High-Intensity Magnetic Separation of Bauxite Residue for Iron Recovery

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Abstract

As a highly alkaline solid waste generated during bauxite refining, bauxite residue poses significant challenges to environmental protection and resource utilization due to its massive accumulation. This study systematically investigates a high-intensity magnetic separation process – referred to as "one roughing, one cleaning, and one scavenging stage" – by exploring the effects of different parameters on the recovery efficiency of magnetic minerals through experiments, optimizing the process flow, and analysing the potential value of this technology in resource recycling and environmental protection. The results show that by properly adjusting key parameters such as background magnetic field intensity and slurry concentration, the recovery rate of metallic elements in bauxite residue can exceed 50 %, providing technical support for the high-value utilization of bauxite residue.

Keywords: Bauxite residue, High-intensity magnetic separation, Metal recovery, Resource utilization

1. Introduction

1.1 Research Background and Significance

Bauxite residue, a highly alkaline solid waste generated during bauxite refining, is produced in massive quantities. As the world's leading aluminium producer, China accounts for over 50 % of both global alumina and aluminium output, generating approximately 100 million tonnes of bauxite residue annually. However, the current comprehensive utilization rate of bauxite residue in China is only 12 %, with 1 to 1.5 tonne of residue generated for every tonne of alumina produced. Such large-scale storage needs of bauxite residue not only impact future land-use but also poses severe environmental threats, as its high alkalinity allows chemical components to impact soil and groundwater.

In this context, high-intensity magnetic separation technology becomes particularly important in bauxite residue treatment. Through this method, valuable metals such as iron can be recovered from bauxite residue, enabling resource recycling, reducing dependence on primary mineral resources, and alleviating China's heavy reliance on imported bauxite and iron ore. At the same time, high-intensity magnetic separation can enhance the overall utilization rate of bauxite residue, mitigate environmental and safety risks associated with its storage, and promote the sustainable development of the aluminium industry. It plays a crucial role in advancing ecological civilization and ensuring resource security.

1.2 Research Status at Home and Abroad

Currently, technologies for treating bauxite residue mainly include storage, landfilling, utilization as a construction material, and resource recovery. Traditional storage methods pose environmental risks, while use as a construction material is limited by fluctuations in residue composition and is generally low value- added. In terms of resource recovery, techniques such as magnetic separation, flotation, and acid leaching have become research hotspots. High-intensity magnetic separation can be widely applied in iron recovery from bauxite residue due to its chemical-free process, high efficiency, and environmental benefits. However, existing high-intensity magnetic separation processes often suffer from low recovery rates and poor concentrate grade. The "one roughing, one cleaning, and one scavenging stage" separation process offers the potential to enhance metal recovery and reduce impurity content through classification and separation, but its parameter optimization and process adaptability require further research.

In the past decade, research on bauxite residue has mainly focused on improving its comprehensive utilization to address the environmental and resource waste problems caused by its large-scale accumulation. Figure 1 shows the comprehensive utilization volume and rate of bauxite residue from 2011 to 2024.

Figure 1. Comprehensive utilization volume and rate of bauxite residue, 2011–2024.

From 2011 to 2024, the comprehensive utilization volume of bauxite residue has shown an overall upward trend, increasing from 2.23 million tonnes in 2011 to 13.8 million tonnes in 2024, with accelerated growth after 2018. From 2022 to 2024, both the increase (5.8 million tonnes) and growth rate (72 %) were significant due to the higher base volume. The utilization rate fluctuated between 2011 and 2024, reaching 8.49 % in 2020, dropping sharply to 4 % in 2021, and then rising again, but staying below 10 % throughout 2023, finally reaching 12 % in 2024.

As shown in the figure, there is no simple linear relationship between utilization volume and utilization rate. From 2011 to 2017, the utilization volume remained relatively stable, with minor fluctuations in the utilization rate; from 2018 to 2020, as utilization volume increased, the utilization rate also rose rapidly; however, in 2021, the volume fell to 4.12 million tonnes, accompanied by a sharp drop in utilization rate; subsequently, from 2022 to 2024, both utilization volume and rate increased steadily, indicating that during this period, companies not only expanded the scale of bauxite residue utilization but also focused on improving efficiency.

1.3 Research Objectives and Methods

This study aims to explore optimal pathways for the "one roughing, one cleaning, and one scavenging stage" high-intensity magnetic separation process of bauxite residue, with the goal of improving the recovery efficiency and purity of metallic elements, thereby providing technical support and theoretical guidance for the resource utilization of bauxite residue.

In terms of methodology, the study first employs literature review to comprehensively summarize research findings and progress on high-intensity magnetic separation of bauxite residue both domestically and internationally, identify existing technical issues and limitations, and lay the theoretical foundation for the research. Next, experimental research is conducted using representative bauxite residue samples to perform the "one roughing, one cleaning, and one scavenging stage" high-intensity magnetic separation experiments. By varying parameters such as magnetic field strength and slurry concentration, the separation performance of metallic elements under different conditions is observed and experimental data recorded. Finally, data analysis is applied to process and interpret the experimental results, identify key factors affecting separation performance, and determine the optimal process parameter combination, providing scientific basis for the practical application of high-intensity magnetic separation in bauxite residue treatment.

2. Properties of Bauxite Residue and Principles of High-Intensity Magnetic Separation

2.1 Basic Properties of Bauxite Residue

2.1.1 Chemical Composition

The chemical composition of bauxite residue varies depending on the type of bauxite and production process. Typical components of bauxite residue include: Fe_2O_3 (10–30 %), Al_2O_3 (15–25 %), SiO_2 (10–20 %), CaO (5–15 %), TiO_2 (1–5 %), along with small amounts of alkaline substances such as Na_2O and K_2O. Its pH typically ranges from 10–12, indicating strong alkalinity.

2.1.2 Mineral Composition

The mineral composition of bauxite residue is complex, mainly consisting of hematite (α- Fe_2O_3), goethite (γ-FeOOH), gibbsite ($Al_2O_3 \cdot H_2O$), cancrinite ($Na_6Ca_2[Al_6Si_6O_{24}] \cdot 2H_2O$), and wollastonite ($CaSiO_3$), among others. Hematite and goethite are the primary magnetic minerals that can be separated through magnetic separation.

2.1.3 Physical Properties

Bauxite residue exhibits a wide particle size distribution (0.01–1 mm), high specific surface area (10–50 m^2/g), low bulk density (0.8–1.2 g/cm^3), poor flowability, and high dusting tendency. These characteristics pose challenges for equipment selection and parameter settings in magnetic separation.

2.2 Basic Principles of High-Intensity Magnetic Separation

High-intensity magnetic separation is a technique that utilizes magnetic force to separate magnetic minerals from bauxite residue. The basic principle is that magnetic minerals are attracted by the magnetic field in a high-intensity magnetic environment, while non-magnetic minerals are largely unaffected. When bauxite residue slurry passes through high-intensity magnetic separation equipment, magnetic minerals such as hematite are attracted and adsorbed onto the magnetic media of the equipment, and are carried out of the magnetic field area along with the movement of the magnetic media, thereby separating them from the non-magnetic components of the bauxite residue.

Typical high-intensity magnetic separation equipment consists of a feed system, magnetic field system, separation tank, rotating magnetic drum, and slag discharge unit. During operation, the equipment distributes bauxite residue evenly using a vibrating motor, which then transports the material into the magnetic field area via conveyor belt. The magnetic system generates a strong magnetic field, attracting magnetic minerals to the rotating magnetic drum. As the drum rotates, the magnetic minerals are collected after leaving the magnetic field, while non-magnetic minerals are discharged from the separation tank. By adjusting parameters such as magnetic field intensity, the recovery performance of magnetic minerals can be optimized to achieve efficient separation and recovery of metallic elements from bauxite residue.

2.3 Classification and Selection of High-Intensity Magnetic Separation Equipment

Common types of high-intensity magnetic separation equipment include:

(1) Wet high-intensity magnetic separators (e.g., LGS-1500 vertical ring magnetic separator): suitable for fine-grained bauxite residue, with background magnetic field intensity up to 1.5 T;

(2) Dry high-intensity magnetic separators: suitable for pre-treated dry bauxite residue, featuring low energy consumption but limited separation precision;

(3) High-gradient magnetic separators (LGS): use magnetic media to create high-gradient magnetic fields, suitable for recovering ultra-fine magnetic minerals.

3. High-Intensity Magnetic Separation Process Flow

3.1 Process Design

The “one roughing, one cleaning, and one scavenging stage” high-intensity magnetic separation process achieves the objectives of roughing enrichment, cleaning upgrading, and scavenging recovery through classification and separation. The specific flow is as follows:

Raw bauxite residue → crushing and screening → slurry preparation → one roughing magnetic separation stage (recovering coarse magnetic minerals) → one cleaning magnetic separation stage (improving magnetic mineral grade) → one scavenging magnetic separation stage (recovering ultra-fine magnetic minerals) → concentrate product + tailings.

3.2 Process Characteristics and Parameter Control at Each Stage

3.2.1 Roughing Magnetic Separation

In the "one roughing, one cleaning, and one scavenging stage" high-intensity magnetic separation process for bauxite residue, rough magnetic separation is the foundational and critical step. Wet high-intensity magnetic separators are commonly used at this stage, as they are suitable for handling the high-moisture content of bauxite residue and can effectively separate magnetic minerals.

During rough magnetic separation, the bauxite residue slurry is first fed evenly into the separation tank of the magnetic separator. By adjusting parameters such as magnetic field strength, the equipment allows magnetic minerals to be adsorbed onto the magnetic medium under the action of the magnetic field. The magnetic field strength should be determined based on factors such as the content and particle size of magnetic minerals in the bauxite residue; if this content is too low, the magnetic minerals won't be fully recovered; too high, and some non-magnetic minerals may be mistakenly attracted. Generally, the magnetic field strength is set in the range of 0.8–1.2 T. Slurry concentration also affects separation efficiency: too high, and magnetic minerals interfere with each other, reducing recovery; too low, and processing volume increases, lowering efficiency; the optimal range is typically 30–40 %. During operation, slurry flow rate and magnetic medium adsorption must be continuously monitored, with timely parameter adjustments to ensure maximum magnetic mineral recovery and favourable conditions for subsequent cleaning.

3.2.2 Cleaning Magnetic Separation

The purpose of cleaning magnetic separation is to further improve the grade of magnetic minerals and reduce impurity content. This operation is more complex and requires precise control.

After roughing magnetic separation, the recovered magnetic minerals serve as the feed for the cleaning magnetic separation stage. First, the feed is re-slurried and adjusted to an appropriate concentration and pH level. Then, the slurry is fed into specialized equipment such as fine magnetic separators. These devices typically feature specially designed magnetic systems, such as a wrap angle of 200–280°, multi-pole configurations, and selection zones located above the slurry surface to enable more precise magnetic mineral adsorption. During operation, strict control of slurry flow rate and magnetic field strength is essential, allowing magnetic minerals to be fully adsorbed while effectively separating impurity minerals. After cleaning magnetic separation, a high-grade magnetic mineral product is obtained, with significantly increased iron and other metal content, laying a solid foundation for subsequent resource utilization.

3.2.3 Scavenging Magnetic Separation

Scavenging magnetic separation plays a finishing role in the "one roughing, one cleaning, and one scavenging stage" process, aiming to recover magnetic minerals that were not fully recovered during the roughing stage, thus improving resource recovery.

Key operational points include: first, selecting suitable high-intensity magnetic equipment such as high-gradient magnetic separators, which offer stronger magnetic force and higher field gradients to effectively capture fine-grained magnetic minerals. Second, magnetic field strength should be appropriately set – generally higher than in one roughing and cleaning stages – typically in the range of 1.2–1.6 T, to enhance magnetic mineral adsorption. Third, slurry concentration and flow rate must be carefully controlled; concentration may be reduced to 20–30 %, and flow rate slowed to ensure sufficient retention time in the magnetic field for adsorption. Following these key practices, sweep magnetic separation can effectively recover residual magnetic minerals in bauxite residue, reduce resource waste, and improve the economic and resource efficiency of the entire process.

4. Experimental Study

4.1 Experimental Materials and Equipment

4.1.1 Experimental Raw Materials

The bauxite residue sample used in this experiment was sourced from a large domestic alumina producer. According to chemical multi-element analysis, the composition of the tested bauxite residue is shown in Table 1. As seen, the primary recoverable component is iron, with a mass fraction of 42.18 %, along with certain impurities such as SiO_2, TiO_2, Al_2O_3, CaO, and Na_2O, which are typical of bauxite residue.

Table 1. Chemical composition of bauxite residue sample (mass fraction, %).

Component	TFe	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O
Content	42.18	16.13	3.73	59.51	4.90	0.041	1.29
Component	CaO	MgO	Hematite	Illite	Quartz	Boehmite	Gibbsite
Content	1.62	0.052	29.50	2.00	1.80	5.00	7.00
Component	Goethite	Diaspore		Anatase	Rutile	Sodium Alumino Silicate	LOI
Content	38.80	1.00		1.60	3.30	5.80	10.89

The bauxite residue sample appears as reddish-brown powder to the naked eye. Through optical identification, X-ray diffraction, scanning electron microscopy, and MLA (Mineral Liberation Analyzer) testing, it was determined that hematite is the primary iron mineral, followed by limonite. Titanium minerals are mainly perovskite, followed by anatase and ilmenite; aluminium minerals include diaspore and gibbsite. The major gangue minerals by mass are calcium silicoaluminate hydrate, sodalite, natisite, and calcite. Other trace minerals include quartz, feldspar, sericite, kaolinite, hydrogrossular, zircon, monazite, xenotime, bastnaesite, apatite, pyrite, and barite, among which calcium silicoaluminate hydrate, sodalite, natisite, and calcite are newly formed during the alumina extraction process.

4.1.2 Experimental Equipment

One roughing high-intensity magnetic separation: LGS-1500 vertical ring high-intensity magnetic separator;
One cleaning high-intensity magnetic separation: LGS-1500 vertical ring high-intensity magnetic separator;
One scavenging high-intensity magnetic separation: LGS-1500 vertical ring high-intensity magnetic separator;
Analytical instruments: X-ray diffractometer (XRD), scanning electron microscope (SEM), energy dispersive spectrometer (EDS).

4.1.3 Experimental Design

An orthogonal experimental design was adopted to investigate the effects of magnetic field intensity (A), slurry concentration (B), and pulsation frequency (C) on the roughing high-intensity magnetic separation; for the cleaning high-intensity magnetic separation, the effects of magnetic field gradient (A'), slurry flow rate (B'), and magnetic medium aperture (C') were studied; for the scavenging high-intensity magnetic separation, the effects of magnetic field intensity (A"), slurry concentration (B"), and arrangement of magnetic medium (C") were analyzed. Each group of experiments was repeated three times, and the average values were taken.

4.2 Experimental Plan and Procedure

4.2.1 Experimental Methods

Based on the results of process mineralogical research, the beneficiation test plan for bauxite residue in this study adopts a wet magnetic separation process using high-intensity magnetic separators in a "one roughing, one cleaning, and one scavenging stage" sequence. Vertical ring magnetic separators were used for both roughing and cleaning separation stages. For the scavenging stage, either vertical or flat ring separators could be considered. This study temporarily selects the vertical ring type for scavenging, mainly due to the fact that after roughing and cleaning separation, the remaining iron minerals in bauxite residue are mainly in fine particle sizes. The scavenging stage is intended to capture these remaining fine-grained iron minerals. The advantage of the flat ring magnetic separator lies in its strong magnetic field, which suits fine-grained iron minerals; however, its low processing capacity and high cost are major drawbacks. Its current application includes the scavenging process at the iron recovery workshop of Chalco Guangxi Branch. The sample preparation process for bauxite residue is shown in Figure 2.

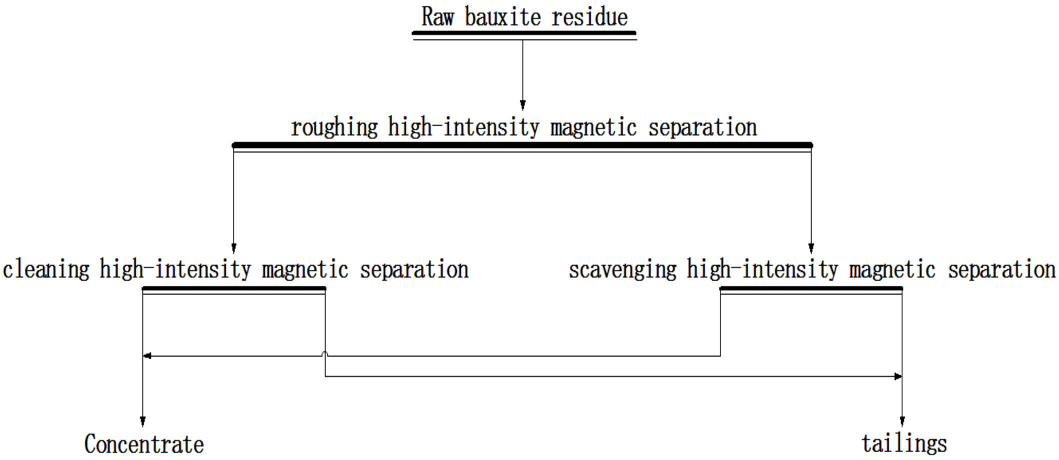

Figure 2. Bauxite residue sample preparation process.

4.2.2 Experimental Procedure

The experiment aimed to investigate the effects of different parameters such as magnetic field intensity and slurry concentration on the separation efficiency of metal elements in bauxite residue, following the principle of single-variable control.

First, the bauxite residue samples were crushed and screened to ensure uniform particle size. Then, roughing high-intensity magnetic separation tests were conducted with magnetic field intensities set at 0.8 T, 1.0 T, and 1.2 T, and slurry concentrations at 30 %, 35 %, and 40 %. Cross-combination experiments were performed, and the recovery rate and grade of magnetic minerals under different conditions were recorded as shown in Tables 2–3.

Table 2. Roughing high-intensity magnetic separation results of bauxite residue (background magnetic field intensity).

Test Conditions	Product Name	Yield %	TFe% Grade %	TFe Recovery %
0.8 T 30 % Concentration	Concentrate	63.46	47.65	71.37
	Tailings	36.54	33.20	28.63
	Feed	100.00	42.37	100.00

1.0 T 30 % Concentration	Concentrate	67.86	47.51	75.39
	Tailings	32.14	32.76	24.61
	Feed	100.00	42.77	100.00
1.2 T 30 % Concentration	Concentrate	68.03	47.55	75.91
	Tailings	31.97	32.10	24.09
	Feed	100.00	42.61	100.00

Table 3. Roughing high-intensity magnetic separation results of bauxite residue (slurry concentration).

Test Conditions	Product Name	Yield %	TFe% Grade %	TFe Recovery %
1.0 T 30% Concentration	Concentrate	67.86	47.51	75.39
	Tailings	32.14	32.76	24.61
	Feed	100	42.77	100
1.0 T 35 % Concentration	Concentrate	68.84	47.63	76.52
	Tailings	31.16	32.29	23.48
	Feed	100.00	42.85	100.00
1.0 T 40 % Concentration	Concentrate	58.17	48.08	66.45
	Tailings	41.83	33.76	33.55
	Feed	100.00	42.09	100.00

Next, the magnetic minerals obtained from the roughing high-intensity magnetic separation were subjected to cleaning high-intensity magnetic separation, with variations in magnetic field intensity and slurry concentration parameters, to observe the changes in the grade of magnetic minerals, as shown in Table 4.

Table 4. Cleaning high-intensity magnetic separation results of bauxite residue.

Test Conditions	Product Name	Yield %	TFe% Grade %	TFe Recovery %
0.8 T	Concentrate	53.57	51.45	57.42
	Tailings	46.43	44.02	42.58
	Feed	100.00	48.00	100.00
0.9 T	Concentrate	62.66	51.06	66.54
	Tailings	37.34	43.08	33.46
	Feed	100.00	48.08	100.00

1.0 T	Concentrate	63.50	51.05	67.35
	Tailings	36.50	43.05	32.65
	Feed	100.00	48.13	100.00

High-intensity magnetic separation tests with “one roughing, one cleaning” configuration were carried out on bauxite residue, with results shown in Table 5 and the process flow illustrated in Figure 3.

Table 5. “One roughing, one cleaning” high-intensity magnetic separation results of bauxite residue.

Product Name	Yield %	TFe Grade %	TFe Recovery %
Concentrate	39.25	51.06	46.77
Middlings	29.59	43.08	29.75
Tailings	31.16	32.29	23.48
Raw bauxite residue	100.00	42.85	100.00

Finally, scavenging high-intensity magnetic separation was conducted, with the magnetic field intensity increased to 1.2–1.6 T and slurry concentration reduced to 20–30 %, to recover magnetic minerals not fully recovered during one roughing stage. The change in magnetic mineral grade under different parameters is shown in Table 6.

Table 6. Scavenging high-intensity magnetic separation results of bauxite residue.

Test Conditions	Product Name	Yield %	TFe% Grade %	TFe Recovery %
1.2T	Concentrate	13.87	44.56	18.86
	Tailings	86.13	30.86	81.14
	Feed	100.00	32.76	100.00
1.4T	Concentrate	14.57	44.54	19.85
	Tailings	85.43	30.68	80.15
	Feed	100.00	32.70	100.00
1.6T	Concentrate	16.24	44.39	21.92
	Tailings	83.76	30.66	78.08
	Feed	100.00	32.89	100.00

High-intensity magnetic separation tests with “one roughing, one scavenging” configuration were also performed on bauxite residue. The test results are shown in Table 7, and the process flow is illustrated in Figure 4.

Table 7. “One roughing, one scavenging” high-intensity magnetic separation results of bauxite residue.

Product Name	Yield %	TFe Grade %	TFe Recovery %
Concentrate	72.46	47.48	80.28
Tailings	27.54	30.68	19.72
Raw bauxite residue	100.00	42.85	100.00

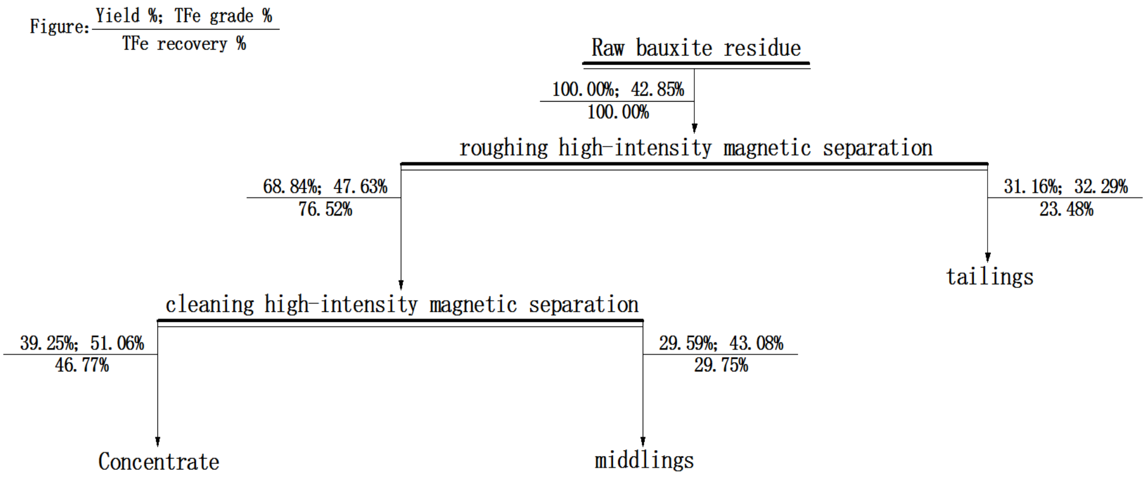

Figure 3. Mass and grade flow diagram of "one roughing, one cleaning, and one scavenging stage" magnetic separation of bauxite residue.

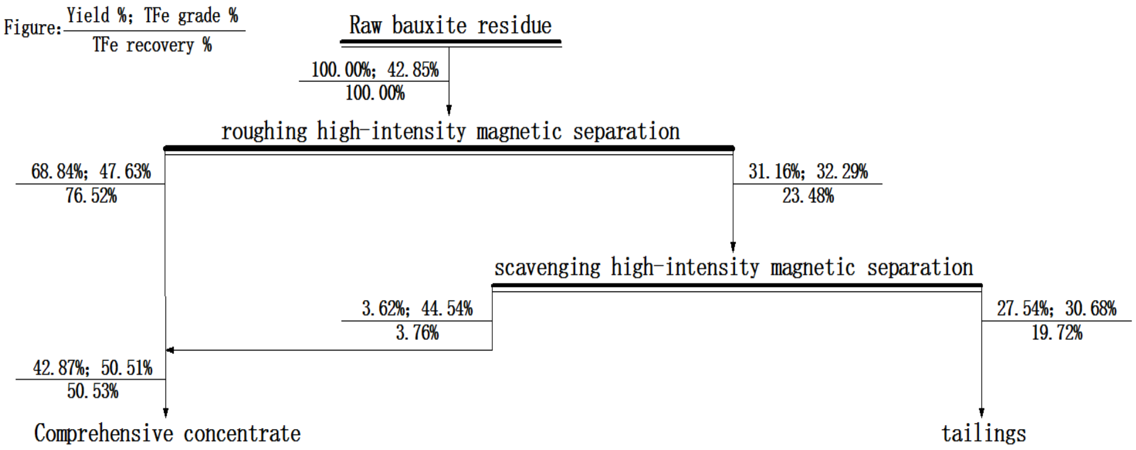

Figure 4. Mass and grade flow diagram of "one roughing, one scavenging" magnetic separation of bauxite residue.

Throughout the experimental process, other variables such as slurry flow rate and equipment operating status were strictly controlled to ensure the accuracy and comparability of the experimental data. Through systematic experimental procedures, experimental data on the high-intensity magnetic separation of bauxite residue under various parameter conditions were obtained, laying the foundation for subsequent result analysis.

4.2.3 Experimental Results and Analysis

The experimental results show that in the roughing high-intensity magnetic separation stage, when the magnetic field intensity is 1.0 T and the slurry concentration is 35 %, the recovery rate of magnetic minerals reaches its highest at 68.84 %, with a grade of 47.63 %. As the magnetic field intensity increases, the recovery rate improves slightly, but the grade decreases; excessively high or low slurry concentrations lead to reductions in both recovery rate and grade.

After cleaning magnetic separation, under the conditions of a 0.9 T magnetic field and 30 % slurry concentration, the magnetic mineral grade increases to 51 %, with a significant reduction in impurity content. This indicates that proper cleaning parameters can effectively enhance the purity of magnetic minerals.

In the scavenging stage, at a magnetic field intensity of 1.4 T and slurry concentration of 25 %, residual magnetic minerals are partially recovered, resulting in an overall metal recovery rate of 50 % for the entire process.

A descriptive statistical analysis was performed on the experimental data, calculating the mean and standard deviation for each parameter. Analysis of variance (ANOVA) revealed that magnetic field intensity has a significant effect on both recovery rate and grade, with slurry concentration having a secondary impact. Correlation analysis indicates a positive correlation between magnetic field intensity and recovery rate, and a negative correlation between magnetic field intensity and grade; slurry concentration exhibits a parabolic relationship with both recovery rate and grade.

Compared to expectations, the experiment achieved favourable results in improving both recovery rate and grade of magnetic minerals, though some deviations occurred – such as recovery rates not meeting expectations under certain parameter combinations – possibly due to the complexity of bauxite residue samples and equipment operational stability. Future efforts may focus on further optimizing equipment performance and exploring more refined parameter control methods to enhance the resource utilization efficiency of bauxite residue.

5. Assessment of Economic and Environmental Benefits

5.1 Cost Benefit Analysis

Cost Estimation: Equipment investment is approximately 50 million RMB (based on an annual processing capacity of 1 million tonnes of bauxite residue), and operating costs (electricity and magnetic media loss) are about 45 RMB/t of bauxite residue.

Revenue Forecast: At a concentrate price of 180 RMB/t (Fe_2O_3 72.23 %), annual processing of 1 Mt of bauxite residue can yield 428.7 kt of concentrate, generating 77.166 million RMB in output value, with annual profit exceeding 17.906 million RMB.

Return on Investment Period: Approximately 1.5 years, indicating significant economic benefits.

5.2 Environmental Benefits

Reduction in bauxite residue storage: Annual processing of 1 million tonnes of bauxite residue reduces land occupation by approximately 120 000 m^2 (12 ha);

Lower environmental risks: Prevents contamination of soil and groundwater by alkaline bauxite residue;

Resource substitution: Recovered iron resources can partially replace imported iron ore, alleviating resource pressure.

6. Discussion and Outlook

6.1 Technical Bottlenecks and Improvement Directions

(1) The recovery efficiency of fine magnetic minerals still has room for improvement, requiring the development of high-gradient magnetic separation equipment;

(2) Due to large fluctuations in bauxite residue composition, it is necessary to establish online detection and adaptive parameter control systems;

(3) Further treatment of tailings is needed (e.g., acid leaching to recover alumina, titanium, etc.) to achieve comprehensive component utilization.

6.2 Research Outlook

There remains significant room for development and optimization of high-intensity magnetic separation technology for bauxite residue. On one hand, research on new high-intensity magnetic separation equipment should be intensified – for instance, further increasing magnetic field strength and gradient, optimizing magnetic circuit design, and enhancing the recovery of fine magnetic particles. On the other hand, in-depth studies on the physicochemical properties of bauxite residue should be conducted to explore more refined parameter control methods. Tailored magnetic separation parameters should be developed based on the origin and characteristics of the bauxite residue to improve recovery rate and grade. In addition, integrating high-intensity magnetic separation with other beneficiation technologies such as flotation and gravity separation may lead to combined beneficiation processes, enabling comprehensive recovery of multiple valuable components from bauxite residue, thereby improving its overall resource utilization and economic viability, and advancing high-intensity magnetic separation technology to a higher level.

6.3 Policy Recommendations

Promote policy support for bauxite residue resource utilization, such as tax incentives, green financing, and the formulation of technical standards, to encourage enterprise participation.

7. Conclusions

(1) The “one roughing, one cleaning, and one scavenging stage” high-intensity magnetic separation process for bauxite residue significantly improves the recovery efficiency of magnetic minerals through classification and separation. During the roughing magnetic separation stage, most magnetic minerals can be effectively recovered by reasonably setting the magnetic field intensity and slurry concentration. At a magnetic field intensity of 1.0 T and a slurry concentration of 35 %, the highest recovery rate of magnetic minerals was achieved, reaching 68.84 % with a grade of 47.63 %. The cleaning stage further improved the purity of magnetic minerals, with the grade increasing to 51 % under the conditions of 0.9 T magnetic field intensity and 30 % slurry concentration. The scavenging stage, as a supplement, recovered some residual magnetic minerals under the condition of 1.4 T magnetic field intensity and 25 % slurry concentration, resulting in an overall metal element recovery rate of 50 % for the process. The process flow is shown in Table 8 and Figure 5, while chemical multi-element analysis results of the products are presented in Tables 9 and 10.

Table 8. Mass and grade flow of the “one roughing, one cleaning, and one scavenging stage” magnetic separation of bauxite residue.

Operation	Product Name	Yield %		TFe Grade	TFe Recovery %	
		Operation	Raw BR		Operation	Raw BR
Roughing Separation	Raw BR		100.00	42.85		100.00
	Concentrate		68.84	47.63		76.52
	Tailings		31.16	32.29		23.48

Concentration	Raw BR	100.00	68.84	47.63	100.00	76.52
	Concentrate	57.02	39.25	51.06	61.12	46.77
	Tailings	42.98	29.59	43.08	38.88	29.75
Scavenging	Raw BR	100.00	31.16	32.29	100.00	23.48
	Concentrate	11.62	3.62	44.54	16.02	3.76
	Tailings	88.38	27.54	30.68	83.98	19.72

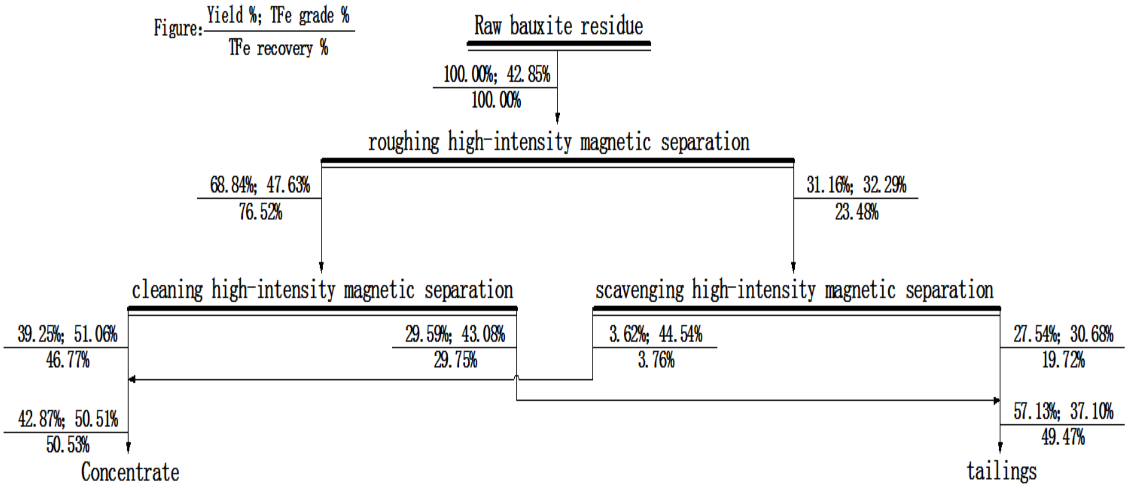

Figure 5. Mass and grade flow diagram of the "one roughing, one cleaning, and one scavenging stage" magnetic separation test for bauxite residue.

Table 9. Chemical composition of combined concentrate (mass fraction, %).

Component	TFe	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O
Content	50.53	12.20	2.38	67.37	4.47	0.023	0.66
Component	CaO	MgO	Hematite	Illite	Quartz	Boehmite	Gibbsite
Content	1.23	0.130	33.70	2.00	1.40	4.00	4.50
Component	Goethite	Diaspore		Anatase	Rutile	Sodium Alumino Silicate	LOI
Content	43.40	1.00		1.40	3.00	3.00	10.30

Table 10. Chemical composition of combined tailings (mass fraction, %).

Component	TFe	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O
Content	37.10	20.63	5.66	50.60	5.61	0.080	1.80
Component	CaO	MgO	Hematite	Illite	Quartz	Boehmite	Gibbsite
Content	2.18	0.130	25.00	2.00	2.90	10.00	8.50
Component	Goethite	Calcite		Anatase	Rutile	Sodium Alumino Silicate	LOI
Content	33.00	4.00		1.80	3.80	8.00	11.69

(2) The optimized parameter combination is: one roughing (1.0 T, 35 % slurry concentration), one cleaning (0.9 T, 0.8 cm/s flow rate), and one scavenging (1.4 T, 25 % slurry concentration).

(3) The process is economically feasible, with a short payback period and significant environmental benefits, providing an effective technical route for the resource utilization of bauxite residue.

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