High-purity Alumina Production Prospect from Alternative Raw Materials

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Abstract

This study investigates a method for producing high-purity alumina (HPA) from non-conventional raw materials, namely bauxite. Various aluminosilicate raw materials, including bauxite tailings, aluminium silicate slags, nepheline-syenite, kaolin samples, and calcium aluminate slags, have been examined as alternative sources for alumina production. The leaching efficiency of these alternative raw materials using hydrochloric acid (HCl) was assessed based on aluminium recovery and the filtration properties of the residues. The precipitation of aluminium chloride hexahydrate (ACH), as a precursor for HPA, was studied in the pregnant leach solutions (PLS) generated from calcium aluminate slag leaching with HCl. During this process, HCl gas is used to precipitate ACH by the salting out phenomenon, and this step must be repeated several times to achieve the desired alumina purity. The study focuses on optimising aluminium recovery while minimising HCl gas consumption during the ACH precipitation process. After precipitation, ACH is calcined to produce HPA, with its purity verified. The results indicate that processing alternative raw materials using the described technologies can provide a sustainable and flexible approach for manufacturing HPA in an environmentally and resource-efficient manner.

Keywords: High-purity Alumina, Alternative Raw Materials, HCl Process.

1. Introduction

High-Purity Alumina (HPA) serves as an essential material in various high-tech applications, including light-emitting diodes (LEDs), lithium-ion batteries, and scratch-resistant glasses [1]. Traditionally, HPA production has primarily relied on bauxite, or bauxite derivatives, as the primary raw material [2]. However, this dependency presents several challenges:

- Resource Depletion**:** The limited availability of high-quality bauxite reserves raises concerns about long-term supply sustainability.
- Environmental Impact**:** Bauxite mining and the subsequent Bayer process significantly contribute to environmental issues, including deforestation, habitat destruction, and the generation of red mud waste.
- Geopolitical Constraints**:** The concentration of bauxite reserves in specific regions can lead to supply chain vulnerabilities and market monopolies [3].

In light of these challenges, there is an increasing interest in exploring alternative, non-bauxite raw materials for HPA production along with the utilization of Bayer by-products [4, 5]. Materials such as bauxite tailings, aluminium silicate slags, nepheline-syenite, kaolin, and calcium aluminate slags are potential options. These alternatives offer abundant and underutilised sources of aluminium and align with the principles of waste valorisation and circular economy by transforming industrial by-products into valuable resources.

The extraction of aluminium from these alternative feedstocks requires a departure from the conventional Bayer process. Given the complex mineralogy of aluminosilicate materials, an acid leaching approach, particularly using hydrochloric acid (HCl), is more effective. The acid route facilitates the dissolution of aluminium-bearing phases, enabling efficient recovery while avoiding silicon dissolution. Moreover, the subsequent precipitation of aluminium chloride hexahydrate (ACH) from the pregnant leach solution (PLS) serves as a precursor to HPA, providing a streamlined production pathway [6, 7].

This study investigates the feasibility of producing high-purity alumina (HPA) from alternative raw materials using the aluminium chloride hexahydrate (ACH) process. As a core focus, HPA production from calcium aluminate (CA) slag is experimentally demonstrated. In parallel, the potential of alternative raw materials is evaluated, with their suitability for HPA production discussed based on the findings from CA slag processing. This investigation aims to provide a sustainable and flexible pathway that reduces reliance on bauxite and addresses both environmental and geopolitical challenges.

2. Materials and Methods

This section presents materials characterisation, along with the procedures and analytical techniques used.

Elemental chemical analysis of the produced aqueous solutions was conducted using a PerkinElmer Optima 800 Optical Emission Spectrometer.

X-ray diffraction (XRD) analysis was conducted using a Miniflex 600 Rigaku diffractometer with Cu-Kα radiation (40 kV, 15 mA). Phase identification was performed with Bruker™ Diffrac EVA software, utilising the ICDD™ Diffraction databases PDF-4+ 2023 and PDF-4 Minerals 2023 [8].

Wet chemical analysis techniques were used to determine the chemical composition of the precipitates and calcined alumina samples. In more detail, calcined samples were fused with a mixture of $Li_2B_4O_7$/$LiBO_2$ and then dissolved into an HNO_3 solution. Precipitate samples, as hydrated salts were directly dissolved in H_2O. For the analysis of the liquid phases, the PerkinElmer Optima 8000 ICP-OES was used, along with a BWB XP Flame Photometer.

The calcium aluminate slag used was the product of the aluminothermic reduction of a calcium silicate slag with aluminium dross (containing 72 %wt. Al) in a graphite crucible at 1650 °C for 1h. Its chemical analysis is presented in Table 1.

Table 1. Chemical analysis of the slag used in this research work.

Al_2O_3	SiO_2	CaO	MgO	Na_2O	Fe_2O_3	Total
51.2 % ± 1.2 %	9.0 % ± 0.7 %	40.0 % ± 2.2 %	0.3 % ± 0.2 %	0.2 % ± 0.1 %	0.1 % 0.2 ± 0.01 %	101.1 % ± 1.6 %

The analysis and dissolution of calcium aluminate slag has been thoroughly investigated in prior research [9, 10], and a summary is given in Table 2. Consequently, this study focuses on the detailed analysis and discussion of the subsequent precipitation and calcination processes applied to the optimal solution derived from the leaching campaign.

the leaching of CA slag used in the experimental work detailed in section 3.1 is also shown for comparison.

CA slag (containing approximately 51 % Al_2O_3) demonstrated a high aluminium dissolution rate of 91.9 % and the highest Al concentration in the PLS at 40.7 g/L, making it a highly productive source. Among the alternatives, bauxite tailings (containing about 38.9 % Al_2O_3) and SiO_2 slag (containing about 25 % Al_2O_3) showed notable Al concentrations of 36.8 and 28.16 g/L, respectively, and higher dissolution rates than CA slags (> 92 %), indicating potential productivity. Kaolin and nepheline-syenite exhibited significantly lower Al dissolution degrees and consequently lower Al concentrations, suggesting limited output without further optimisation. Pretreatment of materials might enhance their dissolution behaviour and ultimately result in high Al-bearing PLS. Preliminary trials on the mechanical activation of kaolin showed promising results [20].

The analysis of experimental trials on CA slag has yielded significant insights into effective purification strategies that could be applicable to other alternative raw materials. In the CA slag process, high calcium concentrations (42.6 g/L) were successfully managed through controlled precipitation. This technique could similarly address the high calcium content in SiO_2 slag solutions. Moreover, silicon, present at relatively low concentrations across all materials (0.03–0.35 g/L), did not interfere with downstream processing. Iron, which appears at elevated levels in bauxite tailings (25.2 g/L) and SiO_2 slag (10.36 g/L) and therefore holds high potential to contaminate high purity alumina (HPA), was effectively removed from the HPA produced from the CA slag pregnant leach solution (PLS) using acetone washing [9] – a method that could be adapted for these materials. Additionally, the high sodium and potassium contents found in the PLS originating from kaolin and nepheline-syenite could be addressed by employing the selective precipitation stage developed for CA slag, wherein a treatment until 3 M free-HCl enabled early-stage sodium removal. These findings underpin a theoretical framework for impurity management in alternative feedstocks, demonstrating that techniques proven effective in CA slag treatment may be transferable with appropriate modifications.

4. Conclusion

This study showed that high-purity alumina (HPA) can be produced from calcium aluminate slag using a process that reduces HCl consumption while achieving 4N purity with aluminium recovery. Compared to methods with multiple HCl sparging steps, this approach provides a more sustainable and resource-efficient pathway.
Future research should aim to experimentally apply these techniques to other alternative raw materials, such as bauxite tailings, SiO_2 slag, nepheline-syenite, and kaolin. It will be crucial to adjust processes according to their specific impurity profiles and solubility behaviours. Furthermore, scaling up the proposed process and assessing its economic and environmental performance will be vital for promoting its industrial application.

5. References

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