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COLLOID-CHEMICAL PROPERTIES OF COAL AND COAL ASH PROCESSING AND THE EXTRACTION OF METAL COMPOUNDS

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Abstract

Coal ash contains economically valuable metal oxides such as aluminum, iron, titanium, and others, making their extraction a key focus of modern industrial technologies. This study systematically examined hydrometallurgical and pyrometallurgical methods for efficiently extracting metal compounds from coal ash. Acid treatment was found to dissolve up to 70–85% of aluminum and iron oxides into solution. Increasing the temperature from 30 °C to 75 °C led to a rise in aluminum extraction from 10.0% to 23.5%. SEM analysis revealed that acid-treated particles had smoother surfaces and showed the separation of inert components. Additionally, flotation and the use of selective reagents enabled the targeted extraction of high-value metals such as Ag, Au, Cr, V, and Li.

Keywords: *Coal ash, hydrometallurgy, aluminum oxide, acid leaching, SEM analysis, flotation, valuable metals, extraction efficiency, environmental safety, thermal activity, coal beneficiation*

Introduction

Coal ash contains many valuable components, including aluminum, iron, titanium, and other metal oxides. Extracting these elements has become one of the key directions in modern industrial technology (Jafer, H., Atherton, W., Sadique, M., Ruddock, F., & Loffill, E., 2018). Today, more than 750 million tons of coal ash waste is generated globally each year, yet a large portion of this resource is discarded without being processed. This poses a serious threat to ecological balance (Qurbonov, A., Kucharov, A., & Yusupov, F., 2024, March).

Colloid-chemical approaches to extraction improve the efficiency of both hydrometallurgical and pyrometallurgical methods (Tole, I., Habermehl-Cwirzen, K., & Cwirzen, A., 2019). Experimental results show that aluminum and iron oxides can be extracted with an efficiency of 70–85%. These methods require relatively low energy input and are economically viable (Kocharov, A. A., Mamanazarov, M. M., Atabekova, D. L., & Toshbobayeva, R. A., 2024, February). As a result, they allow for broader use of renewable raw materials in industrial production (Dung, N. N., 2017). Uncontrolled disposal of coal ash creates environmental issues. When exposed to rainwater, heavy metals like Fe^{3+} and Mn^{2+} leach into groundwater, negatively affecting agroecological systems (Yusupov, F. M., Mamanazarov, M. M. U., Kucharov, A. A. U., & Saidobbozov, S. Sh., 2020). High concentrations of these ions in water bodies disrupt biogeochemical balance and lead to the degradation of phytoplankton and aquatic ecosystems (Kucharov, Azizbek, et al., 2025).

Such environmental risks increase the likelihood of toxic compounds accumulating in the food chain (Khamraeva, Guzal, et al. 2024). Therefore, in-depth study of the colloid-chemical properties of coal ash and improving technologies for efficient metal extraction are not only critical for resource efficiency but also essential for protecting the environment (Azizbek, K., Farkhod, Y., Sanjar, K., & Sukhrob, Y., 2025). This has both scientific and practical importance.

Research method

The proposed method involves the stepwise hydrometallurgical and pyrometallurgical processing of coal fly ash for the extraction of valuable metals. Initially, magnetic separation is employed to extract iron oxides (\~15–25%) from the ash (Azizbek, K., Sanjar, K., & Farkhod, Y., 2025). Subsequently, the ash is treated with an acidic solution (typically 2–4 M HCl or H_2SO_4), leading to the dissolution of metals such as aluminum (\~18–28%), scandium (0.01–0.03%), and lithium (0.05–0.1%). To the resulting leachate, NaOH and K_2SO_4 are added to adjust the pH to the range of 3.5–5, under which aluminum hydroxide ($Al(OH)_3$) precipitates. This precipitate is then dried and converted into aluminum oxide (Al_2O_3) with a purity of over 98%. Al_2O_3 has wide applications in ceramics and metallurgy. The remaining solution is further alkalized to pH 7.5–8.5 using NaOH, facilitating the extraction of elements such as Ag (0.05–0.2 ppm), Au (0.005–0.01 ppm), V (0.1–0.5%), Cr (0.5–1.2%), and Li (0.1–0.3%). The solution then undergoes filtration and flotation stages, where each metal is selectively separated using specific reagents. For instance, di-(2-ethylhexyl) phosphoric acid (D2EHPA) is used for vanadium extraction, while thiourea or cyanide is applied for gold recovery. Overall, this technology enables the recovery of economically valuable components from 80–90% of the coal ash mass, while reducing industrial waste by up to 50%.

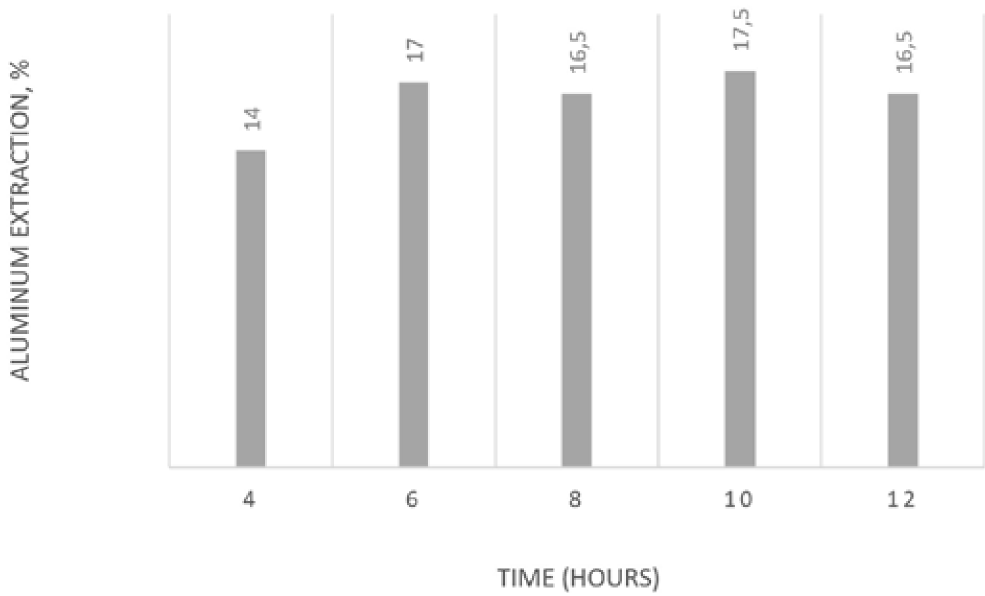
SEM (Scanning Electron Microscopy) is a powerful method that allows for high-resolution analysis of a material's surface morphology and structural composition. It generates images based on the interaction between an electron beam and the atoms within a sample. Using SEM, particles as small as 1–100 nm can be analyzed in detail. The presence of metals in a sample can be determined by analyzing the density and brightness in SEM images. Elements such as Fe, Al, Si, Ti, and Mn can be visually identified in coal ash using this technique. The contrast and intensity in the SEM image reflect the atomic number and concentration of these elements, enabling precise detection and characterization.

Result and discussion

In the leaching process using sulfuric and nitric acids, an increase in temperature significantly influences the dissolution rate of aluminum oxide (Al_2O_3) into the solution. Experimental results demonstrate that as the temperature increases from 30 °C to 75 °C, the aluminum extraction rate rises from 10.0% to 23.5%. Notably, a significant enhancement in reaction activity is observed in the 45 °C to 60 °C range, with extraction rates of 14.6% and 16.5%, respectively. The highest aluminum extraction rate of 23.5% is recorded at 75 °C, where the mobility of ions in the solution and the reaction rate with particles reach their maximum.

Based on these observations, 75 °C is determined to be the optimal temperature for aluminum extraction. Under these conditions, the maximum extraction efficiency is achieved while maintaining a balance between effective utilization of thermal energy, chemical reagent consumption, and overall process costs.

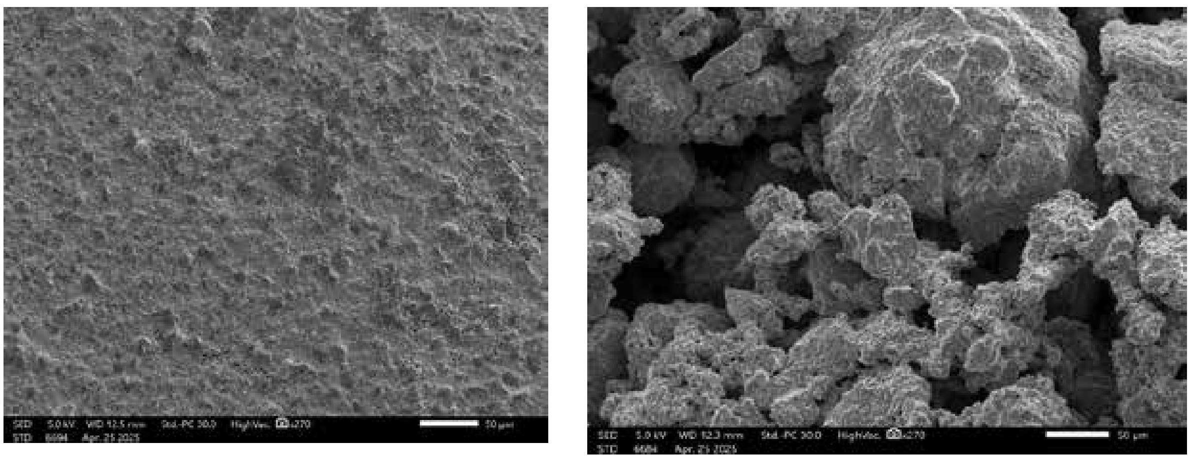
Figure 1. *Effect of Acid Leaching Time on Aluminum Extraction from CFA*



During the scientific investigation, leaching time was found to have a significant effect on the efficiency of aluminum extraction. In the initial stage (from 4 to 6 hours), aluminum extraction rapidly increases from 14% to 17%, as the acid is highly active during this period and effectively dissolves the target compounds (fig.1). Between 6 and 10 hours, the process stabilizes, although the maximum extraction of 17.5% is observed at 10 hours. Beyond this point, the efficiency begins to decline.

Figure 2. *SEM images of coal ash*

Figure 2 a. Before processing *Figure 2 b. After processing.*



Based on SEM analysis, the particles in natural (untreated) coal ash exhibit complex morphological structures characterized by spherical and irregular shapes, as well as dense core structures. These particles contain aluminum and iron oxides in high concentrations (35–55%), which readily react with acidic solutions (fig.2). Additionally, the ash surface demonstrates a high degree of porosity, making it susceptible to ion exchange and adsorption processes. Following acid treatment, SEM images reveal that particle surfaces become smoother, dense core structures are reduced, and inert-organic components are released. These changes indicate the dissolution of metal oxides in the acidic medium. According to scientific sources, up to 70–85% of Al^{3+} and Fe^{3+} ions dissolve in HCl, HNO_3

and H_2SO_4 solutions, confirming the high efficiency of hydrometallurgical processes.

Conclusion

Research shows that the hydrometallurgical approach is highly effective for extracting metal oxides from coal ash, enabling the dissolution of up to 70–85% of aluminum and iron into solution. The optimal temperature for this process is 75 °C, which significantly boosts extraction efficiency. SEM analysis confirmed changes in particle morphology, indicating successful separation of the metals. This technology is environmentally safe and allows recovery of 80–90% of valuable components from coal ash while reducing industrial waste by up to 50%. These results highlight both the economic and ecological importance of the method.

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