Optimization of Potassium Silicate Fertilizer Production from Fly Ash: Effect of KOH Concentration and Extraction Time

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ABSTRACT

Fly ash, a byproduct of coal combustion in power plants, contains a high concentration of silica, making it a valuable and underutilized raw material for synthesizing potassium silicate fertilizer. Potassium silicate is known for its ability to enhance plant resistance to abiotic stresses such as drought and salinity, thereby improving overall crop health, productivity, and yield. This study aims to determine the optimal synthesis conditions of potassium silicate from fly ash by varying potassium hydroxide (KOH) concentrations and extraction times. The experimental design involves extracting silica using five different KOH concentrations (7, 9, 11, 13, and 15 N) and five time intervals (60, 90, 120, 150, and 180 minutes). Results indicate that increasing KOH concentration leads to higher silica extraction efficiency; however, it concurrently decreases potassium content in the final product. This is attributed to increased solubility and subsequent loss of potassium during extraction. Among the tested conditions, the optimum synthesis was achieved using 15 N KOH for 120 minutes, producing a potassium silicate compound with 57.5% silica and 39.4% potassium, as confirmed through compositional analysis. These findings highlight the potential of converting fly ash into a high-value agricultural input, supporting waste valorization and sustainable fertilizer development. Despite these promising results, further research is recommended to evaluate field application efficacy, environmental impact, and economic feasibility in comparison with conventional commercial fertilizers.

1. Introduction

The utilization of fly ash, a byproduct of coal combustion [1], has been increasingly explored due to its potential application in agriculture [2]. Fly ash contains silica (SiO_2), which is beneficial for plant growth [3]. Potassium silicate fertilizer, derived from fly ash, provides essential nutrients such as potassium (K) and silica (Si), enhancing soil quality and plant resilience [4]. The synthesis of potassium silicate from fly ash involves extraction and calcination processes, with potassium hydroxide (KOH) playing a crucial role in silica dissolution [5].

Extraction is a fundamental process in chemical engineering that involves separating specific components from raw materials [6]. In this study, extraction is used to dissolve silica from fly ash using KOH solutions. Extraction efficiency depends on solvent concentration, temperature, and reaction time. As an alkaline solvent, KOH enhances silica dissolution for potassium silicate synthesis [7].

Following extraction, the dissolved silica undergoes calcination, a thermal treatment process that enhances its purity and structural stability. Calcination is another critical step in the synthesis of potassium silicate. This thermal treatment involves heating the extracted material at high temperatures to remove volatile substances, enhance purity, and improve structural properties [8]. Calcination at 800°C enhances the stability of the final potassium silicate product, ensuring its effectiveness as a fertilizer [9] [10]. The controlled heating process also prevents unwanted side reactions that may reduce fertilizer quality [11].

Fly ash is produced in large quantities from coal-fired power plants, and its disposal has become a significant environmental challenge. Without proper management, fly ash can contribute to air and water pollution, posing health risks and environmental degradation [3]. The conversion of fly ash into a valuable agricultural product offers a sustainable approach to waste management, reducing landfill dependency while promoting soil enrichment [12].

Potassium silicate has been widely recognized for enhancing plant resistance to diseases and abiotic stress factors such as drought and salinity. Research has shown that silica helps strengthen plant cell walls, improving structural integrity and reducing susceptibility to pathogens [13]. Additionally, potassium is essential for photosynthesis, enzyme activation, and overall plant metabolism, making potassium silicate fertilizer a highly beneficial agricultural amendment [14] [15].

The demand for eco-friendly fertilizers has increased in recent years due to growing concerns over soil degradation caused by excessive use of chemical fertilizers. The development of potassium silicate fertilizer from fly ash aligns with sustainable agricultural practices, offering an alternative that improves soil fertility and minimizes environmental impact [16]. Furthermore, the economic feasibility of utilizing fly ash as a raw material presents an opportunity for cost-effective fertilizer production.

Previous studies have shown the benefits of potassium silicate fertilizers, but optimizing production conditions remains a challenge. Factors such as KOH concentration and extraction time significantly influence silica and potassium yield, affecting the final product's effectiveness [9]. Identifying the optimal conditions for potassium silicate synthesis is essential to maximizing its agricultural benefits.

This research aims to investigate the optimal conditions for producing potassium silicate fertilizer from fly ash by varying KOH concentrations and extraction times. The study focuses on determining the impact of these variables on silica and potassium yield, ensuring the produced fertilizer meets agricultural quality standards. The findings of this study could contribute to the broader adoption of fly ash-derived fertilizers in modern farming practices, providing a sustainable and effective solution for soil enhancement.

2. Research Methodology

2.1. Materials

The materials used in this research include fly ash sourced from PLTU Paiton, which was collected from the electrostatic precipitator system and stored in airtight containers to prevent contamination and moisture absorption. The fly ash contains silica, as shown in Table 1. Other materials include potassium hydroxide (KOH, ≥ 99% purity, analytical grade) and distilled water (deionized, conductivity < 5 μS/cm), both purchased from Bratachem, Surabaya.

Table 1. Composition of Fly Ash from PLTU Paiton

Component	Percentage (%)
SiO_2	25.4
Al_2O_3	12
CaO	27.8
Fe_2O_3	27.1
SiO_2	25.4

2.2. Procedures

Fly ash was first ground manually using a mortar and pestle to reduce particle size and ensure homogeneity. The ground fly ash was then sieved using a 100-mesh sieve, resulting in a particle size of ≤150 μm. To minimize moisture absorption, the sieved fly ash was stored in a desiccator before further processing. Meanwhile, KOH solutions of varying concentrations (7, 9, 11, 13, and 15 N) were prepared by dissolving the required mass of KOH pellets in 100 mL of distilled water under continuous stirring until fully dissolved.

The extraction process, which occurred in the extraction unit (Fig. 1), was conducted by mixing fly ash with KOH solution at a 1:5 w/v ratio (1 g fly ash per 5 mL KOH solution). The mixture was stirred at 200 rpm for different extraction times (60, 90, 120, 150, and 180 minutes) to evaluate the effects of KOH concentration and extraction time on silica dissolution efficiency. The extraction was performed at room temperature (25°C) without additional heating. After extraction, the mixture was filtered using Whatman No. 42 filter paper to separate the solid residue from the filtrate. The filtrate was then dried at 100°C for 1 hour in a laboratory oven to remove residual water and prevent premature reactions in later steps.

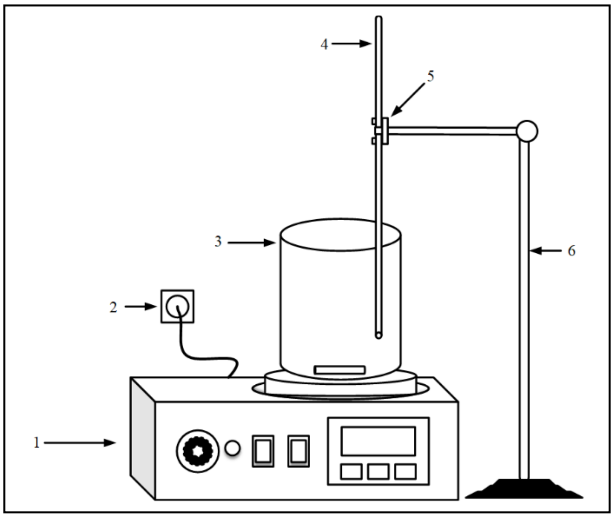

Fig. 1. Extraction equipment: 1. Hot plate magnetic stirrer, 2. Plug, 3. Beaker glass, 4. Thermometer, 5. Clamp, 6. Stand

Following drying, calcination was performed at 800°C for 1 hour using a muffle furnace with a heating rate of 10°C/min to enhance the structural properties of the final product. The sample was then allowed to cool gradually inside the furnace to prevent thermal shock. Finally, the calcined product was ground into a fine powder using a mortar and pestle to ensure uniform particle size and improve its application potential as a fertilizer.

3. Results and Discussion

The findings indicate that KOH concentration significantly influences silica and potassium extraction efficiency. Increasing KOH concentration enhances silica solubility but concurrently reduces potassium retention, likely due to ion complexation and leaching effects [17]. Additionally, longer extraction times improved silica extraction but led to potassium degradation [18]. These findings align with previous studies highlighting the trade-off between silica and potassium recovery, emphasizing the need for optimization in fertilizer production.

X-ray fluorescence (XRF) analysis of fly ash revealed a silica content of 25.4%, demonstrating its potential for fertilizer production [19]. The extraction process effectively isolates silica, enhancing its usability as a soil amendment [20]. The presence of other minerals, such as aluminum oxide and iron oxide, suggests that fly ash can also contribute additional micronutrients to soil health [21].

Fig. 2. shows a steady increase in silica concentration up to 13 N KOH, beyond which the growth slows, suggesting a saturation point. Meanwhile, Fig. 3. highlights a sharp decline in potassium retention beyond 9 N, implying that excessive alkalinity accelerates potassium leaching and decreases

its availability in the final product [9]. Therefore, identifying an optimal balance between silica and potassium retention is crucial for developing an effective fertilizer formulation.

Under highly alkaline conditions due to increased KOH concentration, silica in fly ash dissolves more readily [22]. This explains why silica recovery increases with higher KOH concentrations. However, excessive KOH also causes potassium ion leaching, preventing its incorporation into the final product [23].

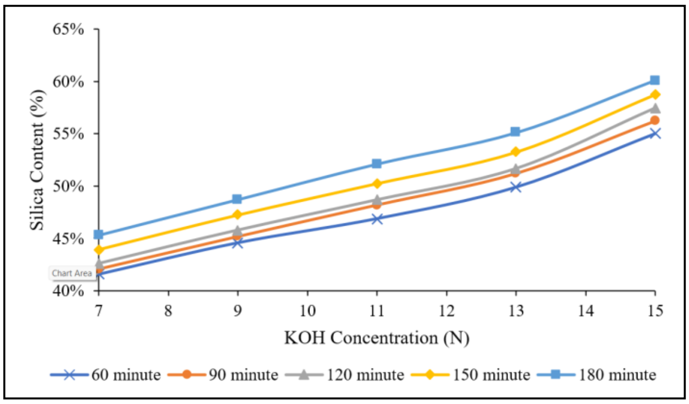

Fig. 2. Effect of KOH Concentration on Silica Concentration

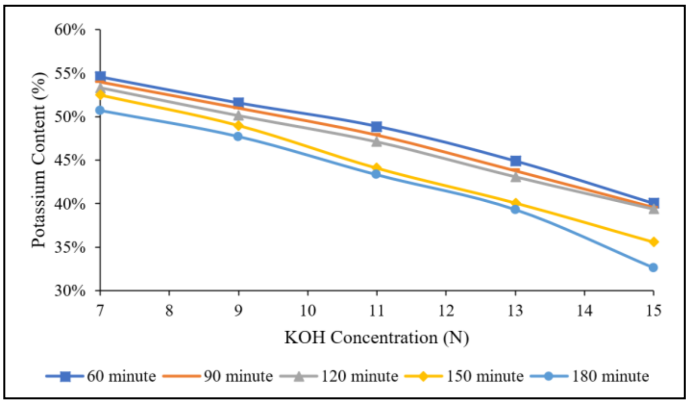

Fig. 3. Effect of KOH Concentration on Potassium Concentration

Besides KOH concentration, extraction time (as shown in Fig. 4. and Fig. 5.) is another critical factor in determining the product composition. Longer extraction times allow for more silica dissolution, increasing availability [24] [25]. However, prolonged exposure to strong alkaline conditions produces potassium precipitation as potassium hydroxide, reducing availability in the final fertilizer [14]. Experiments show silica recovery increases with KOH concentration, peaking at 13 N. Beyond this point, additional KOH does not significantly enhance silica dissolution, indicating a saturation limit. Similarly, potassium retention is maximized at 120 minutes before declining due to prolonged exposure to excess KOH.

The final composition (57.5% silica, 43.1% potassium) is comparable to commercial potassium silicate fertilizers, which typically contain 50-60% silica and 35-45% potassium. This balance supports plant nutrient uptake while maintaining soil stability. The high silica content enhances plant structural integrity, whereas potassium plays a vital role in enzymatic activation and water regulation. This supports the feasibility of fly ash-derived potassium silicate as an alternative to conventional fertilizers [26]. Additionally, calcination temperature influences the final fertilizer product's structural integrity [7]. The selection of 800°C for calcination is based on its ability to remove volatile impurities without excessive material loss efficiently. Studies indicate that temperatures below 700°C may leave residual carbonates, while temperatures above 850°C can lead to excessive sintering, reducing the bioavailability of nutrients [27].

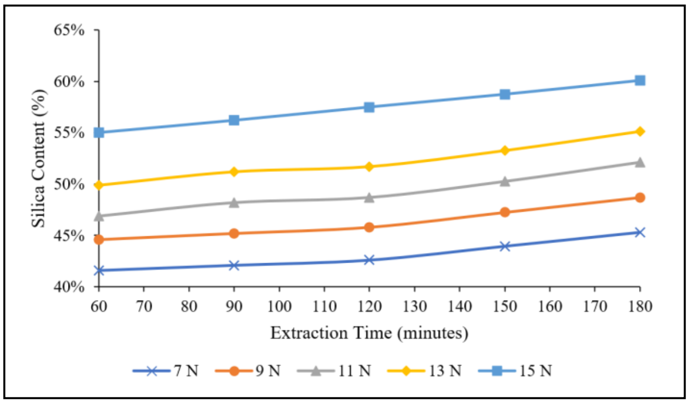

Fig. 4. Effect of Extraction Time on Silica Concentration

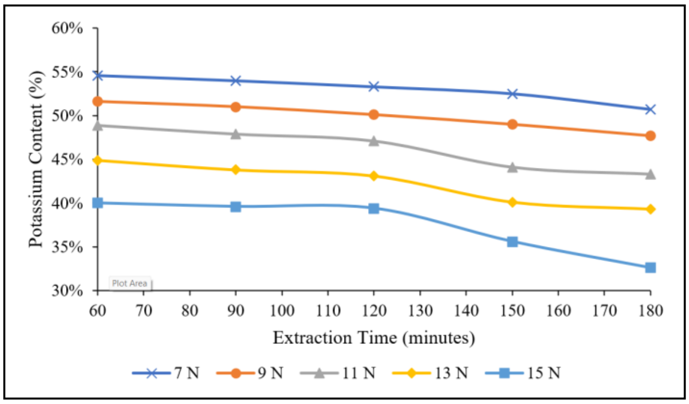

Fig. 5. Effect of Extraction Time on Potassium Concentration

Furthermore, potassium silicate fertilizer contributes to soil pH regulation [28]. Its alkaline nature improves acidic soils, making nutrients more accessible to plants. This characteristic is particularly beneficial for crops sensitive to soil acidity [29] [30]. Each year, coal-fired power plants generate millions of tons of fly ash, with only 50% being repurposed. Converting fly ash into fertilizers could reduce landfill dependency by at least 20%, decreasing heavy metal leaching into groundwater. Sustainable practices like these help address agricultural and environmental challenges [31]. A quantitative assessment of waste reduction potential and carbon footprint analysis would further strengthen the case for large-scale adoption.

While these findings confirm the feasibility of fly ash-derived potassium silicate fertilizer, further research is necessary to evaluate its large-scale production and field performance. Challenges such as production scalability, formulation stability, and economic feasibility must be addressed before commercialization. Future studies should also assess the long-term effects of this fertilizer on different soil types and crops to validate its efficacy under real agricultural conditions.

4. Conclusion

Based on the findings, the optimal conditions for potassium silicate fertilizer production were observed at a KOH concentration of 13 N and an extraction time of 120 minutes. Under these conditions, the highest silica content of 57.5% and potassium content of 43.1% were obtained. Higher KOH concentrations beyond this point led to further potassium degradation due to excessive alkalinity and hygroscopic effects, where potassium ions absorbed atmospheric moisture, reducing their stability in the final product. The resulting fertilizer, comparable to commercial products, enhances plant resilience and soil quality, particularly in acidic conditions. Utilizing fly ash for fertilizer production supports sustainable agriculture and waste management. Further research should focus on large-scale applications, nutrient stability, and long-term effects on soil health.

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