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Extraction of Alumina from Low-grade Jajarm's Bauxite by Lime Soda Sintering Method

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Abstract

The components of low-grade bauxite were 28.4% silica, 34.9% alumina, 16.1% iron oxide as ferric oxide and 11.26% loss on ignition. Due to the high silica content of this type of bauxite, it couldn't be processed by Bayer method. Therefore, a sintering method with limestone and sodium carbonate was used for selective extraction of alumina. Experimental design was performed by surface response method (RSM) using central composite design. Selected parameters were temperature, soaking time, mole ratio of sodium oxide to alumina, mole ratio of calcium oxide to silica. The maximum amount of extraction of alumina from low-grade Jajarm bauxite by sintering method was 74.2%, which was obtained in the optimal values of the parameters as follows: A temperature of 1157°C, a soaking time of 35 minutes, a mole ratio of alkaline oxide (K2O + Na2O) of 1.25 and a mole ratio of calcium oxide to silica of 1.99. In 31 run experiments, the mixture of materials powder was transferred to an alumina crucible and heated in a muffle furnace at temperatures and soaking times determined by the experimental design. The sintered material was pulverized. The resulting powder was leached by 150 mL of a boiling alkaline solution (20 g/L NaOH + 20g/L Na2CO3) for 30 minutes at a stirring speed of 300rpm. Extracted aluminum from the leaching stage was analyzed by atomic absorption spectrometry.

1. Introduction

The worldwide requirement for alumina, an essential precursor in the aluminum manufacturing process, has experienced a remarkable increase in recent years. As of the year 2024, the global output of aluminum has attained 67 million metric tons, with a projected annual growth rate of 3.3% [1]. This escalation in the demand for aluminum has directly impacted the necessity for augmented alumina production, given that it constitutes the principal raw material utilized in the aluminum refining process. Nonetheless, one of the most critical obstacles faced by the alumina sector is its dependence on high-grade bauxite ores, which are becoming progressively scarce in terms of both availability and quality. Low-grade bauxite, characterized by a substantial presence of impurities such as silica, iron oxides, and various other minerals, presents formidable challenges in extraction methodologies [2]. In light of these challenges, the Lime Soda Sintering Method has garnered attention as a viable alternative to conventional techniques for the extraction of alumina from low-grade bauxite ores [3].

The significance of addressing the challenge associated with low-grade bauxite extraction is paramount. As high-grade bauxite resources become increasingly depleted, a substantial proportion of the world's bauxite reserves is now categorized as low-grade [2]. This transition towards low-grade ores has engendered a heightened demand for extraction methodologies that are not only more efficient and cost-effective but also environmentally sustainable. The traditional Bayer process, which is extensively employed for the extraction of alumina from high-grade bauxite, encounters considerable limitations when applied to low-grade ores, attributable to their elevated impurity levels, diminished alumina content, and more intricate chemical compositions [5]. The challenges associated with the efficient

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processing of low-grade bauxite ores underscore the necessity for the development of alternative methodologies, which would mitigate dependence on high-grade bauxite and assist in fulfilling the escalating global demand for aluminum [4,5].

The lime soda sintering method presents a potential solution to these challenges. This method involves the use of lime and soda to sinter low-grade bauxite at high temperatures, allowing for the separation of alumina from the gangue minerals through a series of complex chemical reactions [6]. Several studies have explored the potential of this method, including investigations into the optimum temperature conditions, the types and quantities of additives, and the overall efficiency of the process [7-9].For example, research by Khodadadi et al. [10] demonstrated the feasibility of the Lime Soda Sintering Method in extracting alumina from low-grade bauxite, yielding alumina at high purity levels with relatively low energy consumption. Other studies have focused on the effects of different sintering parameters on alumina extraction efficiency, such as the influence of sintering time, temperature, and chemical additives on the recovery rates [11]. Despite these advances, challenges remain in optimizing the process for a wide range of low-grade bauxite ores, which vary significantly in mineral composition.

While research into the Lime Soda Sintering Method has provided valuable insights, there remain notable gaps in the current body of knowledge. The predominant focus of current research has been confined to particular bauxite ores, and there exists a deficiency of thorough investigations that assess the method's efficacy across a more extensive array of low-grade bauxite resources [12]. Moreover, the environmental ramifications of this methodology, especially concerning waste management and energy utilization, have not been adequately explored. There is an imperative for additional research to refine the sintering process, aimed not only at enhancing alumina extraction efficiency but also at reducing its ecological footprint. Furthermore, a substantial portion of the prevailing literature is concentrated on laboratory-scale investigations, with insufficient attention paid to industrial-scale implementations, which are essential for the successful commercialization of this approach [2].

The purpose of the current research is to investigate the feasibility of the Lime Soda Sintering Method for extracting alumina from a variety of low-grade bauxite ores, with a particular focus on improving the efficiency of the process and minimizing its environmental footprint. This study aims to optimize the sintering parameters and evaluate the economic and environmental implications of the process, contributing to the development of more sustainable extraction techniques. The primary research question guiding this study is: "How can the Lime Soda Sintering Method be optimized to improve the efficiency of alumina extraction from low-grade bauxite ores while minimizing environmental impact?"

2. Materials and Method

2.1. Materials

Bauxite and limestone were received from Iran alumina company located in North Khorasan province (Jajarm County). Table 1 shows the chemical composition of these two minerals.

Table 1. Chemical composition of minerals

	Al_2O_3%	SiO_2%	CaO%	K_2O%	Na_2O%	Fe_2O_3%	MgO%	LOI
Bauxite	34.9	28.4	1.27	0.90	0.18	16.1	0.024	11.26
Limestone	0.15	0.77	52.8	0.024	0.36	0.087	1.39	43.03

Industrial grade sodium carbonate with a purity of 99% was used in this research work.

2.2. Instruments

Atomic absorption spectrometry analysis (Varian 220 atomic absorption spectrometer, Australia) was used to determine the aluminium in the pregnant solution resulting from the leaching of sintered material.

Sintering of the dry powder mixture of materials was carried out in an electric furnace with a capacity of 60 dm^3 manufactured by Sanat Ceram Company (Iran).

Roller crusher and disc mill manufactured by Danesh Faravaran Company (Iran) were used to crush.

2.3. Experimental design

The design of experiments was carried out using the response surface methodology (RSM) and the Central Composition Design (CCD) technique using version 19 of Minitab software. Four parameters affecting the process (the number of factors, k = 4) were defined as RSM factors: sintering temperature, soaking time of the reactants at the sintering temperature, the mole ratio of alkaline oxide (K_2O + Na_2O) to alumina and the mole ratio of calcium oxide to silica. In all experiments, 5 g of bauxite were used. The yield of alumina leached was selected as the response of the model.

The evaluation of the obtained model was carried out by analysis of variance (ANOVA). The modality of the polynomial equation was assessed statistically by the determination coefficient (R^2), and its statistical importance was evaluated by F-test. Table 2 shows Actual and coded values of independent factors. Table 3 shows the design of the experiments.

2.4. Processing procedure

Bauxite powder, limestone powder and industrial sodium carbonate were mixed according to the experimental design (Table 3). 5 grams of bauxite were used in each experiment. The powder mixture of materials was transferred to ceramic crucibles (Figure 1) and the materials were sintered (Figure 2) in an electric furnace at the temperatures and times specified in the experimental design (Table 3).

Table 2. Actual and coded values of independent factors

Factor	Symbol	-α	-1	0	+1	+α
Temperature	A	1100 °C	1150 °C	1200 °C	1250 °C	1300 °C
Soaking time	B	0 min	15 min	30 min	45 min	60 min
Mole ratio of alkaline oxides to alumina	C	0.6	0.8	1	1.2	1.4
Mole ratio of calcium oxide to silica	D	1	1.5	2	2.5	3

Table 3. Design of the experiments

Run	A (T°C)	B (min)	C	D	R%
1	1150	15	0.8	1.5	26.08
2	1250	15	0.8	1.5	15.07
3	1150	45	0.8	1.5	27.64
4	1250	45	0.8	1.5	8.68
5	1150	15	1.2	1.5	55.07
6	1250	15	1.2	1.5	39.81
7	1150	45	1.2	1.5	57.38
8	1250	45	1.2	1.5	16.53
9	1150	15	0.8	2.5	42.23
10	1250	15	0.8	2.5	56.71
11	1150	45	0.8	2.5	52.76
12	1250	45	0.8	2.5	49.55
13	1150	15	1.2	2.5	54.36
14	1250	15	1.2	2.5	47.56
15	1150	45	1.2	2.5	64.12
16	1250	45	1.2	2.5	25.13
17	1100	30	1.0	2.0	52.71
18	1300	30	1.0	2.0	5.45
19	1200	0	1.0	2.0	56.05
20	1200	60	1.0	2.0	66.31
21	1200	30	0.6	2.0	28.42
22	1200	30	1.4	2.0	73.67
23	1200	30	1.0	1.0	16.23
24	1200	30	1.0	3.0	55.68
25	1200	30	1.0	2.0	64.47
26	1200	30	1.0	2.0	63.07
27	1200	30	1.0	2.0	63.26
28	1200	30	1.0	2.0	73.31
29	1200	30	1.0	2.0	69.25
30	1200	30	1.0	2.0	65.91
31	1200	30	1.0	2.0	62.88

Figure 1. Mixed materials before sintering

Figure 2. Sintered materials

After sintering, the sintered materials were powdered to dimensions below 100 µm and subsequently leached. To perform leaching, a leachant solution was first prepared by dissolving industrial sodium hydroxide (20 g/L) and industrial sodium carbonate (20 g/L). Each sintered powder sample was leached with 150 ml of the leachant solution. The alumina in the leaching solution was determined by atomic absorption spectrometry method and the alumina extraction from bauxite was calculated.

3. Results and Discussion

Response surface methods are very useful for quantifying and internalizing the relationship between parameters and response [13]. The experimental model resulting from these methods consists of second-order polynomials in the parameters. When the experimenter is relatively close to the optimum point, it is usually necessary to approximate the response with a model that has curvature. In most cases, a second-order model is obtained by the equation below, where y is the response value of the parameter x.

In the extraction of alumina from any of the alumina-bearing minerals (in this case bauxite) by sintering with limestone and sodium carbonate, the parameters affecting the process are: sintering temperature, soaking time of the reactants at the sintering temperature, the mole ratio of sodium oxide to alumina and the mole ratio of calcium oxide to silica. In the CCD (full factorial two-level design) experimental design method, the number of experiments is obtained from the equation1:

$$N = 2^{K} + 2K + C \quad (1)$$

Where are:

N – the number of experiments,

K – the number of parameters,

C - the number of central point's repetition.

3.1. Statistical analysis

The factor's levels and the experimental conditions are presented in Table 3. In column R%, the amount of alumina extracted by leaching the sintered material is entered as the response (experimental result). The effects of factors affecting response, including sintering temperature, soaking time of the reactants at the sintering temperature, the mole ratio of alkaline oxide ($K_2O + Na_2O$) to alumina and the mole ratio of calcium oxide to silica by the surface response method using the Central Composition Design. Data analysis by RSM provides the following model for the amount of alumina extracted (equation 2):

$$R\% = -6488 + 9.86\,A + 9.22\,B + 1030\,C + 55.3\,D - 0.003987\,A^2 - 0.00864\,B^2 - 111.9\,C^2 - 33.00\,D^2 - 0.00695\,A{\times}B - 0.520\,A{\times}C + 0.1289\,A{\times}D - 0.670\,B{\times}C + 0.137\,B{\times}D - 63.4\,C \times D \quad (2)$$

Where are:

A- sintering temperature (°C),

B - soaking time of the reactants at the sintering temperature (min),

C - the mole ratio of alkaline oxide (K_2O + Na_2O) to alumina,

D - the mole ratio of calcium oxide to silica.

ANOVA was used to evaluate the significance and quality of the obtained model. The p-values smaller than 0.05 at the significance level of 95% indicate the significance of the regression model. For the model of alumina extraction, the p-value was equal to 0.000, which is less than 0.05.

The residual plots (Figure 3) indicate the Gaussian distribution of the residuals and the absence of significant bias in the residuals. The maximum amount of extraction of alumina from low-grade Jajarm bauxite by sintering method was predicted to be 74.2% The model predicts that the maximum amount of alumina extraction will be happened at a temperature of 1157 °C, a soaking time of 35 minutes, a mole ratio of alkaline oxide (K_2O + Na_2O) to alumina of 1.25, and a mole ratio of calcium oxide to silica of 1.99 (Figure 4). Plotting the predicted alumina extraction versus the actual values (Figure 5) is linear (R^2 predicted = 0.938). Contour plots (Figure 6) and surface plots (Figure 7) show changes in the alumina extraction as a function of factors values.

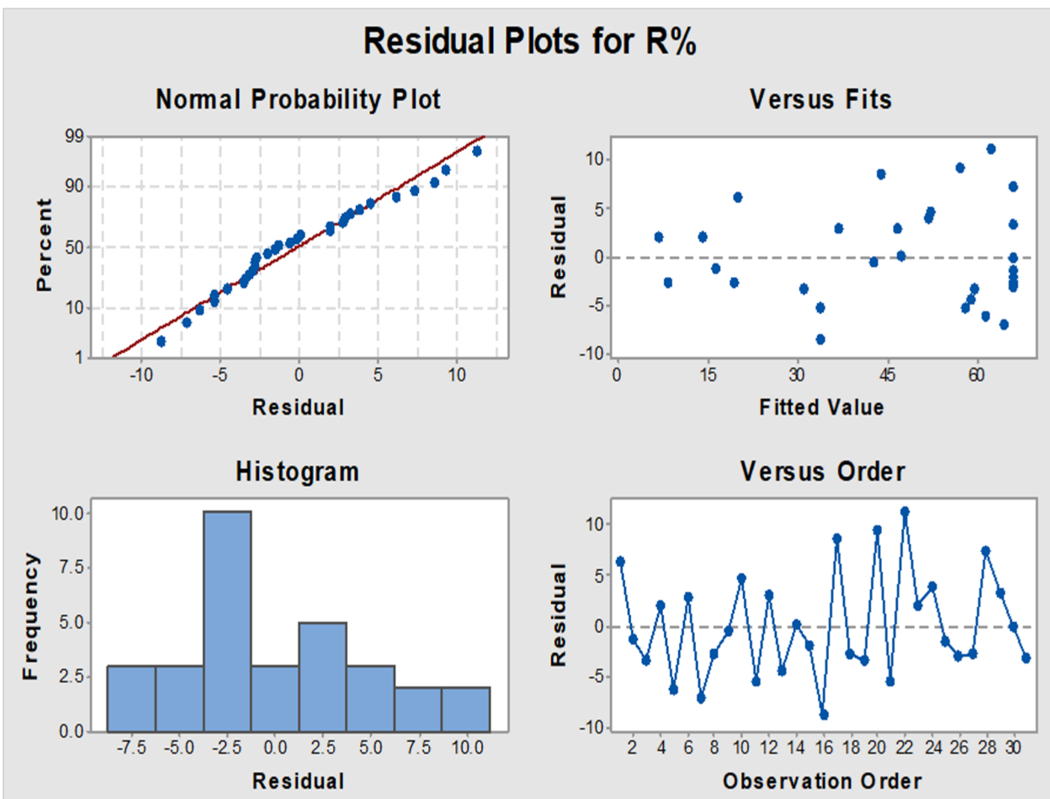

Figure 3. The residual plots

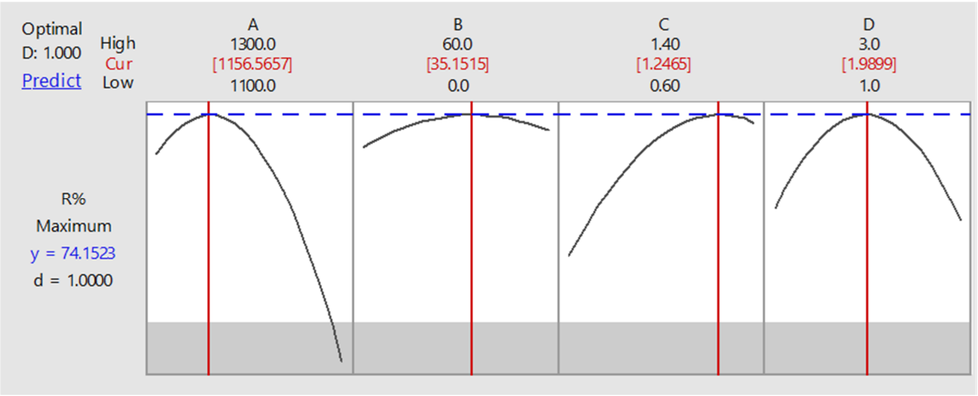

Figure 4. Factor's levels at maximum extraction of alumina

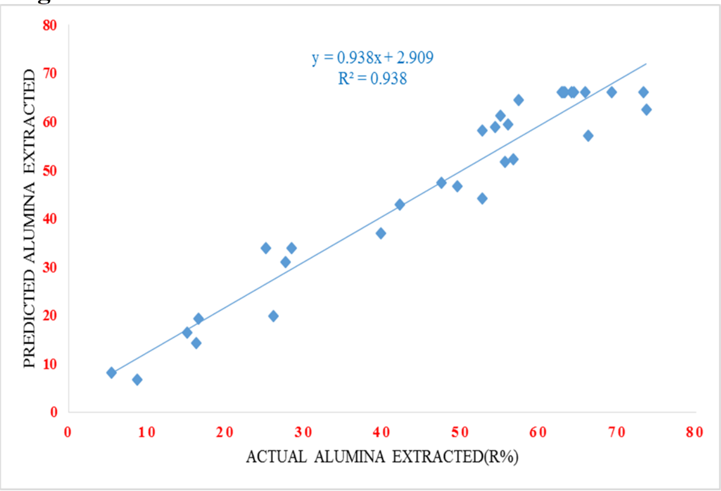

Figure 5. Predicted alumina extraction versus the actual values

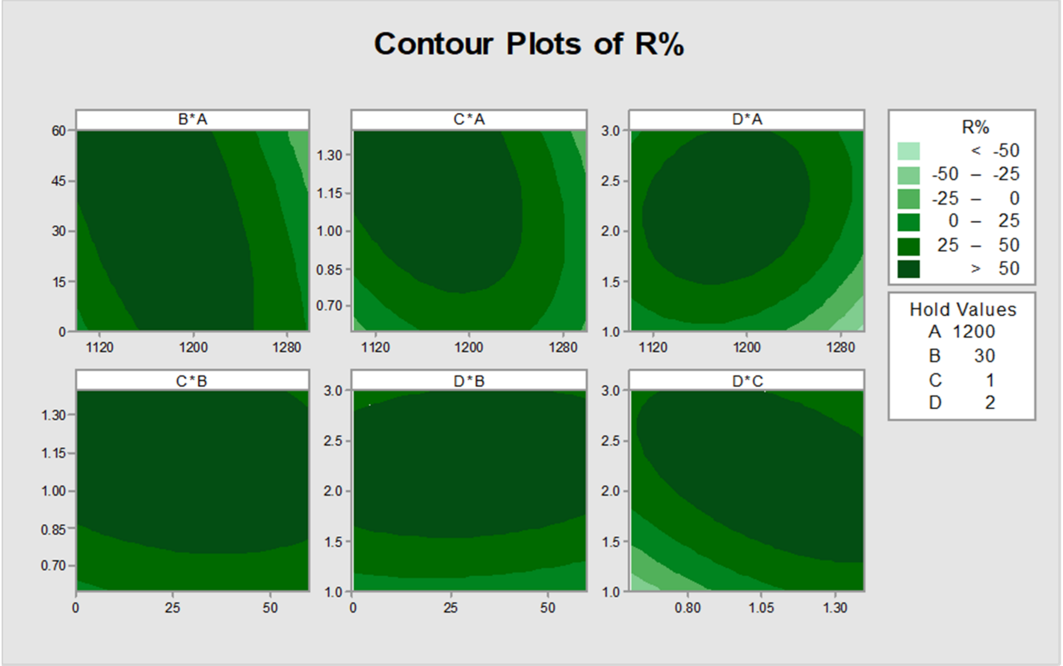

Figure 6. The contour plots

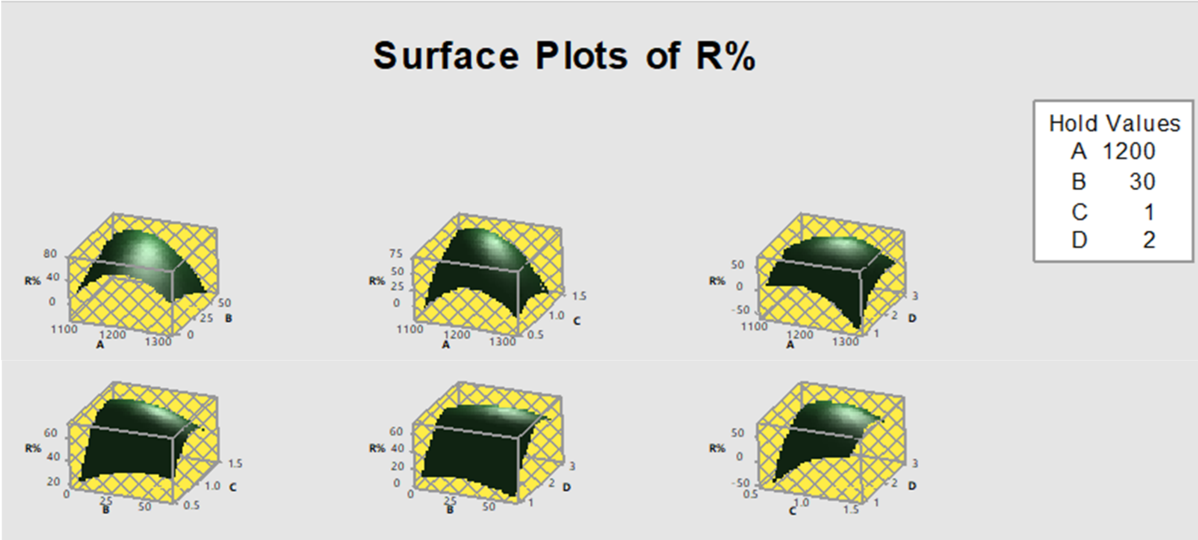

Figure 7. The surface plots

3.2. Comparison of Bayer process and lime-soda sintering for alumina extraction

The Bayer process and lime-soda sintering are two main methods for alumina extraction, each suited to different ore types.

3.2.1. Bayer process

This method uses caustic soda to digest bauxite under high pressure and temperature. It is efficient for low-silica, high-grade bauxites.

Advantages: High alumina recovery, industrially mature, lower energy requirement.

Disadvantages: Ineffective for high-silica ores due to sodalite formation, red mud generation, high-pressure equipment needed.

3.2.2. Lime-soda sintering

In this method, ore is mixed with Na_2CO_3 and $CaCO_3$ and sintered at 1100–1300 °C. Alumina forms soluble sodium aluminate, while silica is fixed as inert calcium silicates.

Advantages: Suitable for high-silica or low-grade ores, minimizes alumina loss, enables recovery of by-products.

Disadvantages: High energy consumption, more complex and costly, produces lime-rich solid waste.

Accordingly, the Bayer process is optimal for high-grade ores with low silica, while sintering is preferred for silica-rich aluminosilicates. Selection depends on ore composition and economic factors.

4. Conclusions

This work successfully demonstrated the feasibility and efficiency of the lime soda sintering method for extracting alumina from low-grade Jajarm bauxite, which contains high levels of silica (28.4%) and is not amenable to the conventional Bayer process. Through response surface methodology and central composite design, the optimal conditions for maximum alumina extraction (74.2%) were identified as a sintering temperature of 1157 °C, a soaking time of 35 minutes, a mole ratio of alkaline oxides (K_2O + Na_2O) to alumina of 1.25, and a mole ratio of calcium oxide to silica of 1.99. The strong statistical significance of the model ($p < 0.05$) and a high predicted R^2 value of 0.938 affirm the model's reliability. These findings confirm that sintering with lime and soda is a technically viable and promising alternative for alumina recovery from bauxites with high silica content.

Laboratory-scale studies on the extraction of alumina from low-grade Jajarm bauxite via the lime-soda sintering route have demonstrated promising results. To enable the transition from bench-scale experimentation to semi-industrial application, a structured scale-up strategy is essential.

The transition from laboratory to semi-industrial scale requires an integrated approach encompassing process engineering, material science, energy optimization, and environmental stewardship. The successful implementation of a pilot-scale operation will be a critical milestone toward the industrialization of alumina production from low-grade Jajarm bauxite.

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Conflict of Interest Statement

We, the undersigned corresponding author, also certify that We have no commercial associations (e.g., consultancies, stock ownership, equity interests, patent-licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article, except as disclosed on a separate attachment. All funding sources supporting the work and all institutional or corporate affiliations of ours are acknowledged in the article.

References

[1]. Liu, J. (2025). IAI: Global alumina production falls in Nov 2024 m-o-m.

[2]. Zhao, X., Liu, Y., Wang, L., Hua, Y., Cheng, T., Zhang, T., & Zhao, Q. (2024). Co-Extraction of Aluminum and Silicon and Kinetics Analysis in Carbochlorination Process of Low-Grade Bauxite. *Materials (Basel)* 17. 10.3390/ma17143613

[3]. Ghaemmaghami, E., Samadzadeh Yazdi, M. R., Darvishi, M. A., Sadati, A. A., & Najafi, A. (2022). Alumina extraction by lime-soda sinter process from low-grade bauxite soil of Semirom mine. *Journal of mining and environment 13*, 1159-1169

[4]. Bhukte, P. G., Daware, G. T., Masurkar, S. P., Chaddha, M. J., & Agnihotri, A. (2021). Beneficiation of low-grade Bauxite: A case study of Lateritic Bauxite of India. In *Innovations in Sustainable Mining: Balancing Environment, Ecology and Economy*, pp. 85-98, Springer

[5]. Landek, D., Ćurković, L., Gabelica, I., Kerolli Mustafa, M., & Žmak, I. (2021). Optimization of sintering process of alumina ceramics using response surface methodology. *Sustainability* 13, 6739

[6]. Kar, M. K., Önal, M. A. R., & Borra, C. R. (2023).Alumina recovery from bauxite residue: A concise review. *Resources, Conservation and Recycling* 198, 107158

[7]. Toama, H., Al-Ajeel, A.-W., & Jumaah, A. (2018). Studying the Efficiency of Lime-Soda Sinter Process to Extract Alumina from Colored Kaolinite Ores Using Factorial Technique of Design of Experiments. *Engineering and Technology Journal* 36 Part A, 500-508. 10.30684/etj.36.5A.4

[8]. Smith, P. (2009). The processing of high silica bauxites — Review of existing and potential processes. *Hydrometallurgy* 98, 162-176.

[9]. Jumaah, A.H. (2017). Extraction of Alumina from Colored Kaolin by Lime-Soda Sinter Process.

[10]. Khodadadi Bordboland, R., Azizi, A., & Khani, M. R. (2024). Extracting alumina from a low-grade (Shale) bauxite ore using a sintering process with lime-soda followed by alkali leaching. *Journal of Mining and Environment* 15, 1131-1148

[11]. ElDeeb, A. B., Sizyakov, V. M., Brichkin, V. N., & Kurtenkov, R. V. (2020). Effect of sintering temperature on the alumina extraction from kaolin. In *Advances in raw material industries for sustainable development goals*, pp. 136-145, CRC Press

[12]. Tian, Y., Pan, X., Yu, H., Han, Y., Tu, G., & Bi, S. (2016). An Improved Lime Sinter Process to Produce Al 2 O 3 from Low-Grade Al-Containing Resources: TMS/Light. In, pp. 1-9,

[13]. Hazrati, R., Alizadeh, E., Soltani, S., Keyhanvar, P., & Davaran, S. (2024). Development of a Composite Hydrogel Containing Statistically Optimized PDGF-Loaded Polymeric Nanospheres for Skin Regeneration: In Vitro Evaluation and Stem Cell Differentiation Studies. *ACS omega* 9, 15114-15133

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استخراج آلومینا از بوکسیت کم عیار جاجرم به روش زینترینگ آهک-سودا

راحله حضرتی بهنق[1*]، شهرام رستمی[1] و صادق مراحم[1]

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کلمات کلیدی

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چکیده

ترکیبات بوکسیت کم‌عیار شامل ٪ ۲۸/۴ سیلیکا، ٪۳۴/۹ آلومینا، ٪۱۶/۱ اکسید آهن به صورت اکسید فریک و ٪ ۱۱/۲۶ کاهش وزن هنگام احتراق است. به دلیل محتوای بالای سیلیکا در این نوع بوکسیت، نمی‌توان آن را به روش بایر فرآوری کرد. بنابراین، برای استخراج انتخابی آلومینا از روش زینترینگ با استفاده از سنگ آهک و کربنات سدیم استفاده شد. طراحی آزمایش‌ها با روش پاسخ سطحی (RSM) و با استفاده از طراحی مرکب مرکزی انجام گردید. پارامترهای انتخاب شده شامل دما، زمان خیس‌خوردگی، نسبت مولی اکسید سدیم به آلومینا و نسبت مولی اکسید کلسیم به سیلیکا بودند. حداکثر میزان استخراج آلومینا از بوکسیت کم‌عیار جاجرم به روش زینترینگ برابر با ٪۷۴.۲ بود که در مقادیر بهینه پارامترها به دست آمد: دمای ۱۱۵۷ درجه سانتی‌گراد، زمان خیس‌خوردگی ۳۵ دقیقه، نسبت مولی اکسید قلیایی ($K2O + Na_2O$) برابر با ۱/۲۵ و نسبت مولی اکسید کلسیم به سیلیکا برابر با ۱/۹۹. در ۳۱ آزمایش انجام شده، مخلوط پودر مواد به یک بوته آلومینا منتقل شده و در کوره مافل در دماها و زمان‌های خیس‌خوردگی تعیین شده توسط طراحی آزمایش حرارت داده شد. ماده زینتر شده آسیاب شد. پودر حاصل به مدت ۳۰ دقیقه در ۱۵۰ میلی‌لیتر محلول قلیایی جوشان (۲۰ گرم بر لیتر ۲۰NaOH + گرم بر لیتر Na2CO3) با سرعت هم‌زدن ۳۰۰ دور در دقیقه شسته شد. آلومینیوم استخراج شده از مرحله شستشو با استفاده از اسپکتروسکوپی جذب اتمی آنالیز گردید.

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