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Fly Ash Waste for Silica Synthesis using the Caustic Method

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ABSTRACT: Fly ash is a significant industrial byproduct of coal combustion, typically accounting for 80% of total ash production, yet its global utilization remains low at approximately 20%. This waste contains high concentrations of valuable oxides, including SiO_2 (64.97%), Al_2O_3 (26.64%), and Fe_2O_3 (5.69%), making it a potent precursor for material synthesis. This study investigates the extraction and synthesis of silica from coal fly ash using the caustic leaching method with sodium hydroxide (NaOH). The process was conducted at a heating temperature of 100 °C and a stirring speed of 500 rpm. The experimental results yielded white silica powder with particle diameters ranging from 0.02 mm to 0.09 mm. These findings demonstrate that the caustic method is an effective route for recovering high-purity silica from coal fly ash, offering a sustainable solution for industrial waste management and the production of value-added eco-materials.

Keywords: Coal fly ash, silica synthesis, caustic method, waste valorization, eco-materials.

1. INTRODUCTION

Global energy consumption remains heavily dependent on coal combustion, which consequently generates massive quantities of coal fly ash (CFA) as a primary industrial byproduct [1]. In the context of coal-fired power plants, approximately 80% of the total ash produced is fly ash, yet its effective utilization in various sectors remains remarkably low, often not exceeding 20% globally [2]. The accumulation of untreated fly ash poses significant environmental risks, but it is also a rich source of inorganic oxides, primarily silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), which can be strategically recovered [3].

The chemical composition of fly ash, which typically contains over 60% silica, makes it an excellent precursor for the synthesis of silica-based materials [4]. Previous studies have explored various extraction pathways, including the use of fly ash as a partial substitution in concrete to improve compressive strength [5] or as an adsorbent for removing organic dyes from wastewater [3]. Furthermore, the recovery of silica from industrial waste aligns with the principles of green chemistry and circular economy [6].

Among the various recovery techniques, the caustic leaching method using sodium hydroxide (NaOH) has gained prominence due to its efficiency in breaking down the complex aluminosilicate glassy phase of fly ash [7], [8]. This process transforms the insoluble silica into soluble sodium silicate, which can then be precipitated into high-purity silica gel [9]. The efficiency of this extraction is highly dependent on operational parameters such as alkali concentration and heating temperature [4]. Comparative analyses with other biomass sources, such as rice husk ash, have further highlighted the unique requirements of coal fly ash for optimal recovery [10].

This study focuses on the synthesis of silica from coal fly ash using the caustic method at a controlled temperature of 100 °C and a constant stirring speed of 500 rpm. The investigation aims to provide further insights into the valorization of industrial waste into functional eco-materials [11].

2. MATERIALS AND METHODS

2.1 Materials

The primary raw material for this study was fly ash obtained from a coal-fired power plant. The chemical reagents used for the synthesis process included 3 M sodium hydroxide (NaOH) as the alkaline solvent, 2 M sulfuric acid (H_2SO_4) as the precipitating agent, and distilled water for the washing and purification process. The laboratory equipment utilized consisted of a magnetic stirrer with a heating mantle, a thermometer, an analytical balance, and standard laboratory glassware. A digital tachometer was used to monitor and maintain a constant stirring speed of 500 rpm.

2.2 Methodology

The synthesis was conducted using various masses of fly ash: 25 grams, 30 grams, and 35 grams. Each sample was mixed with 500 mL of 3 M NaOH solution in a reaction vessel. The mixture was heated on a heating mantle at a constant temperature of 100 °C and stirred at 500 rpm for 60 minutes. After the reaction, the solution was filtered to separate the sodium silicate filtrate from the unreacted solid residue. The formation of silica was initiated by adding 2M H_2SO_4 dropwise into the filtrate until a neutral pH (7–9) was achieved, resulting in the formation of a white silica gel. The gel was filtered and washed repeatedly with distilled water to remove salt impurities. Finally, the purified silica was dried in an oven at 105°C for 24 hours to produce a dry silica powder.

3. RESULTS AND DISCUSSION

The potential of coal fly ash as a viable precursor for silica synthesis is supported by its chemical composition. As presented in the initial analysis, the fly ash contains significant oxides, specifically SiO_2 (64.97%), Al_2O_3 (26.64%), and Fe_2O_3 (5.69%). The high concentration of silica in the raw material (see Table 1) facilitates the conversion into soluble silicates through the caustic leaching method [3], [4].

Table 1. Morphological Test Result Data

No.	Form	Color	Size Min (mm)	Size Max (mm)
1	Powder	White	0.25	4
2	Powder	White	0.03	1.5
3	Powder	White	0.02	1.2

The experimental results yielded a fine powder with a distinct white color, as shown in Figure 1. This visual observation confirms that the synthesis and purification process effectively removed the dark carbonaceous matter and metallic impurities originally present in the coal fly ash [12].

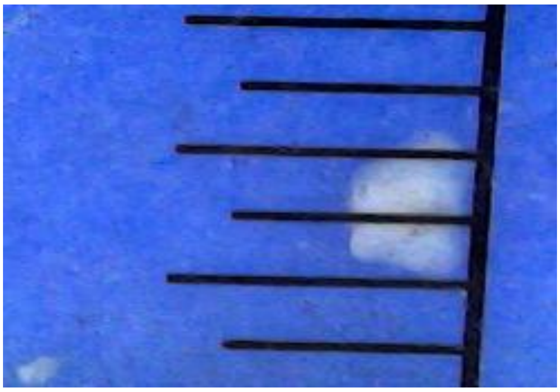

Figure 1. Results of the first experiment

Figure 2. Results of the second experiment

Figure 3. Results of the third experiment

Based on the microscopic analysis summarized in Table 1, the synthesized silica exhibits a particle diameter ranging from 0.02 mm to 4.0 mm. The visual evidence in Figure 1 shows that the particles maintain a stable morphology, which is influenced by the stirring intensity of 500 rpm during the gelation phase [13]. This stirring speed ensures a homogeneous reaction environment, preventing excessive particle agglomeration and maintaining the desired size distribution for eco-material applications [14].

The quantitative performance of the synthesis process across different fly ash masses is detailed in Table 2. The data indicates that increasing the mass of fly ash correlates with a higher product recovery. The highest yield achieved was 12% using 35 grams of fly ash, compared to 9.3% and 9.36% for lower masses (see Table 2). This trend suggests that a higher concentration of precursors in the alkaline solution promotes the formation of more sodium silicate species [7], [9].

Table 2. Experimental Result Data

No.	Mass *Fly Ash* (grams)	Yield (%)	Mass of Water Absorbed (grams)	Absorptivity (%)
1	25	7.84	0.27	54
2	30	10.83	0.29	58
3	35	12	0.36	72
Average		10.22	0.31	61.3

Furthermore, the water absorption capacity was measured to evaluate the porosity of the produced silica. As recorded in Table 2, the average adsorptivity was 61.3%, with the highest capacity of 72% observed in the 35-gram sample. These high absorption values, consistent with previous studies on biomass and industrial waste-derived silica, indicate that the material possesses a high surface area suitable for environmental applications such as moisture control or adsorbent media [5], [10].

4. CONCLUSION

This study successfully demonstrated the synthesis of silica from coal fly ash using the caustic method at 100 °C and 500 rpm. The process yielded a white silica powder with a particle diameter range of 0.02 mm to 4.0 mm (see Table 1 and Figure 1). The experimental data in Table 2 confirms that a fly ash mass of 35 grams produced the optimal results, with a maximum yield of 12% and a water absorption capacity of 72%. With an average yield of 10.22% and adsorptivity of 61.3%, this research highlights a sustainable pathway for converting industrial waste into high-value functional eco-materials.

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AUTHOR CONTRIBUTION

Conceptualization, A.L. and Z.F.; methodology, A.F.D.; software, A.L. and Z.F.; validation, A.L. and A.F.D.; formal analysis, Z.F.; investigation, A.L.; resources, A.L.; data curation, Z.F. and A.F.D.; writing—original draft preparation, A.L.; writing—review and editing, A.L. and A.F.D.; visualization, Z.F.; supervision, C.S. All authors have read and agreed to the published version of the manuscript.

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