Waste to Value – Sustainable Valorization of Bauxite Residue

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Abstract

Globally, the production of alumina generates approximately 175 million tonnes of bauxite residues (BR) per year, containing bulk metals such as aluminum (Al) and iron (Fe) as well as valuable critical metals such as Scandium (Sc), Rare-Earth Elements (REE), Titanium (Ti) and Gallium (Ga), which mainly accumulate in storage ponds. Currently, over 4 billion tonnes of BR have been accumulated worldwide. Due to limited storage space, stricter environmental regulations, and the growing demand for REEs, there is an urgent need for a sustainable approach to valorize these residues while minimizing waste volume. The industry is seeking a scalable and feasible solution to significantly reduce waste volume and extract metals for marketable off-takes. Many proposed routes have been studied, but they often lack economic viability or fail to reduce waste volume sufficiently, shifting environmental impacts to effluents or other difficult-to-manage waste.

INNORD proposes a multi-step process aimed at recovering bulk metals (Fe, Al, Na) and producing valuable metal concentrates (Sc/REE), achieving a volume reduction of over 85 %, and improving process economy by generating multiple marketable off-takes. The development objectives include a limited number of steps, extensive reagent recycling and minimizing regular effluent production. The process involves an alkalinity and DSP removal circuit, an iron conversion and recovery circuit, and a Sc/REE/TiO_2 extraction circuit.

This paper discusses the main steps of the proposed flowsheet, such as caustic recovery, DRI-grade iron production (DRI = Direct Reduced Iron), smelter grade alumina (SGA) production and critical metal concentrate generation. Additionally, experimental results from bench-scale testwork conducted on six different BR samples collected from alumina refineries worldwide are presented. The paper also reports on the main parameters influencing extraction steps and their impact on recoveries. Finally, a summary of technoeconomic assessment (TEA) and life cycle analysis (LCA) is provided for six BR feeds, discussing the impact of BR feed composition and off-take product selection on the TEA.

Keywords: Valorization, Waste volume reduction, Critical metals, DRI-grade iron, REE and Scandium.

1. Introduction

In the context of the battle against climate change, the demand for light metals such as aluminum is increasing, especially for the manufacturing of vehicles with lower fuel consumption. While this will result in decreasing greenhouse gas (GHG) emissions, aluminum production creates large amounts of waste. Aluminum smelters require pure alumina (aluminum oxide, Al_2O_3) for the Hall-Héroult process which consists of the electroreduction of the oxide to metal aluminum. Alumina is produced from bauxite ore via the Bayer process. During this process, the aluminum-containing minerals are dissolved in hot caustic soda (NaOH), and a slurry is produced that contains unreacted minerals, precipitated aluminosilicates (known as desilication products or DSP) and excess caustic soda solution. This slurry before filtration or pressing generally has a solid content of 10–30 % which generates an alkaline residue with a pH value between 10–13. This waste is known as bauxite residue (BR) or "red mud". For every tonne of alumina, between 1 and 1.5 tonnes of BR are created. The global annual production is estimated at 150 to 300 million tonnes per annum (Mtpa). Annual production of alumina in 2020 was over 133 million tonnes resulting in the generation of over 175 million tonnes of BR, (Based on the statistics published by World-aluminium, the amount of BR is estimated using an average factor of 1.3 tonnes of BR per tonne of alumina produced) [1]. Currently, more than 95 % of this production is stockpiled, leading to over 4 billion tonnes accumulated globally to date.

In general, environmental issues associated with bauxite residue storage and disposal include its high pH (10–13), the potential for alkali (Na, K) and ecotoxic (V, As) metals seepage into groundwater, instability of storage and the impact of alkaline airborne dust on plant life. In several places, failure of storage pond dams has resulted in incidents in the past (Ajka, Hungary in 2010 and Barcarena, Brazil in 2018) which had significant environmental impacts on soil and water [2]. Various solutions have been developed to mitigate these issues such as neutralization of the causticity prior to storage and improved stacking techniques [3]. However, these solutions do not sufficiently reduce the volume of waste and do not prevent long-term groundwater contamination [4].

Moreover, BR is usually rich in iron, aluminum, titanium (Ti), as well as strategic and/or critical metals such as vanadium (V), scandium (Sc) and other rare-earth elements that are left unexploited. The value loss is estimated be up to 120 to 400 USD/tonne of BR based on the oxide content of dry BR, resulting in a loss of 21–70 billion USD per year worldwide.

The valorization of BR has been researched for decades, yet there is still no large-scale process in place to extract these metals and effectively reduce waste volume. One of the main challenges is achieving a significant waste volume reduction (> 70 %) in a way that is economically feasible. One potential solution is to extract bulk metals (such as Fe and Al) simultaneously with strategic metals (like Sc/REE and Ti) to increase potential revenue. It is crucial to consider capital and operating costs, as well as total energy consumption per tonne when evaluating economic viability.

Proposed methods for recovering multiple metals are often assessed based on the market price of commercial-grade metal oxides. However, this approach may complicate the process by making it difficult to meet market specifications and increase capital risks. It is essential to also consider the environmental impacts of any alternative solution to BR stockpiling. The goal should not be to create large amounts of effluent or additional solid waste that is even more challenging to manage. Creating such waste would delay the large-scale implementation of innovative processes due to additional regulatory constraints.

2. Innord Process

INNORD has developed a unique process to reduce the volume of BR by over 85 % through the recovery of bulk metals (Fe, Al, Na) and valuable metals concentrate (Sc/REE). The major reagents used in this process are recycled to minimize effluent generation. A simplified diagram for the proposed process is illustrated in Figure 1. The process developed by Innord addresses the sustainability challenge of BR accumulation and disposal in the following ways:

a) The volume reduction exceeds 85 %, saving significant storage space and allow for soil remediation work on BR-free areas, if accumulated tailings are processed.
b) The potential residues are amorphous silica with reduced causticity and toxicity compared to untreated BR. The pH is closer to 7 and the concentration of ecotoxic metals is lower.

7. Conclusion

The proposed bauxite residue valorization process was proven to be technically feasible, economically profitable and environmentally viable for a variety of BR samples, including fresh samples and those from legacy sites. The recovery of aluminum hydroxide, NaOH (50 %), DRI-grade iron oxide, REO and TiO_2 concentrates reduced waste volume by more than 85 %, offering a solution to the accumulation of disposed BR. The high level of integration between the various process units maximized the extraction of products while reducing the need for fresh reagents. Experimental testwork on six BR samples validated the performance and versatility of the valorization process, providing data for simulation of all major process steps.

The economic assessment of the process enabled by simulation, demonstrated that the process is generally profitable on a larger scale, with poste-construction payback periods ranging from 2.8 to 5.9 years. The yield of the iron leaching reaction was shown to be one of the process parameters with the most significant impact on profitability, along with plant location and BR composition. Consequential life cycle analysis showed that BR valorization results in a net decrease in environmental impacts, despite the high utility demand of the process, leading to increased total GHG emissions. As process heat was assumed to be generated by fossil natural gas combustion, transitioning to less carbon-intensive utilities would directly reduce the environmental impacts of the plant. Further optimization of the process parameters identified in the TEA would decrease technical and economic risks, with process scale-up as the ultimate objective.

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