silica (HCl-GW) will be used for the synthesis of silica granule.

The purified silica (from leaching) was then converted into silica with soft-templating method. A solution of Pluronic P123 0.017 mol (8.22 g) was dissolved in 120 mL of 3.8 M HCl. Separately, a 4 M NaOH solution (8 g in 50 mL water) was heated to 90 °C with stirring, into which the dried silica powder was added to form sodium silicate. After 6 h reaction (90 °C, 270 rpm), the resulting Na₂SiO₃ sol was added dropwise into the P123/HCl solution under stirring (300 rpm) over 30 min.

The combined mixture was stirred for 24 h at room temperature and then **hydrothermally treated** at 100 °C for 24 h. The acidic environment (pH ~1) favors silanol formation and condensation around the P123 micelles. Finally, the solid was filtered, washed, dried (100 °C, 3 h), and calcined at 550 °C for 6 h to remove the P123 template. Variations with P123 molar amounts of 0.013 and 0.021 were also prepared to study the effect of surfactant content on pore structure because too little surfactant yields incomplete micelle formation, while excess can cause pore collapse upon calcination [4].

# Preparation of Silica Granule

Sodium alginate (1.5 g) was dissolved in 100 mL of 40 °C warm water under stirring until uniform. In parallel, 1.5 g of the calcined silica powder (from one synthesis batch) was dispersed in 10 mL water by stirring. The silica dispersion was slowly added to the alginate solution and mixed thoroughly. Separately, a crosslinking bath was prepared by dissolving calcium nitrate in 100 mL water. The alginate–silica mixture was then extruded dropwise (via a 24G syringe) into the calcium nitrate solution to form spherical beads by ionic gelation. The beads were allowed to cure in the Ca²⁺ solution for 24 h to ensure complete crosslinking and bead hardening. Finally, the beads were collected, rinsed to pH 5, and dried at 40 °C for 24 h.

The ratio of alginate to silica (1.5 g each in solution) and 24 h Ca²⁺ curing is standard for forming stable hydrogel beads. The mild drying preserves bead integrity. This immobilization approach is known to enhance mechanical strength and reusability compared to powder adsorbents [8].

# Characterization

# The silica obtained from the leaching process and the synthesized silica were characterized to evaluate their structural, functional, and morphological properties. X-ray fluorescence (XRF) was conducted to determine the elemental composition before and after the leaching process. Fourier-transform infrared spectroscopy (FTIR) was performed to identify the functional groups present in the material (12). FTIR Characterization begins with the preparation of silica samples that have been dried and ground into fine powder and then mixed with KBr with a proportion of 1-2% by weight. The homogeneous mixture is then pressed into a thin plate to form pellets. Furthermore, the sample is placed on a pellet holder for characterization. The FTIR spectrum is measured in the wavelength range of 400 to 4000 cm-1. Additionally, scanning electron microscopy (SEM) provided insight into morphology.

# Adsorption of Methylene Blue with Silica Granule

Adsorption tests were conducted using methylene blue (MB) dye in water. In a typical experiment, 0.5 g of dry silica-alginate granules was added to 50 mL of 40 mg/L MB solution and stirred (ambient conditions, 298 K) for up to 3 h. At set time intervals (every 10 min), aliquots were withdrawn and analyzed by UV-Vis spectrophotometry at 665 nm (MB λ\_max). Dye concentrations were quantified using a pre-established calibration (R²=0.9978). Removal efficiency (%) and adsorption capacity Qt (mg/g) were calculated from concentration differences. Control tests with “wet” (not fully dried) beads were also performed for comparison.

# Results and discussion

**Leaching Efficiency and Silica Recovery**

Geothermal sludge was successfully leached using 2 M hydrochloric acid, sulfuric acid, and citric acid to remove metal impurities such as Al₂O₃, CaO, Fe₂O₃, and P₂O₅. Among the three acids, HCl showed the highest leaching efficiency, with a silica recovery rate of 94.9% which is shown in **Table 1**, outperforming sulfuric acid (87.31%) and citric acid (92.9%). This clearly indicated that **HCl is more effective** in breaking down and solubilizing the matrix that traps silica, thereby freeing it for later collection. Acid leaching markedly improved the purity of the geothermal sludge. As shown in Table 2, HCl leaching raised the SiO₂ fraction from 85.0% to 93.9% (w/w), with concomitant reduction of Al₂O₃ and Fe₂O₃. The overall silica recovery (filtered yield) was 94.9% with HCl, higher than for H₂SO₄ (87.3%) or citric acid (92.9%). These results confirm that HCl is particularly effective at dissolving metal silicates and oxide impurities (2). The removal of Fe, Ca, etc. is essential, since these metal oxides can disrupt the silica framework and templating during synthesis. By contrast, minimizing residual impurities promotes consistent pore formation.

The importance of this purification is twofold: it enhances material quality and demonstrates waste valorization. The high recovery (94.9%) means most silica was conserved, and the reduced impurity levels (Al₂O₃ to 1.3%, CaO to 1.35%) mean the precursor is now comparable to commercial silica. The purified silica (termed HCl-GW) thus provided a suitable feedstock for templating.

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**Table 1**. The percentage of recovery of powder from geothermal waste leaching using acid solvents

|  |  |
| --- | --- |
| **Acid Solution Used** | **The Percentage of Recovery** |
| Hydrochloric acid (HCl) | 94,90 % |
| Sulfuric Acid (H2SO4) | 87,31 % |
| Citric Acid (C₆H₈O₇) | 92,90 % |

This purification step is essential because metal oxides such as Fe and Ca can interfere with the template formation during silica synthesis or cause structural disorder. By reducing these impurities, the leaching process enhances both the quality and structural fidelity of the final silica material. HCl leaching not only maximizes silica recovery but also plays a critical role in improving precursor purity, which is vital for the successful synthesis of silica with consistent morphology.

**Table 2**. XRF Analysis of geothermal waste before and after leaching treatment

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | **Before Leaching** | **After Leaching** |
| **No.** | **Element** | **Content (%)** | |
| 1 | SiO2 | 85 | 93,9 |
| 2 | Al2O3 | 4,6 | 1,3 |
| 3 | CaO | 3,57 | 1,35 |
| 4 | Fe2O3 | 3,39 | 1,61 |
| 5 | P2O5 | 1,3 | 0,85 |
| 6 | K2O | 0,81 | 0,37 |
| 7 | MnO | 0,613 | 0,3 |
| 8 | TiO2 | 0,26 | 0,19 |
| 9 | V2O5 | 0,02 | 0,02 |
| 10 | CuO | 0,092 | 0,078 |
| 11 | ZnO | 0,02 | 0,02 |
| 12 | As2O3 | 0,067 | 0,02 |
| 13 | Rb2O | 0,023 | 0,03 |
| 14 | SrO | 0,038 | 0,02 |
| 15 | Re2O7 | 0,06 | 93,9 |
| 16 | PbO | 0,02 | 1,3 |

**Silica from Geothermal Sludge**

The synthesis of silica was carried out using the silica purified from the leaching of geothermal sludge (referred to as HCl-GW) as the silica source. The procedure followed the hydrothermal synthesis method with Pluronic P123 as the structure-directing agent. A solution of 8.22 grams of P123 was prepared in 120 mL of 3.8 M HCl, creating an acidic micellar environment. In parallel, 8 grams of NaOH was dissolved in 50 mL of distilled water to make a 4 M solution, which was then reacted with the leached silica at 90°C for 6 hours and stirred at 270 rpm. This alkaline fusion led to the formation of sodium silicate (Na₂SiO₃), which serves as a reactive silica species in the synthesis, the reactions that occur are shown below:

(1)

The Na₂SiO₃ solution was added dropwise to the P123–HCl mixture and stirred at 300 rpm for 24 hours at room temperature to allow self-assembly of silica around P123 micelles. The acidic environment facilitated silanol protonation and condensation. The mixture then underwent hydrothermal treatment at 100°C for 24 hours to increase structural regularity. The resulting solid was filtered, washed, and dried at 100°C for 3 hours, followed by calcination at 550°C for 6 hours to remove the surfactant, which was then characterized.

A group of white objects

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**FIGURE 1**. Results of silica synthesis, a) 0.013 mol; b) 0.017 mol; and c) 0.021 mol

# Preparation of Silica Granule

Before the composite was made, the synthesis results of silica formed in the form of a white solid as shown in **Figure 1** were made by adding sodium alginate and 100 mL of deionized water. The addition of sodium alginate was used as a binder of metal ions in the material. Alginate has a main component of brown algae in the form of a polysaccharide biopolymer consisting of anionic blocks 1,4 connected alpha-L-glucuronic acid (G) and beta -D-mannuronic acid (M). The carboxyl group functions as a place to bind heavy metal ions and the ability of alginate to bind heavy metal ions has been investigated in previous studies which showed a higher affinity for metal ions (13). Silica powder was dispersed in a sodium alginate solution and dropped into calcium nitrate to form beads via ionic crosslinking. The resulting hydrogel beads were allowed to stabilize for 24 hours before drying. Granulation improved the mechanical stability and reusability of the silica material. A white silica granule composite was obtained in dry and wet conditions.

A glass plate with white substance on it

AI-generated content may be incorrect. A white round object on a white surface

AI-generated content may be incorrect.

b

a

**FIGURE 2**. Silica Granule Composite: a) dry granule; b) wet granule

The purified silica was successfully synthesize via the P123 template method. FTIR spectra of the calcined silica (Figure 3) exhibit characteristic silica network peaks: a strong asymmetric Si–O–Si stretching at ~1086 cm⁻¹ and a symmetric Si–O–Si band at ~801 cm⁻¹ (3,12). A broad –OH stretching band at ~3487 cm⁻¹ indicates surface hydroxyls (silanol groups) and adsorbed water. Importantly, no significant C–H peaks (2800–3000 cm⁻¹) were observed, confirming complete removal of the Pluronic template. These features mirror literature reports for mesoporous SBA-15 silica, confirming successful siloxane network formation. The silanol terminations (–OH) on the surface are advantageous for adsorption, providing sites for hydrogen bonding or electrostatic interaction with dye molecules.

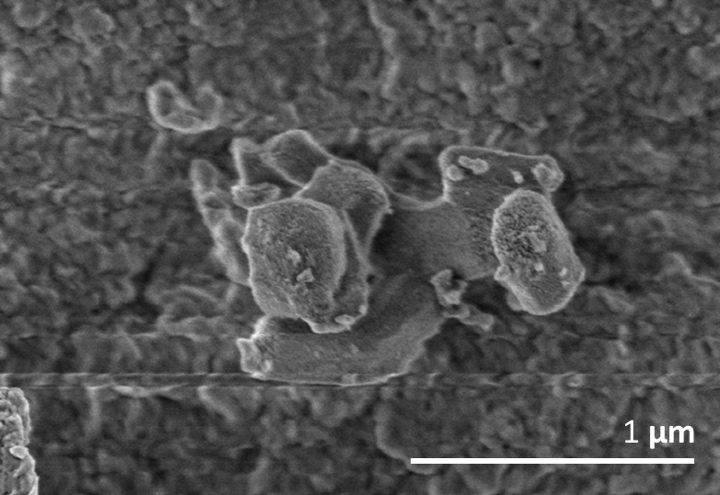
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**FIGURE 3.** FTIR Spectra of Silica Synthesis Results

**Figure 3.** shows the FTIR spectra of silica synthetic materials at variations of surfactants of 0.013 mol, 0.017 mol, and 0.021 mol. Silica material with a surfactant amount of 0.017 shows the main absorption peak located at 1086 cm⁻¹, indicating the presence of condensed siloxane bonds with asymmetric Si-O-Si (14). While the absorption peaks at around 3487 cm⁻¹, 801 cm⁻¹, 798 cm⁻¹, and 574 cm⁻¹ indicate the presence of -OH bond vibrations, Si-O stretching modes of free silanol groups Si-O-H, and lattice vibrations (15).

SEM imaging (Figure 4) revealed aggregated silica particles with rough, irregular surfaces. Such aggregation is common for calcined silica (due to high surface energy). The packing is relatively loose, with interparticle voids visible. This loose, porous morphology is beneficial for adsorption, as it increases surface area exposure and enables dye molecules to penetrate between particles. In summary, the templated synthesis produced a silica structure with high surface area and accessible silanol groups, setting the stage for effective dye adsorption.



**FIGURE 4**. SEM image of silica from geothermal sludge

**Adsorption of Organic Molecule by Silica Granule**

The adsorption performance was evaluated based on the relationship between contact time and adsorption capacity (Qt) (16). Adsorption capacity can be calculated with:

(2)

Where, Qt presents the amount adsorption capacity at time (mg/g), C0 is the initial concentration of adsorbate (mg/L), Ct is concentration of adsorbate at time (mg/L), v is volume of solution (L), and W is mass of adsorbent (g) (17). The adsorption capacity of silica–alginate composite granule was evaluated using methylene blue (MB) as the adsorbate model which shown in **Figure 5**. The study investigated the effect of contact time on the adsorption efficiency for both wet and dry composite granule, with varying concentrations of Pluronic P123 surfactant (0.013 mol, 0.017 mol, and 0.021 mol) during synthesis.

A graph of a graph

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**FIGURE 5**. Graphic of the Relationship between Contact Time and Adsorption Capacity for Dry Silica-Granule and Wet Silica-Granule

As presented in the experimental results which shown in **Table 3** and **Table 4**, the percentage of MB adsorbed increased significantly within the first 30–40 minutes of contact for wet and dry beads which showed rapid uptake: most dye adsorption occurred within the first 30–40 minutes (see Figure 5). After 60 minutes, the *dry* beads removed 64.15% of MB, whereas *wet* beads reached only 57.39%. The difference reflects the beads water content: wet beads retain internal moisture which partly blocks pores and dilutes interaction, whereas drying exposes more silica surface. In the dry beads, pores and silanol sites are more accessible and diffusion resistance is lower, so MB can more fully occupy binding sites. This behavior is consistent with known effects of moisture on adsorbent performance. Among the tested conditions, the composite granule synthesized using 0.017 mol of Pluronic P123 demonstrated the most optimal performance in methylene blue adsorption, both in terms of removal efficiency and adsorption capacity. This particular surfactant concentration resulted in a balanced structure with sufficiently ordered pores and accessible surface area, which facilitated efficient mass transfer and dye diffusion into the internal structure of the silica matrix [8,11].

In terms of adsorption capacity (Q), which reflects the amount of dye adsorbed per gram of adsorbent, the dry silica–alginate granule at 0.017 mol P123 achieved a value of 2.48 mg/g, surpassing the performance of both the lower (0.013 mol) and higher (0.021 mol) P123 concentrations. The wet granule at this concentration recorded a slightly lower capacity of 2.29 mg/g.

Among the three P123 levels, the 0.017 mol sample was optimal. It yielded the highest final removal efficiency (64.15%) and adsorption capacity (2.48 mg/g) for dry beads. The 0.013 mol sample gave lower capacity (2.19 mg/g, 57.39% removal) and the 0.021 mol sample also underperformed. We attribute this to pore structure: the 0.017 mol P123 produced a well-balanced network, as evidenced by its superior MB uptake. Lower P123 (0.013) likely formed fewer or smaller micelles, yielding less pore volume, while higher P123 (0.021) may have led to micelle overcrowding and partial collapse upon calcination. Indeed, excessive surfactant can over-template and cause pore wall thinning or collapse when burnt out. Thus, 0.017 mol struck the right balance: enough template to create interconnected pores, but not so much as to destabilize the silica walls.

**Table 3**. Effect of contact time on the percentage of adsorption of wet silica granule (surfactant = 0.013 mol, 0.017 mol and 0.021 mol), adsorbate concentration = 50 mg/L, dose of silica granule = 0.5 g/L

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Time (min) | Wet Silica-Granule | | | | | | | | |
| 0,013 | | | 0,017 | | | 0.021 | | |
| Cr remaining (mg/L) | % Ads | Q (mg/g) | Cr remaining (mg/L) | % Ads | Q (mg/g) | Cr remaining (mg/L) | % Ads | Q (mg/g) |
| 0 | 38,10 | 0 | 0 | 40 | 0 | 0 | 39,43 | 0 | 0 |
| 10 | 30,90 | 18,89 | 0,71 | 29,42 | 26,44 | 1,05 | 31,62 | 19,80 | 0,78 |
| 20 | 26,89 | 29,42 | 1,12 | 24,52 | 38,69 | 1,54 | 26,02 | 34,01 | 1,34 |
| 30 | 23,46 | 38,40 | 1,46 | 20,67 | 48,31 | 1,93 | 23,09 | 41,44 | 1,63 |
| 40 | 20,25 | 46,84 | 1,78 | 19,33 | 51,65 | 2,06 | 20,34 | 48,40 | 1,90 |
| 50 | 18,65 | 51,02 | 1,94 | 17,60 | 55,99 | 2,23 | 18,18 | 53,87 | 2,12 |
| 60 | 17,25 | 54,72 | 2,08 | 17,04 | 57,39 | 2,29 | 17,485 | 55,66 | 2,19 |

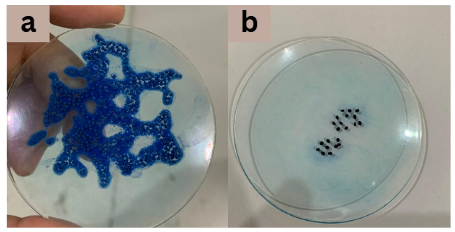
**Table 4**. Effect of contact time on the percentage of adsorption of dry silica granule (surfactant = 0.013 mol, 0.017 mol and 0.021 mol), adsorbate concentration = 50 mg/L, dose of silica granule = 0.5 g/L

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Time (min) | Dry Silica-Granule | | | | | | | | | |
| 0,013 | | | 0,017 | | | 0.021 | | | |
| Cr remaining (mg/L) | % Ads | Q (mg/g) | Cr remaining (mg/L) | % Ads | Q (mg/g) | Cr remaining (mg/L) | % Ads | Q (mg/g) |
| 0 | 38,71 | 0 | 0 | 38,71 | 0 | 0 | 40,28 | 0 | 0 |
| 10 | 26,35 | 31,92 | 1,23 | 27,07 | 30,04 | 1,16 | 34,16 | 15,19 | 0,61 |
| 20 | 25,83 | 33,26 | 1,28 | 23,27 | 39,86 | 1,54 | 30,83 | 23,46 | 0,94 |
| 30 | 23,09 | 40,34 | 1,56 | 22,90 | 40,83 | 1,58 | 25,99 | 35,45 | 1,42 |
| 40 | 19,50 | 49,61 | 1,92 | 19,03 | 50,83 | 1,96 | 23,51 | 41,62 | 1,67 |
| 50 | 18,72 | 51,61 | 1,99 | 15,09 | 61,00 | 2,36 | 20,62 | 48,78 | 1,96 |
| 60 | 15,37 | 60,28 | 2,33 | 13,87 | 64,15 | 2,48 | 19,45 | 51,70 | 2,08 |

Overall, the 0.017 mol P123 condition represents a critical balance point between pore structure, surface area, and composite stability, enabling the composite granule to function effectively in removing methylene blue from aqueous solution. This supports the importance of optimizing surfactant concentration in soft-templated silica synthesis for targeted environmental applications After 60 minutes, the adsorption process reached a plateau, indicating adsorption equilibrium had been established and most of the active sites had become saturated.

When compared to other silica-based adsorbents reported in the literature, the performance of the present silica–alginate granules are within the expected range. For instance, Boukoussa et al. [8] reported MB adsorption capacities of 2–6 mg/g for SBA-15/alginate composites, while Cheraghali et al. [18] found values around 3 mg/g for alginate–SBA-15 beads. Although the capacity in this work (2.48 mg/g) is moderate, it is significant considering the precursor is geothermal sludge rather than commercial silica. This highlights that waste-derived silica can achieve comparable performance to more conventional precursors, thereby supporting the feasibility of sustainable conversion of waste into useful adsorbents.

The capacity difference between dry (2.48 mg/g) and wet (2.29 mg/g) forms at 0.017 mol highlights again the effect of water content on site accessibility. The rapid initial adsorption (steep first 30 min in Figure 5) suggests high affinity sites; subsequent slower uptake likely corresponds to diffusion into smaller pores or less accessible sites. A detailed kinetic or isotherm analysis could further characterize this, but the equilibration begins by 60 min.



**FIGURE 6.** The results of silica granule after adsorption, a) dry silica granule, and b) wet silica granule

The underlying mechanism of MB adsorption on these silica–alginate beads is likely electrostatic and hydrogen bonding in nature. MB is a cationic dye; at neutral pH, the silica surface carries negatively-charged silanol (Si–O⁻) groups, and the alginate provides carboxylate (–COO⁻) sites [7,8]. Thus, electrostatic attraction is a primary driver for capturing MB ions. The broad FTIR OH band (3487 cm⁻¹) indicates abundant surface –OH groups on silica, which can also form hydrogen bonds with the amino groups of MB. The SEM image (Figure 4) showing a rough, high-surface-area morphology suggests that physical entrapment in pores and at particle junctions also contributes. In short, MB likely attaches to the bead via a combination of ion exchange (MB⁺ with H⁺ on Si–OH), electrostatic binding to silanol and carboxylate sites, and van der Waals interactions [14]. Similar mechanisms have been noted in other silica–alginate adsorbents for cationic dyes [8,15].

# Conclusion

This study demonstrates that geothermal sludge waste can be converted into functional silica–alginate adsorbent beads for dye removal. Key findings include efficient purification of sludge via 2 M HCl leaching (90 °C, 5 h) raising silica purity from ~85% to 93.9% and 94.9% recovery, Successful synthesis of silica by P123 templating, evidenced by FTIR siloxane bands and SEM morphology and Granule formation with alginate that imparts mechanical stability and additional adsorption sites. Adsorption performance: the optimized beads (0.017 mol P123, dry) achieved 64.15% MB removal and 2.48 mg/g capacity, with rapid kinetics (most uptake within 30–40 min).

While promising, this work has limitations. The adsorption capacity is modest compared to engineered nano-adsorbents, reflecting the compromise of granulation. The beads regeneration and long-term stability under cyclical use remain to be evaluated. The experiments were performed in idealized batch conditions, real wastewater matrices (with competing ions, variable pH) may alter performance. Future studies should evaluate reusability and performance in real wastewater to validate practical applicability. By addressing these aspects, the present approach can be further advanced toward scalable, sustainable conversion of geothermal sludge into effective water treatment materials.

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