Recovery of Scandium and Iron from Bauxite Residue by Carbothermic Smelting, Acid Baking – Water Leaching, and Solid–Liquid Extraction

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Abstract

Bauxite residue produced during the Bayer process represents a major cost in alumina production, as the conventional disposal of this complex alkaline byproduct by landfilling is expensive, requires large amounts of land and carries environmental risks. However, this residue contains considerable amounts of iron, aluminum, and critical materials such as scandium. In this work, a closed-loop valorization process is developed to sustainably recover these valuable materials. This process employs carbothermic smelting at 1600 °C to recover 99% of the iron content from the residue as crude metallic iron for steelmaking, combined with acid baking – water leaching with sulfuric acid to efficiently extract 99% of the scandium in the resulting slag into solution. This extraction process employs thermal desulfation of the acidic leaching residue to regenerate the sulfuric acid used in the acid baking step and the calcium silicate flux used in the smelting step; thus, eliminating the production of solid waste and reducing the consumption of reagents. To purify and recover scandium in the leachate, solid–liquid extraction, employing reusable silicon micropillars impregnated with bis(2,4,4-trimethylpentyl) phosphinic acid is employed. The engineered surface efficiently extracts 93% of scandium with high selectivity (140× over aluminum) and a high enrichment ratio (443× higher scandium concentration in the final solution over the initial leachate) without the environmental risks and process complexity associated with conventional liquid–liquid extraction. This solid–liquid extraction technology enables high-efficiency scandium recovery with minimal reagent consumption, energy use, and process complexity. The overall process enables the extraction of critical materials from bauxite residue with minimal waste production and supports efforts to achieve full productive utilization of bauxite residue and to reduce the environmental footprint of alumina production.

Keywords: Bauxite Residue Valorization, Carbothermic Smelting, Acid Baking – Water Leaching, Solid–Liquid Extraction, Extractant Impregnated Surfaces

1. Introduction

Current worldwide bauxite residue stockpiles are estimated at approximately 3–4 billion tonnes, and continues to increase by 150–165 million tonnes annually, a rate which is accelerating, since the primary aluminum production is expected to further increase by up to 38% by 2040 [1–4]. The conventional landfill management of the Bayer process bauxite residue represents a major environmental, land-use, and opportunity cost, since this side product can be considered an abundant, readily-available, and low-cost resource for scandium and iron.

Bauxite residue's high iron content and scandium-enriched nature have made it the subject of several previous studies which have sought to utilize it as a resource for critical materials; [5–9] however, widespread adoption of these valorization processes has been impeded by the technical challenges associated with the alkaline and mineralogically complex characteristics of bauxite residue. Most previous studies seeking to extract the critical minor elements within bauxite residue using direct leaching usually employ hydrochloric, sulfuric, or nitric acid solutions and they typically suffer from large rate of reagent consumption, long residence time requirement, the production of large volumes of hazardous wastewater and solid residue, and the non-specific coextraction of other elements. [5,6,10,11]

Some studies have attempted to address some of these challenges by employing multistep extraction processes which combine the dry (no added water) mixing of concentrated acids with bauxite residue, heat treatment steps at various temperatures, and leaching in water at ambient conditions.12 Acid baking – water leaching in particular, was shown to enable high extraction efficiencies, while allowing for rapid extraction kinetics, reduced acid and water use, and relatively mild operating conditions [12]. However, one common remaining challenge is that these multistep processes typically do not enable the productive recovery of iron, which accounts for 24 wt% of the dry bauxite residue mass.

One solution that has been proposed to enable the productive recovery of iron from bauxite residue, while enabling the extraction of critical materials is the carbothermic smelting of bauxite residue.13 In this process, bauxite residue is reacted with a reducing agent, in this case carbon, at high temperature (1400–1600 °C) to reduce the iron(III) content, primarily as Fe2O3 and FeO(OH), into crude metallic iron(0) which is immiscible with the slag formed by the remaining non-reduced elements, and can be readily separated to be used in steelmaking.14 Multiple studies have explored the extraction of critical materials from the slag remaining after bauxite residue smelting by acid leaching; however, these processes face many of the same challenges as direct leaching, notably, the production of acidic leaching residue [13,15,16].

The proposed process aims to extract scandium from the smelting slag with high efficiency by employing acid baking – water leaching, and the elimination of acidic waste production by employing thermal desulfation to convert the residue back to a recycled flux for smelting, while regenerating acid for the acid baking step. Acid baking – water leaching + thermal desulfation offers high (99%) extraction efficiency with reduced water and acid consumption, and rapid leaching kinetics at ambient conditions, without the production of hazardous acidic waste, and allowing the recapture of any scandium that was not extracted in the single pass process.

The product of the acid baking – water leaching step of the process is an aqueous solution containing scandium, at a relatively low concentration (~ 3.0 mg/L), with comparatively higher concentrations of aluminum (~ 6000 mg/L), iron (~ 100 mg/L), titanium (~ 85 mg/L), magnesium (~ 50 mg/L), calcium (~ 600 mg/L), and silicon (~ 250 mg/L). To separate scandium from the mixture, liquid–liquid extraction (LLE), also known as solvent extraction, is the most commonly used method which separates compounds based on their different solubility in two immiscible liquids, usually water and an organic solvent. Although widely adopted, LLE comes with the following operational disadvantages: (1) the large volumes of organic solvents required can lead to environmental and safety issues; (2) the regeneration and reusability of extractant is poor due to solvent lost during phase separation procedure [17], which is less ecologically and economically efficient; (3) these processes are generally not efficient for the recovery of trace elements in highly concentrated solutions, such as those in the slag leachate; and (4) high intensity agitation of the solvent and aqueous phases is critical for high extraction efficiency, which requires high energy input for continuous and vigorous stirring [17–19].

In comparison, solid–liquid extraction (SLE) is a greener approach for extraction of elements, in part because it drastically reduces the consumption of the solvent and product of pollutants. The SLE category includes supported-liquid extraction and solid-phase extraction methods, both utilize the affinity of a flowing liquid containing the dissolved analytes with a solid, leading to the separation of the mixture into extracted and unextracted parts of the components, as the target components bind preferentially to the solid extractant [20].

baking – water leaching, which allows over 99% of the scandium in the slag to be extracted into solution at milder conditions than would be required for direct acid leaching. The acidic leaching residue can then be thermally desulfated to regenerate reagents for smelting and acid baking, recapture any scandium that was not extracted during leaching, and eliminate the production of acidic solid waste. Scandium can then be separated and purified from the aqueous solution by employing solid–liquid extraction using solvent-impregnated surfaces. The proposed solvent-impregnated micro-posts substrate design presents promising performance for selectively recovering scandium from bauxite residue slag leachate, without the typical challenges associated with liquid–liquid extraction systems. The high scandium extraction efficiency (~93%) and selectivity (140 times larger than aluminum) make this solid–liquid extraction system appealing for the recovery of dilute concentrations of scandium with the presence of more abundant competing ions. Overall, the proposed integrated bauxite residue valorization process enables the efficient extraction, separation, and recovery of iron and scandium from bauxite residue with minimal waste production and reagent consumption.

5. References

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