

## Current Prospects and Status of Research on the Recovery of Scandium from Bauxite Residue

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### Abstract

Whilst scandium resources are abundant in China, it is invariably found in nature in complex mineralogical forms, making its separation and extraction difficult and complicated. During the refining of bauxite, over 98 % of scandium is concentrated in the bauxite residue, making bauxite residue a major source of scandium. The main focus has been on developing leaching methods for bauxite residue and techniques for recovering scandium from it, in particular solvent extraction and ion exchange. This article reviews the current status of scandium recovery and aims to develop a new, simpler process for extracting scandium, providing technical support for the efficient separation of scandium in bauxite residue.

**Keywords:** Scandium, Bauxite residue, Acid leaching method, Solvent extraction method, Ion exchange method.

### 1. Introduction

Bauxite residue, frequently called red mud, is an alkaline slurry residue produced during the production process to make aluminium hydroxide which is subsequently converted to aluminium oxide [1]. Approximately 1–2.5 t of bauxite residue are produced for every tonne of alumina. In the past decade, China's alumina industry has experienced rapid development. In 2023, China produced 107 million tonnes of bauxite residue, with a comprehensive utilization of 10.5 million tonnes, a utilization rate of only 9.8 %.

During the Bayer process, the bauxite residue is typically separated from the liquor by thickeners, washers or filtration [2]. However, bauxite residue itself possesses characteristics such as a large specific surface area, ultra-fine particle size distribution, strong water absorption capacity, and long-lasting alkalinity [3]. As a result, dealing with bauxite residue is more complicated. The treatment and effective utilization of bauxite residue presents significant challenges for the alumina industry in various countries. Due to the unique physical and chemical properties of bauxite residue, there have been numerous studies on recycling and utilizing of bauxite residue as a secondary resource. This includes using it as a building material or recovering other metal elements such as iron, titanium and rare earth elements such as scandium. Simply using bauxite residue as a building material may lead to the wastage of precious metal resources. Therefore, from a perspective of sustainable resource development, recycling valuable metals from bauxite residue is a feasible and environmentally friendly approach.

Scandium is a rare metal with a wide range of applications in industries such as electronics, optics, transportation, and the production of advanced materials [4, 5]. However, due to its rare and trace distribution in natural minerals, extracting scandium directly from ores containing is difficult. As a result, scandium is primarily recovered as a by-product from tailings, waste residue, and waste liquid in the production process of metals like aluminium, titanium, nickel, tungsten, tantalum,

uranium, niobium, and rare earth [6]. Because of its huge reserves, bauxite residue can be considered as an important potential source of scandium [7].

This article reviews recent research progress on the recovery of scandium from bauxite residue both domestically and internationally. The main methods discussed include the use of acid leaching to extract scandium from bauxite residue, as well as solvent extraction and ion exchange adsorption to recover scandium from the leaching solution. The goal of this article is to identify a simple new process for scandium extraction, providing technical guidance for the efficient separation of scandium from bauxite residue.

## 2. Acid Leaching Method for Leaching Scandium from Bauxite Residue

Metallic species in bauxite residue mainly exist in the form of metal oxides, which react with acids to generate soluble metal cations and enter into solution. In order to improve the recovery rate of scandium and other rare earth metals, an acid leaching method is usually used to dissolve bauxite residue.

Diana et al. [8] extracted Sc (III) from solid bauxite residue using three acids (HCl, HNO<sub>3</sub> and H<sub>2</sub>SO<sub>4</sub>) at different concentrations (10 %, 20 %, and 30 % respectively). By changing experimental parameters such as the solid-liquid ratio, initial acid concentration, contact time, and temperature, the optimal experimental plan was designed, and the extraction kinetics of Sc (III) with acid were evaluated using first-order and second-order kinetic models, including kinetic parameters, rate constants, saturation concentration, and activation energy. In addition, the study also outlined the mass transfer mechanisms involved in the Sc (III) acid extraction process. Based on the research results, it is possible to design, optimize, and control large-scale bauxite residue recovery processes from a theoretical calculation perspective, saving experimental time and improving efficiency.

Zhou et al. [9] proposed a new method for selective leaching of scandium and iron from bauxite residue, using EDTA (ethylenediamine tetraacetic acid) as a complexing agent to redistribute the types of scandium and iron ions in the leaching process, greatly improving the selectivity of scandium over iron. The optimal process parameters are leaching agent (HCl+H<sub>2</sub>O) volume of 40 mL for 10 g of bauxite residue and 2 g of EDTA, hydrochloric acid dosage is 40 % of the theoretical (stoichiometric) value, at a temperature of 70 °C with a reaction time of 4 h. Under optimal conditions, the leaching efficiencies of scandium and iron are 79.6 % and 6.12 %, respectively, and the leaching rate ratio of Sc/Fe reaches 13.0, which is twice the leaching rate ratio of Sc/Fe without the addition of EDTA. This method not only reduces acid consumption, but also greatly improves the Sc/Fe leaching rate ratio, making subsequent separation of iron and scandium easier. In addition, this work provides another method for recovering and separating valuable metals from solid waste.

Wang et al. [10] used HCl as a leaching agent to recover scandium from bauxite residue and found that the most important factor affecting the extraction rate of scandium was the liquid solid ratio (L/S). At the same time, the concentration of HCl also has a significant impact on the extraction rate of iron. At a HCl concentration of 6 mol/L and under the conditions of an L/S ratio of 5, temperature of 60 °C, and reaction time of 1 h, the leaching efficiency of scandium can reach over 85 %. In addition, according to the experimental research, the estimated consumption of hydrochloric acid per kilogram of bauxite residue is about 21.2 mol. The experimental results described above were used to optimize the subsequent leaching work.

Borra et al. [11] conducted a series of leaching experiments on MYTILINEOS bauxite residue, studying the leaching of rare earth elements from bauxite residue by inorganic and organic acids

(such as HCl, HNO<sub>3</sub>, H<sub>2</sub>SO<sub>4</sub>, CH<sub>3</sub>COOH, CH<sub>3</sub>SO<sub>3</sub>H and citric acid). Extraction of the rare earth elements was the highest for HCl leaching compared to other acids. Under the condition of 25 °C, HCl concentration is 6 mol/L, L/S ratio is 50, leaching time is 24 h, and the extraction rates of Nd, Dy, and Y are all above 80 %. The extraction rates of La, Ce, and Sc are around 70–80 % (as shown in Figure 1)

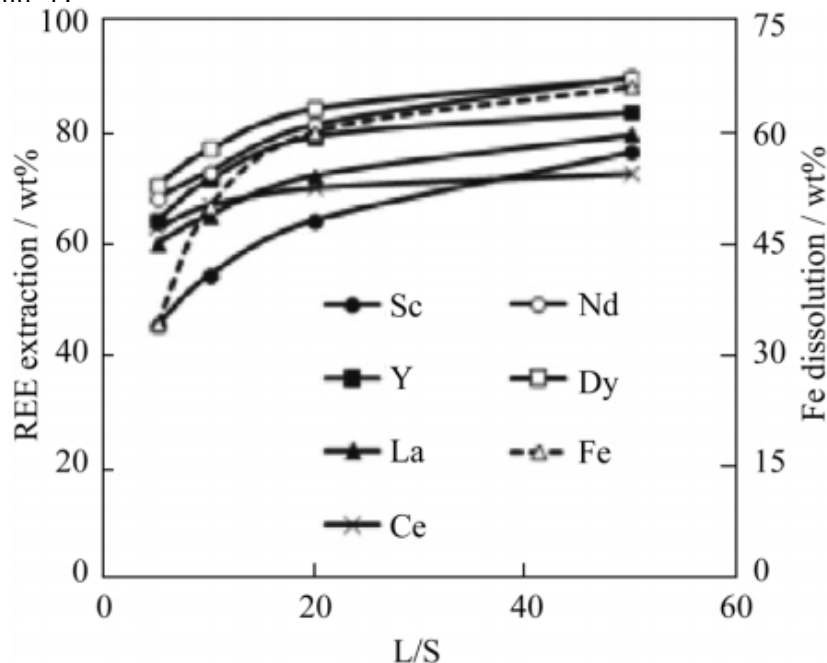


Figure 1. Extraction of rare earth elements and dissolution of iron in MYTILINEOS bauxite residue under different L/S ratios [12].

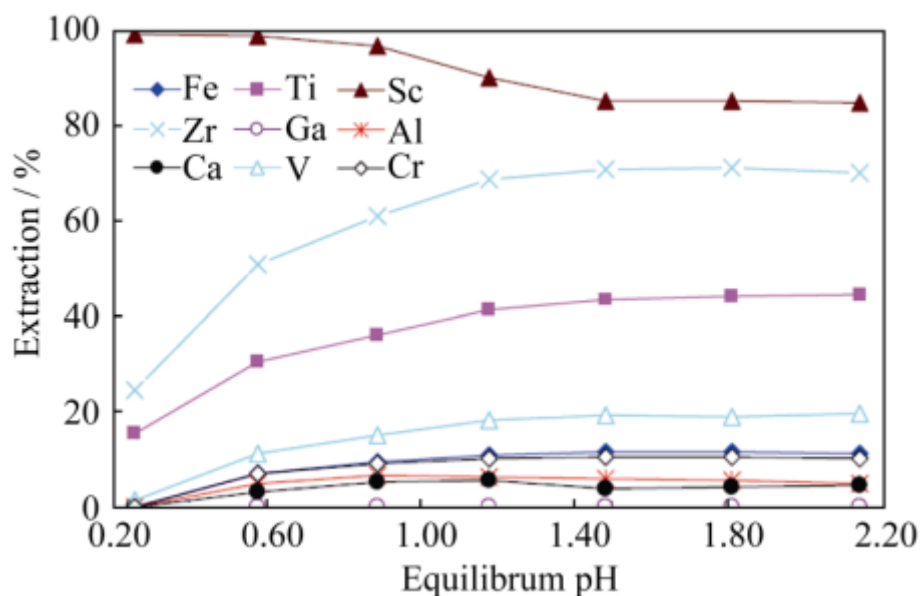
### 3. Recovery of Scandium from Leaching Solution

#### 3.1 Solvent Extraction

The solvent extraction method involves adding an extractant to organic solvents such as kerosene and solvent oil that are incompatible with water, allowing scandium ions to transfer from the aqueous phase to the organic phase. Then, strong acids or bases are used for back extraction to separate them from the organic phase and enter the aqueous phase, achieving the purpose of scandium enrichment and purification [12]. In solvent extraction, the extractant is the most crucial part. A high-performance extractant requires good separation efficiency, high extraction efficiency, strong hydrophobicity, safety, solubility, and low cost. In the process of separating and recovering Sc, it is divided into acidic phosphorus extractants, neutral phosphorus extractants, amine extractants, chelating extractants, carboxylic acid extractants, etc. according to their properties.

Wang et al. [13] conducted an experiment on the recovery of scandium from synthetic leachate using bauxite residue from an Australian alumina refinery using solvent extraction. The scandium content in the bauxite residue leaching solution used in the experiment is 5.53 mg/L. The selected extractants include three organic phosphates – D2EHPA (di-(2-ethylhexyl) phosphate), Ionquest 801, and Cyanex 272, one carboxylic acid (Versatic 10), one primary amine (Primene JMT), and two chelating extractants (LIX 984 N and LIX 54-100). According to the extraction results, more than 99 % of scandium was extracted using D2EHPA, Ionquest 801, Cyanex 272, and Primene JMT. The iron co-extraction rates of D2EHPA, Ionquest 801, and Prime JMT are over 54 %. Due to the poor phase separation efficiency of D2EHPA, Ionquest 801, and Cyanex 272, TBP (tributyl

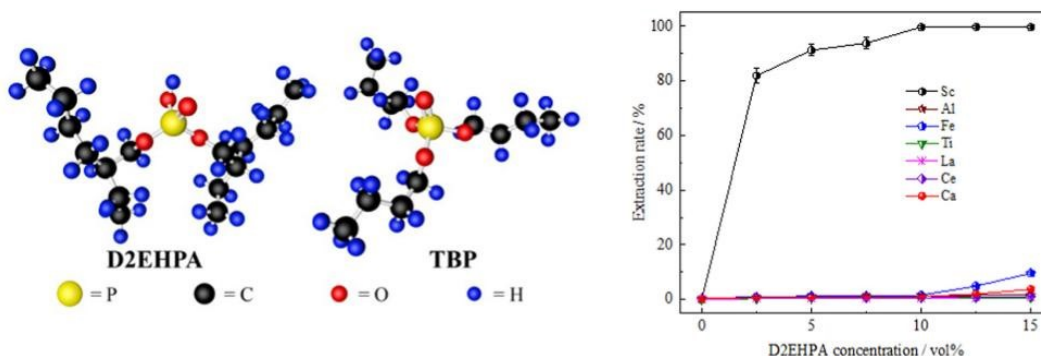
phosphate) was added as a phase modifier to improve the extraction efficiency. Further research found that under the optimal conditions, the extraction rate of scandium was higher than 99 % after adding TBP. The co-extraction of Zr was 25 %, Ti was 15 %, V was 2 %, and Fe, Cr, Ga, Ca, and Al were not extracted (as shown in Figure 2). Therefore, after adding TBP modifier, three organic phosphate extractants were selected for synergistic extraction, which can efficiently separate scandium from this Australian bauxite residue.



**Figure 2.** The metal extraction pH isotherms of 0.05 mol/L D2EHPA and 0.05 mol/L TBP in Shellsol D70 at a ratio of 5:1 volume of liquid to oil and a temperature of 40 °C [14].

Zhou et al. [14] proposed a synergistic process for the recovery of scandium, using acidic titanium dioxide waste acid (TWWA – titanium white waste acid) to leach alkaline bauxite residue and adjusting acidity with concentrated sulfuric acid. Under optimal experimental conditions, scandium was extracted from the leaching solution using 10 % di-(2-ethylhexyl) phosphate, 5 % TBP, 85 % sulfonated kerosene (volume fraction). At room temperature, scandium was continuously adsorbed for 30 minutes in a volume ratio of 10:1 of liquid to oil (A/O), resulting in the extraction of over 99 % Sc. Almost no Fe and Al were co extracted. Then, using a 3 mol/L NaOH solution as a counter extractant, Sc was enriched with a 99 % extraction efficiency. Finally, the experiment was able to produce a final Sc enriched product with a purity of 17.4 %, with a total recovery rate of 68.6 %.

The leaching solution of scandium containing bauxite residue used in the study by Fucheng Li et al. [15] was prepared by an environmentally friendly ammonium sulfate roasting and water leaching process. This study used a mixture of di-(2-ethylhexyl) phosphate (D2EHPA) and tributyl phosphate (TBP) for synergistic extraction of scandium from bauxite residue leaching solution. The effects of D2EHPA concentration, H<sub>2</sub>SO<sub>4</sub> concentration, rare earth elements, TBP dosage, A/O ratio, contact time, and other factors on scandium extraction were studied. The results showed that under optimal conditions, the extraction rate of scandium could reach over 99 % (Figure 3), while the extraction rates of Fe, Al, Ti, Ca and rare earth elements (Ce, Y, La, Nd, Er, etc.) were lower. Under the optimal stripping conditions of 5 mol/L NaOH, A/O ratio of 1, 90 °C and 30 min, the stripping efficiency of Sc reached over 92.37 %. This technology can provide an effective method for extracting scandium from bauxite residue leaching solution.



**Figure 3. The synergistic extraction of D2EHPA and TBP mixture is the recovery of scandium from bauxite residue leaching solution [15].**

### 3.2 Ion Exchange

The ion exchange method is also widely used to recover low concentrations of scandium from solutions with high recovery rates. Compared to solvent extraction, using ion exchange technology to recover low concentrations of scandium from acid leaching solutions with low impurity (iron, zirconium, titanium plasma) content has a certain cost advantage.

Zhang et al. [16] synthesized a chelating resin with titanium phosphate functional group for recovering scandium from acid leaching solution of Mytilineos bauxite residue, with a recovery rate of 91 %. Regarding the elution of ion exchange resins, studies have shown that sodium carbonate and bicarbonate have high selectivity for the elution of scandium, but ammonium fluoride and sodium fluoride are more selective than sodium carbonate and bicarbonate.

The biggest challenge in recovering scandium from bauxite residue leaching solution is the separation of scandium from other metals, especially iron, because scandium (III) and iron (III) have similar chemical properties. To address this issue, an increasing number of functionalized resin materials have been developed in recent years, such as chitosan silica hybrid materials [17] and ion imprinted polymer materials [18], to achieve high selectivity for scandium (III) to iron (III). Roosen et al. [18] studied the recovery of scandium (III) and iron (III) from Greek bauxite residue leaching solution. The team synthesized a chitosan silica hybrid material and functionalized it with chelating ligands of diethylenetriamine pentaacetic acid (DTPA) and ethylene glycol tetraacetic acid (EGTA). The chemical structure is shown in Figure 4 [18]. Research has found that EGTA chitosan silica resin has higher separation selectivity than DTPA chitosan silica resin. The results indicate that it is feasible to separate high recovery pure scandium fractions from chromatographic columns using EGTA chitosan silica resin materials.

Zhang et al. [19] developed a new method for selectively separating iron and scandium from bauxite residue acid leaching solution using D201 resin. Theoretical calculations have shown that when the chloride concentration exceeds 6.65 mol/L, trivalent iron mainly exists in the form of  $\text{FeCl}_3$  or  $\text{FeCl}_4^-$ , while scandium still exists in the form of  $\text{ScCl}_2^+$ . Therefore, iron and scandium can be selectively separated through anion resin adsorption. Batch experiments were conducted on factors that affect the adsorption of iron and scandium, such as chloride concentration, resin dosage, adsorption time, temperature, etc. The Langmuir model was successfully applied to the adsorption of iron and scandium, with maximum adsorption capacities of 147.06 and 0.95 mg/g, respectively, indicating a significant difference between iron and scandium. Raman analysis further indicates that iron is adsorbed on D201 resin in the form of  $\text{FeCl}_4^-$  anion.

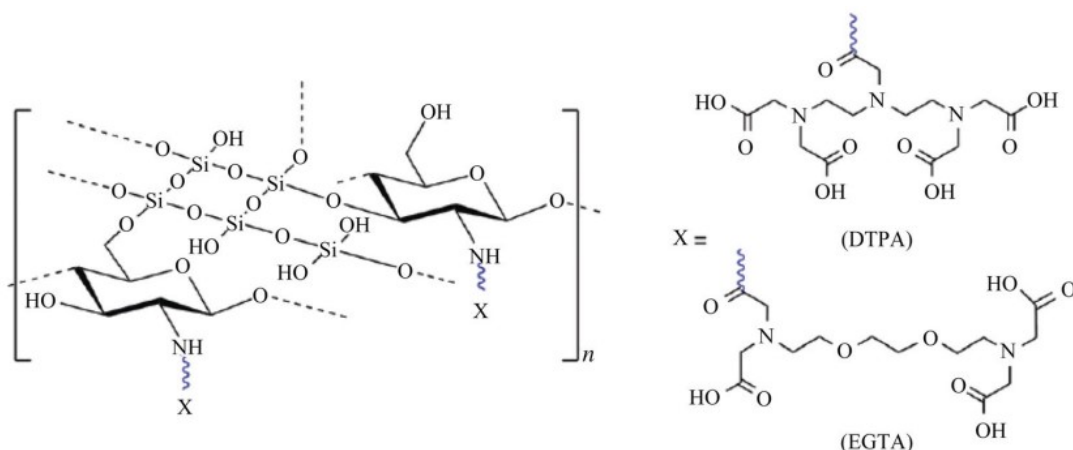


Figure 4. Chemical structure of DTPA and EGTA functionalized chitosan silica hybrid materials [18].

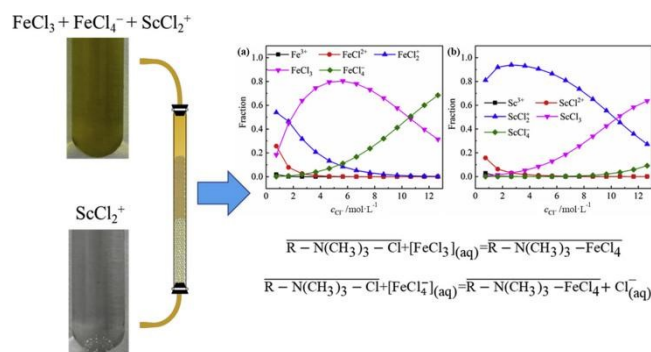


Figure 5. The forms of Fe (III) and Sc (III) in chlorine rich solutions [19].

#### 4. Conclusion

Bauxite residue can be neutralized to reduce its strong alkalinity before landfilling, thus lowering its environmental risk. However, this treatment method only meets environmental protection goals but does not achieve the aim of improved resource utilization. Due to the relatively high content and availability of scandium in bauxite residue, it can be seen as an important and promising scandium resource rather than solid waste. However, because bauxite residue also contains a large amount of iron, aluminium, and silicon, direct acid leaching treatment which have been often considered, not only consumes a significant amount of acid, but also creates complications in the extraction and separation of scandium. Additionally, the presence of impurities in the solution can result in low purity of scandium oxide in the final product. Therefore, when dealing with bauxite residue from different bauxite ores and processes, it is essential to consider the feasibility of comprehensive utilization technology by taking account raw materials, production processes, and bauxite residue components.

Due to scandium being a rare and expensive metal with a wide range of uses and increasing market demand, the recovery of scandium from bauxite residue should be considered a direct goal rather than a by-product in the development of the entire process. The extraction efficiency, comprehensive cost, and environmental benefits are key factors determining whether the scandium recovery process in bauxite residue can be industrialized.

At present, solvent extraction is still a common method to extract scandium from acid leaching solution, which has the advantages of large processing capacity and simple operation. The ion exchange method has the advantages of being a simpler process, creates low environmental pollution, and is more cost advantageous when the scandium concentration in the recovered solution is low.

In order to achieve environmentally friendly processes with a high scandium recovery rate and low cost, it is necessary to further optimize the selective leaching of scandium to reduce mineral acid consumption and pollution and to develop new solvent extraction systems and ion exchange adsorption materials with high selectivity and recognition for scandium. In addition, from the perspective of zero emissions and full utilization of bauxite residue, the slag extracted from scandium can be further used for the preparation of building materials and ceramics.

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