

Characteristics analysis and pre-enrichment beneficiation of scandium from complex silicate ore

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Abstract: Scandium is regarded as a critical raw material for the material industry, and the beneficiation from various primary sources is gaining attention. The utilization and development of the super-large silicate scandium ore in the Chuxiong area of Yunnan Province is becoming increasingly urgent. Therefore, systematic characterization was performed on raw ore samples to identify scandium-bearing mineral types and occurrence features. The results reveal that the valuable component in this ore is scandium with a grade of 87.8×10^{-4} wt.%, and the main scandium bearing mineral are diopside, plagioclase, amphibole, etc. Direct leaching is impractical owing to the low scandium content and complex mineral composition of the raw ore. A combined beneficiation pre-enrichment process was employed for the utilization of this ore, including magnetic separation, and shaking table. The main purposes include increasing the grade of the concentrate and discarding a portion of the gangue. Under the optimized conditions of low-intensity magnetic separation at 0.40 T, shaking table for particles greater than 0.074 mm at a stroke of 14 mm and punching frequency of 340 times per minute, a stroke of 12 mm and punching frequency of 380 times per minute, the high-intensity magnetic separation at 1.40 T, a scandium concentrate was obtained with a grade of 122×10^{-4} wt.%, recovery of 57.94%, and yield of 41.70%, respectively. This approach provides a technical basis for an integrated beneficiation process to support the comprehensive development and utilization of this critical resource.

Keywords: scandium, mineralogical characteristics, silicate ore, magnetic separation, pre-concentration

1. Introduction

Scandium is a critical metal and an important strategic material for the national defense industry (Yan et al., 2019; Zhang et al., 2005). It is widely used in aerospace, nuclear energy, superconductivity, rockets, lightweight vehicles, high-speed locomotives, ships, warships, missiles, aircraft, and other high-tech fields (Yin et al., 2007; Lin et al., 2010; Zhang et al., 2006). Scandium is primarily extracted from bauxite and ilmenite (Akcil et al., 2018; Celik et al., 1995), as well as uranium ore, tungsten ore (Well et al., 2020; Liu et al., 2017), tin ore, and various rare metal ores (Kim et al., 2020; Jindal et al., 2006; Smirnov et al., 1997; Giret et al., 2018). The mineral types containing scandium are relatively complex, and most occur as secondary resources. Given the limited distribution of scandium reserves, researchers have long sought new alternative sources for scandium extraction. Ores with scandium content ranging from 0.002% to 0.005% are considered potential resource worthy of exploitation (Xu et al., 1996).

Large independent scandium deposits are extremely scarce worldwide, with most scandium recovered as a by-product (Jyothi et al., 2020; Gambogi, 2021). Some studies have attempted to extract scandium from secondary resources such as titanium white waste acid and chlorinated soot (Jiang et al., 2019; Fergus, 2007; Ahmad, 2003). However, these processes face challenges including unstable feedstock supply, inconsistent process flowsheets, and difficulties in large-scale production. To date,

the reported large-scale independent deposits primarily include the OWENDAL scandium deposit (Yan, 2004) in New South Wales, Australia; the SCONI scandium deposit (Metallica, 2012) in Queensland, Australia; as well as deposits in central Yunnan Province (Guo et al., 2012) and southwest Guizhou Province (Nie, 2018) in China. These deposits are characterized by large reserves, low grades, and complex mineral compositions, with scandium dispersed in mafic-ultramafic rocks (e.g., ilmenite, pyroxene, mica, uranothorite) through isomorphism or ionic adsorption (Dong, 2016). Hydrometallurgical processing is the primary method for exploiting these ores (Junior et al., 2022). To achieve more economical extraction, beneficiation and pre-concentration prior to leaching are essential. Direct leaching results in excessive consumption of leaching reagents by gangue minerals, leading to poor economic efficiency. A combination of Low-intensity and high-gradient magnetic separation was adopted in preconcentration of scandium and removing of gangue minerals (Kallio et al., 2021). Meanwhile, thermal treatment through acid roasting demonstrates superior extraction of rare earth elements (REEs) and reduced iron recovery compared to direct leaching (Junior et al., 2022). Therefore, these methods are specifically designed for a certain mineral with a relatively high scandium content. However, on account of the dispersed silicate minerals containing scandium, limited research has been conducted on the pre-concentration of scandium-bearing minerals (Kallio et al., 2021; Wang et al., 2011; Yin et al., 2007; Lin et al., 2010).

This paper presents a combined method of magnetic separation and shaking table for pre-concentration that fully considers the dispersed occurrence of scandium and the comprehensive utilization of the ore. The proposed method offers advantages such as a simplified flowsheet, low cost, and environmental friendliness (Kallio et al., 2021). It can serve as a foundation for an integrated beneficiation process, enabling the efficient and comprehensive exploitation of this important strategic resource.

2. Materials and methods

2.1. Raw materials

The scandium-containing complex silicate ore utilized in this study was obtained from Yunnan Province, China, selected based on its geological and distribution features. About 500 kg of ore collected from several drilling locations was crushed to particles smaller than 2 mm using a three-stage jaw crusher. After thorough mixing and splitting, a 50 kg representative sample was prepared for physical property testing and preliminary enrichment experiments. The remaining ore underwent physical beneficiation for pre-concentration before being used in subsequent leaching tests.

2.2. Magnetic separation

Magnetic separation was carried out using equipment with a gradient magnetic field. When the ore is introduced into the separation zone of the magnetic separator, it is influenced by both magnetic and mechanical forces. Particles with varying magnetic properties experience different magnetic forces and follow distinct trajectories (Wang et al., 2011). The magnetic response of a particle is determined by its volume magnetic susceptibility. Under a constant external magnetic field strength and gradient, the magnetic force on a particle is proportional to its volume magnetic susceptibility. Minerals with higher magnetic susceptibility are subjected to stronger magnetic forces and are more easily separated by the magnetic separator. The magnetic separation apparatus employed in this study is depicted in Fig. 1 and was supplied by Jiangxi Shichen County Guobang Mining Machinery Co., Ltd. and Jiangxi Ganzhou Jinhuan Magnetic Separation Equipment Co., Ltd.

As indicated in Eqs 1 and 2, a particle's magnetic behavior is influenced by its volume magnetic susceptibility ratio (x_o) (Wang et al., 1986; Wills et al., 2006). During magnetic separation of minerals, the external magnetic field strength ($H_o \cdot \text{grad}H_o$) is kept constant, and the magnetic force (F_m) exerted on the particles is directly proportional to their volume susceptibility ratio (x_o). Consequently, minerals with higher magnetic susceptibility experience stronger magnetic forces and are more readily captured by the magnetic separator.

$$f_m = \mu_o \cdot k_o \cdot V \cdot H_o \cdot \text{grad}H_o \quad (1)$$

$$F_m = f_m/m = \frac{\mu_0 \cdot k_0 \cdot V \cdot H_0 \cdot \text{grad} H_0}{\delta \cdot V} = \mu_0 \cdot x_0 \cdot H_0 \cdot \text{grad} H_0 \quad (2)$$

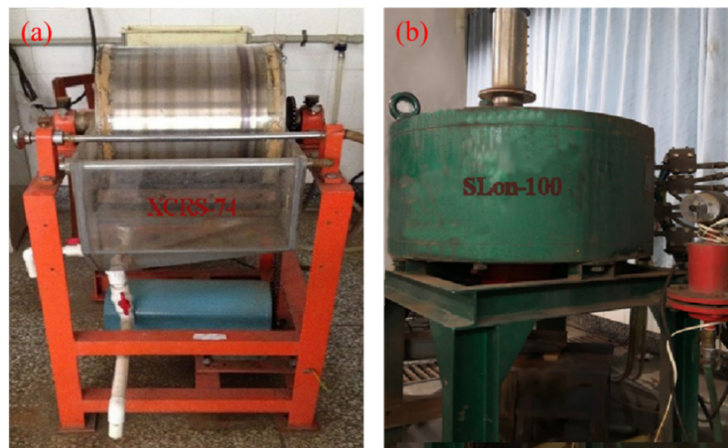


Fig. 1. The magnetic separation equipment used in this research

Because of the pronounced magnetic contrast between iron-bearing minerals and other materials, magnetic separation can remove iron minerals from the rough concentrate to produce a scandium-rich concentrate. Minerals such as magnetite, titanomagnetite, and ilmenite can be separated to obtain a rough iron concentrate. Additionally, scandium-bearing biotite can be recovered through magnetic separation, while minerals like diopside, zircon, and amphibole can be further refined using electrostatic separation to yield a high-purity scandium concentrate.

2.3. Shaking table

Shaking table mineral processing employs the combined effects of mechanical shaking and water flow to separate mineral particles based on their density, offering benefits like a high concentration ratio and low production costs. Due to significant density differences among minerals, separation occurs during the shaking table's reciprocating motion, effectively distinguishing minerals such as magnetite, ilmenite, diopside, and quartz. Given the distinct specific gravity differences between scandium-rich minerals and gangue minerals, the LYS-6S shaking table used in this study (shown in Fig. 2) was supplied by Jiangxi Shicheng County Guobang Mining Machinery Co., Ltd.



Fig. 2. The shaking table equipment used in this research

2.4. Analytical equipment

To characterize the raw ore and determine how scandium occurs within different minerals, various analytical techniques were applied to core samples. These included X-ray diffraction (XRD, Shimadzu

XRD-7000, Japan) for phase identification, X-ray fluorescence spectrometry (XRF, ARL Perform X 4200, USA) for major elemental content, and polarization microscopy (Leica DM2700P, Germany) for mineral composition analysis. Additionally, scanning electron microscopy (JEOL JXA-8230, Japan) combined with energy-dispersive spectroscopy (EDS Ultim Max, UK) was used to examine microscopic morphology and elemental composition, while inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Fisher iCAP-7400, USA) measured scandium content.

Then the scandium recovery (β_{Sc}) are calculated as follows:

$$\beta_{Sc} = \left(\frac{M_r C_r}{M_0 C_0} \right) \times 100\% \quad (3)$$

The yield (η_{Sc}) of scandium concentrate can be written as:

$$\eta_{Sc} = \left(\frac{M_r}{M_0} \right) \times 100\% \quad (4)$$

where M_r and M_0 are weights of the concentrate and initial sample (g). C_r and C_0 are the content of Sc in concentrate and raw sample ($\times 10^{-4}$ wt. %, mean part per million), respectively.

3. Results and discussion

3.1. Characterization studies of raw ore

In order to determine the primary characterization of the raw ore and the occurrence of scandium within various minerals, several analytical techniques were applied to core samples, with the results presented in Figs. 3-4 and Tables 1-3.

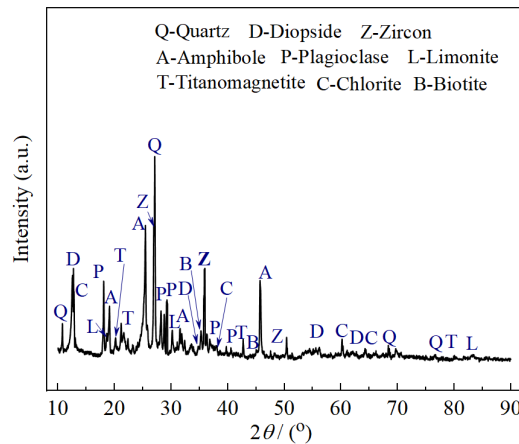


Fig. 3. XRD plot results of raw ore

As illustrated in Fig. 3, the raw ore predominantly consists of silicate minerals such as quartz (SiO_2), diopside ($CaMgSi_2O_6$), zircon ($ZrSiO_4$), amphibole ($Fe_2Mg_2Si_8O_{22}(OH)_2$), limonite (Fe_2O_3), titanomagnetite ($FeTiO_3$), biotite ($Al_2K_2O_6Si$) and plagioclase ($CaAl_2Si_2O_8$), etc. As depicted in Fig. 4, the sample from complex Silicate ore is mostly gray-black, dark gray, and most of the plagioclase, amphibole and diopside in the ore are semi-self-shaped, then constituting a semi-self-shaped granular structure. Therefore, different minerals directly exhibit a close interbedding relationship. The ore exhibits a low concentration of sulfide minerals, predominantly composed of pyrite. The carbonate fraction within the ore is minimal, with calcite being the principal carbonate mineral present. Conversely, the oxide content is relatively higher, primarily consisting of quartz, magnetite, and ilmenite. The results of spectral analysis are shown in Table 1, and the chemical compositions are shown in Table 2. The Scandium content in different minerals is shown in Table 3. The most valuable element is Scandium, which is distributed in the form of isomorphism in Scandium-containing minerals. Based on the above results, scandium in silicate ores is mainly distributed in diopside with Sc of 158.1×10^{-4} wt. %, amphibole with Sc of 85.8×10^{-4} wt. %, zircon with Sc of 320×10^{-4} wt. %. Zircon and monoclinic zircon in silicate ores are mostly encased by other minerals, and more are encased in pyroxene. When the

grinding is too fine, more zircons enter the tailings during the separation process, which is not conducive to improving the recovery rate of scandium. Scandium enrichment can be achieved by concentrating diopside and amphibole. Since diopside contains magnetic minerals like iron and titanium, both diopside and amphibole can be enriched through magnetic separation. However, biotite, which is also magnetic, may enter the concentrate during this process, lowering the scandium grade. Biotite can be further removed from the concentrate by an additional magnetic separation step.

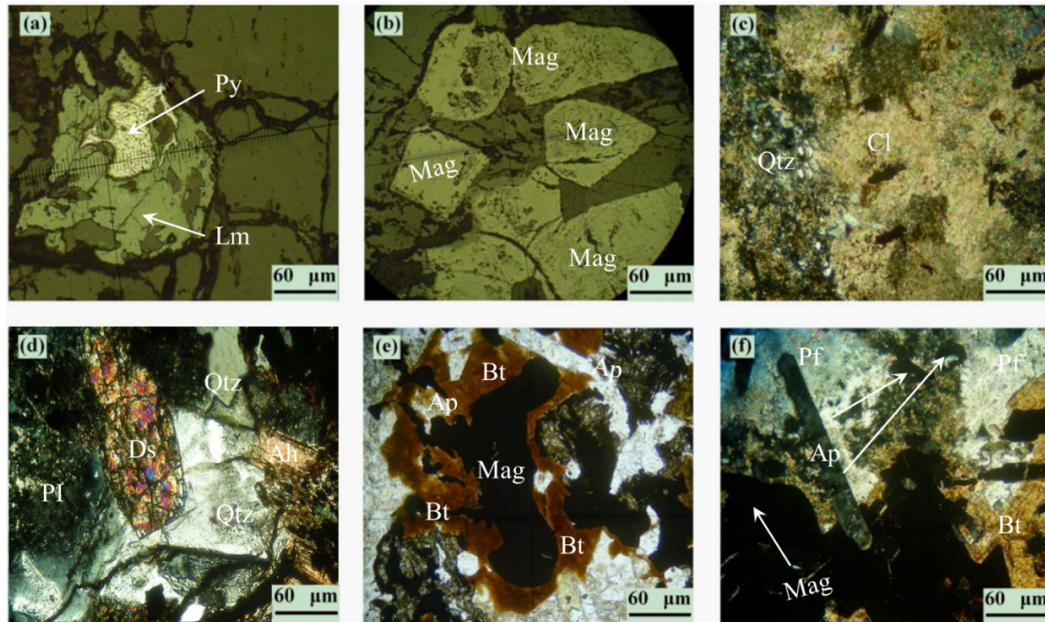


Fig. 4. The POM (Polarizing Optical Microscope) analysis results. (a) Mineral of the sulfide, Pyrite (Py) and Limonite (Lm); (b) Mineral of the oxide, magnetic iron ore (Mag); (c) Mineral of the carbonate, Calcite (Cl) and Quartz (Qtz); (d) Mineral of the feldspar in silicates, Plagioclase (Pl), Amphibole (Ah) and Diopside (Ds); (e) Mineral of the mica in silicates, Biotite (Bt); (f) Mineral of the phosphate, Apatite (Ap)

Table 1. XRF results of the sample (wt.%)

Element	Ag	Al	As	B	Ba	Be	Bi	Ca
Content	0.0004	1	0.08	<0.001	<0.03	<0.001	0.001	0.2
Element	Cd	Co	Cr	Cu	Fe	Ga	Ge	Mg
Content	<0.001	0.01	0.1	0.04	9.5	0.001	<0.001	2
Element	Mn	Mo	Ni	P	Pb	Sb	Si	Sn
Content	0.2	0.001	0.03	0.1	0.002	0.01	>>10	0.005
Element	Ti	V	W	Zn	In	Ta	Nb	
Content	2.81	0.003	0.007	0.01	<0.01	<0.005	<0.01	

Table 2. Analysis of main chemical components of the sample (wt.%)

Element	Fe	P	As	S	TiO ₂	MgO
Content	9.50	0.10	0.017	0.006	2.81	12.35
Element	CaO	SiO ₂	Al ₂ O ₃	Pt (10 ⁻⁴)	Sc (10 ⁻⁴)	Total rare earth
Content	14.38	45.68	5.80	0.042	87.8	0.025

Table 3. Analysis of main Scandium-containing minerals in the sample

Minerals	Diopside	Biotite	Magnetite	Amphibole	Zircon	Quartz	Plagioclase
Distribution ratio (%)	38	7	6	5	<1	23	18
Sc Content (10^{-4} wt.%)	158.1	6.2	8.0	85.8	320	43.8	43.8
Sc Distribution (%)	69.50	0.50	0.56	4.96	3.71	11.65	9.12

3.2. Low-intensity magnetic separation

The wet low-intensity magnetic separator is an efficient tool for separating strongly magnetic minerals. Analysis of the complex silicate ore sample shows it contains ferromagnetic minerals such as magnetite and titanium magnetite. Therefore, wet low-intensity magnetic separation is employed to isolate ferromagnetic scandium-bearing minerals, which have a high specific gravity, and to remove ferromagnetic minerals. This process positively impacts subsequent high-gradient magnetic separation. Consequently, low-intensity magnetic separation is used to separate the ferromagnetic minerals, with the ore ground to a particle size of -0.074 mm, accounting for 80%. The results are presented in Fig. 5.

From the experimental data shown in Fig. 5, it is clear that low-intensity magnetic separation primarily targets the ferromagnetic minerals in the ore. The results indicate that the beneficiation indices for both iron

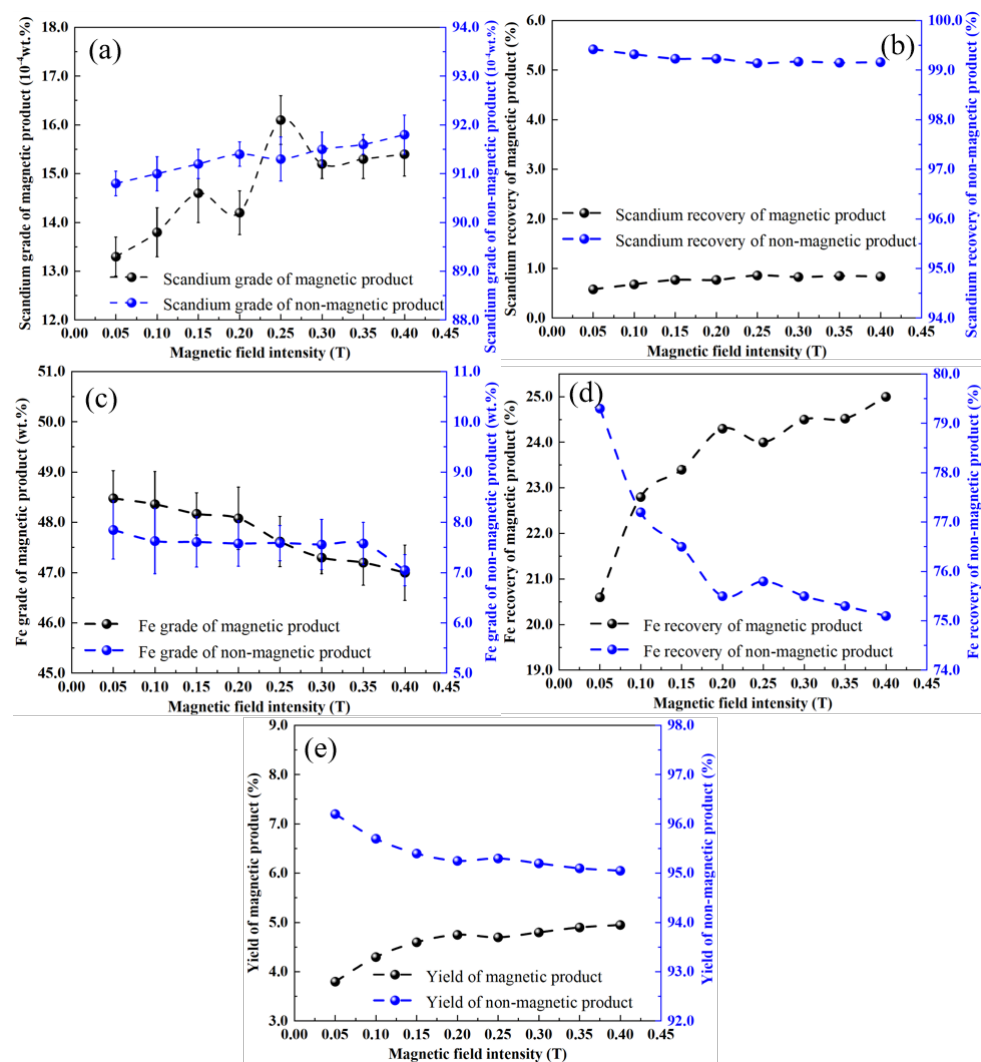


Fig. 5. Results of low-intensity magnetic separation for complex Silicate ore: (a) Scandium grade; (b) Scandium recovery; (c) Fe grade; (d) Fe recovery; (e) Mineral yield

concentrate and scandium concentrate are not optimal, due to the low content of magnetic iron minerals and the presence of titanomagnetite. As the magnetic field intensity increases gradually from 0.05 T to 0.40 T, the iron grade in the magnetic products decreases from 48.46% to 47.06%, while iron recovery rises from 20.66% to 24.87%. In the non-magnetic products, the iron grade decreases from 7.86% to 7.51%, and iron recovery falls from 79.34% to 75.13% over the same range of magnetic field intensities. Additionally, the yield of magnetic products increases from 4.05% to 5.02%, whereas the yield of non-magnetic products decreases from 95.95% to 94.98%. The mineral is a type of weathered silicate mineral, which has resulted in the close values of magnetic and non-magnetic products. On the one hand, the proportion of magnetic iron in this mineral is relatively low; on the other hand, the ultra-fine particles cannot be effectively separated during the magnetic separation process. These factors result in the situation that during weak magnetic separation, as the field strength increases, the output of magnetic minerals does not change significantly. These findings confirm that the ferromagnetic mineral properties align with those identified in mineral analysis, specifically titanium-containing magnetite. Regarding scandium content, the magnetic minerals have a low scandium grade, which slightly increases from 13.30×10^{-4} wt.% to 15.40×10^{-4} wt.% as the magnetic field strength rises from 0.05 T to 0.40 T. Conversely, the non-magnetic minerals have a high scandium content, with the grade increasing from 90.87×10^{-4} wt.% to 91.63×10^{-4} wt.% over the same magnetic field range. Low-intensity magnetic separation effectively enriches scandium in the non-magnetic products, achieving a scandium grade of 91.63×10^{-4} wt.% and recovery of 99.20% at magnetic field intensity of 0.40 T. Even though there is no significant increase in scandium content, compared to feed material. On the one hand, a portion of the magnetite resources is recycled. Meanwhile, iron is should be reduced to minimize its interference in the subsequent scandium extraction and back-extraction processes. Because the extraction process of scandium, iron will also be extracted, and a large amount of acid will be consumed during the washing process.

3.3. Shaking table separation

Magnetic minerals such as magnetite, titanomagnetite have significant differences in magnetism and gravity compared to the main scandium-containing minerals, such as diopside and plagioclase (Wei, et al., 2019; Li, et al., 2014). Therefore, the shaking table is a key gravity separation method, commonly used to separate the tailings from low-intensity magnetic separation. To minimize the impact of particle size variation on shaking table separation, the material was divided into two particle size ranges, and the separation results are presented in Fig. 6.

As shown in Fig. 6 (a) and (c), the grade of scandium concentrate first increase and then decreases with the increase of amplitude and frequency increase. The scandium content in concentrate products

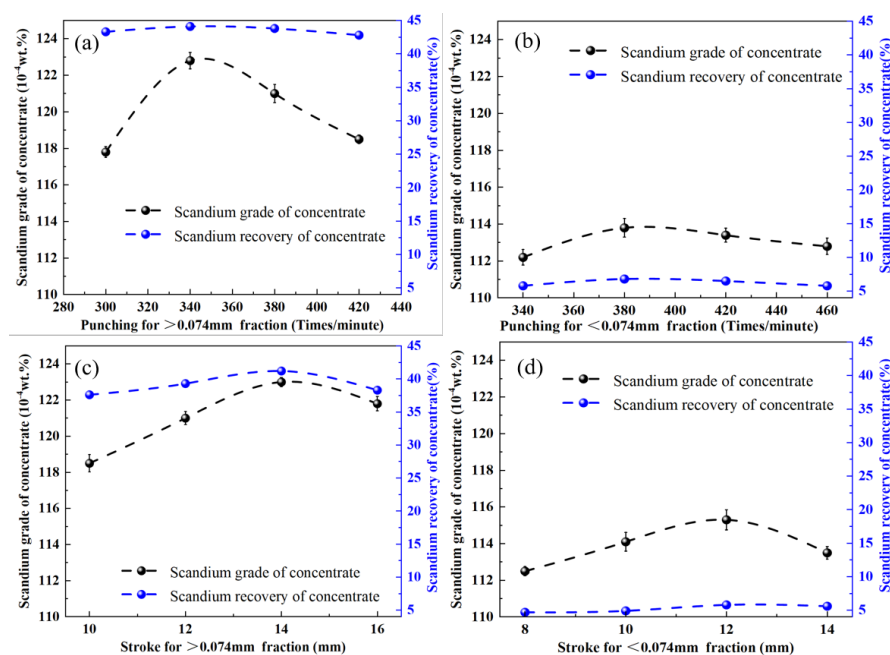


Fig. 6. Results of Shaking table Separation for complex Silicate ore: (a) Punching for >0.074mm fraction; (b) Punching for <0.074mm fraction; (c) Stroke for >0.074mm fraction; (d) Stroke for <0.074mm fraction.

with particle sizes greater than 0.074 mm reaches 123×10^{-4} wt. % with a recovery rate of 41.35%, at a stroke of 14 mm and punching frequency of 340 times per minute. Because there is a significant difference in density difference between diopside ($3.2\text{--}3.6$, g/cm^3), amphibole ($2.8\text{--}3.6$, g/cm^3) and quartz (2.65 , g/cm^3). However, the trend becomes less obvious, for the particle sizes smaller than 0.074mm. The scandium content reaches 115.50×10^{-4} wt. % with a recovery of 5.8%, at a stroke of 12 mm and punching frequency of 380 times per minute. Because the finer silicate minerals would be washed away by the water flow, resulting in a lower recovery rate and grade. Based on these findings, the optimal shaking table parameters were determined: for particles larger than 0.074 mm, a stroke of 14 mm and a punching frequency of 340 times per minute; for particles smaller than 0.074 mm, a stroke of 12 mm and a punching frequency of 380 times per minute. Meanwhile, the shaking table process can discard a portion of the quartz gangue. The classification operation is also necessary for subsequent high-intensity magnetic separation to prevent a too wide particle size range from causing severe contamination and thereby affecting the strong magnetic separation.

3.4. High-intensity magnetic separation

The results from low-intensity magnetic separation and shaking table separation indicate that it is challenging to significantly enrich Scandium using a single method. Therefore, high-intensity magnetic separation was employed for testing. Initially, low-intensity magnetic separation at 0.4 T was used to remove strongly magnetic minerals. The feed particle size was predominantly under 0.074 mm, accounting for 80%. The test outcomes are presented in Fig. 7.

From the high-intensity magnetic separation results shown in Fig. 7, it is observed that scandium content in magnetic products initially decreases and then gradually increases as the magnetic field intensity rises. When the magnetic field strength increased from 0.20 T to 1.40 T, scandium content in the magnetic product rose from 71.0 to 102.0×10^{-4} wt. % and scandium recovery improved from 2.15% to 27.86%. Meanwhile, iron content in the magnetic product decreased from 17.29% to 9.96%, with iron recovery increasing from 6.38% to 33.20%. This is mainly attributed to the fact that some iron-containing silicate minerals are recovered under high magnetic field intensities. For the non-magnetic products, scandium content dropped from 92.22 to 88.17×10^{-4} wt. % and scandium recovery fell from 97.85% to 72.14% as the magnetic field increased from 0.20 T to 1.40 T. Iron content in the non-magnetic products also decreased slightly from 7.23% to 6.69%, with iron recovery declining from 93.62% to 66.80%. Additionally, the yield of magnetic products increased from 2.27% to 25.30%, while the yield of non-magnetic products decreased from 97.23% to 74.97%. In addition, the results in Figs. 5 and 7 show significant differences, even when the background field strength was the same. Because some weakly magnetic minerals with relatively low scandium content, such as iron-containing biotite, inclusions containing scandium and iron etc, can be captured during the strong magnetic separation process with the action of steel rod magnetic medium.

When the magnetic field intensity is 1.4T, the magnetic products have the highest scandium content and recovery. Especially for some fine-grained scandium-containing weakly magnetic minerals such as high-iron diopside, they will be captured during the strong magnetic separation process. So, the main purpose is to recover some fine-grained weakly magnetic minerals with high scandium content, especially the portion washed away during the shaking table process. Furthermore, the strong magnetic separation is beneficial for the subsequent leaching process, as it enables the consumption of a large amount of gangue to deplete the leaching agent and energy.

Therefore, the results indicate that scandium enrichment is optimal at a magnetic field intensity of 1.4 T. However, the scandium content does not significantly increase because the changes in scandium content in both magnetic and non-magnetic products are minimal with varying magnetic field intensity. The experimental data also suggest that a single separation process is insufficient for substantial scandium enrichment. Therefore, it is necessary to select the best parameters under various conditions and conduct comprehensive tests involving combined separation processes.

3.5. Pre-concentration of Scandium

Experiments involving low-intensity magnetic separation, shaking table separation, and high-intensity magnetic separation demonstrate that no single separation technique can achieve satisfactory Scandium enrichment. In the subsequent leaching process, the concentrate requires an economical scandium

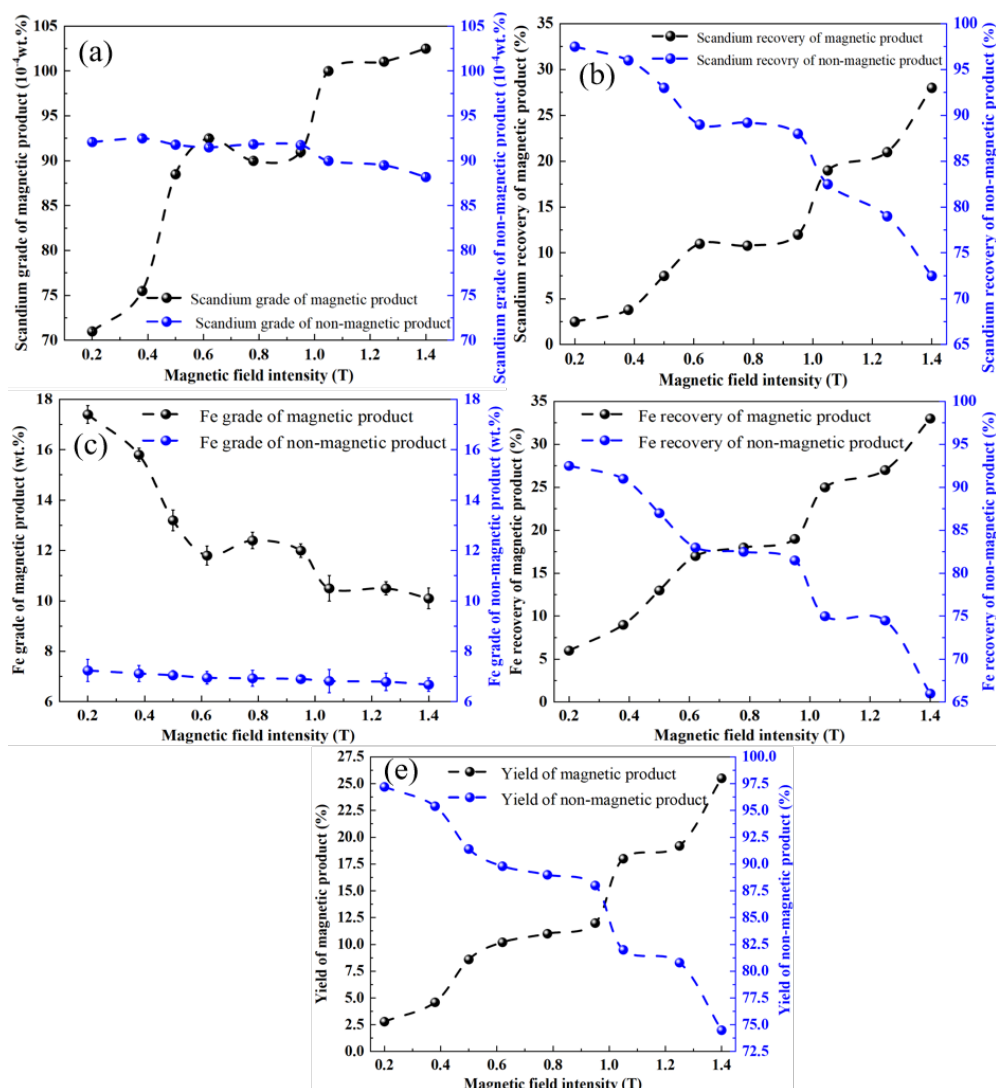


Fig. 7. Results of high-intensity magnetic separation for complex Silicate ore: (a) Scandium grade; (b) Scandium recovery; (c) Fe grade; (d) Fe recovery; (e) Yield

content with the value greater than $120 \times 10^{-4} \text{ wt. \%}$. Then, the iron in the ore needs to be recovered first to prevent excessive consumption of the leaching agent during the subsequent leaching process, and to avoid the loss of resource utilization. Furthermore, most of the gangue minerals can be removed through the beneficiation pre-enrichment process. Consequently, this study utilizes a combined process consisting of low-intensity magnetic separation, graded shaking table separation, and high-intensity magnetic separation to enrich Scandium from complex silicate minerals. Based on the results from individual tests, the optimal single-condition process was selected for scale-up testing. The goal of this expanded test was to verify the stability of the process flow and to prepare samples for leaching tests. The combined beneficiation process flow, including the movement of Scandium throughout, is illustrated in Fig. 8. In the low-intensity magnetic separation, the field was determined at 0.4T, to recover as much weakly magnetic iron ore as possible. Subsequently, the shaking table is mainly used to separate the high-scandium silicate minerals from the gangue. And, optimum parameter for particles greater than 0.074 mm is stroke of 14 mm and punching frequency of 340 times per minute. For the portion smaller than 0.074 mm, the parameter is stroke of 12 mm and punching frequency of 380 times per minute. At last, the high-intensity magnetic separation is determined at 1.40 T, to recover some fine-grained weakly magnetic minerals with high scandium content, especially the portion washed away during the shaking table process. The results of combined beneficiation flow are summarized in Table 4, and microscopic analysis of the Scandium concentrate is shown in Fig. 9.

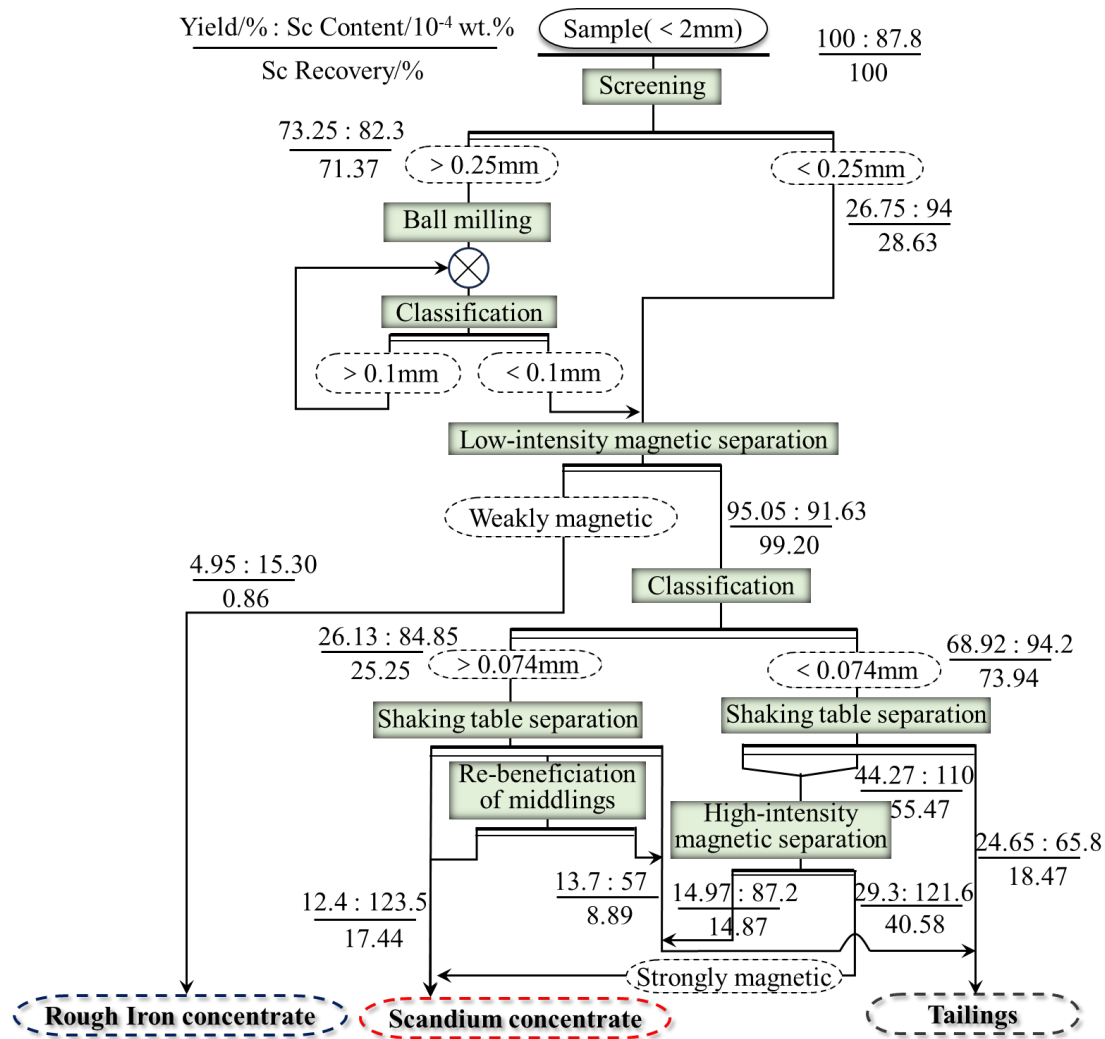


Fig. 8. The combined beneficiation flow for a complex Silicate ore.

Table 4. Test results of combined beneficiation process for complex Silicate ore.

Product	Mineral Yield (%)	Sc Content ($\times 10^{-4}$ wt. %)	Sc Recovery (%)
Rough Iron concentrate	4.95	15.30	0.86
Scandium concentrate	41.70	122.0	57.94
Tailings	53.35	67.80	41.20

Data from Table 4 confirm that the combined process of low-intensity magnetic separation, graded shaking table separation, and high-intensity magnetic separation is effective for the beneficiation and enrichment of Scandium from complex silicate ore. The Scandium concentrate achieved a grade of 122.0×10^{-4} wt. % with a recovery rate of 57.94% and a yield of 41.70%. As seen in Fig. 9(a), the microscopic structure of the Scandium concentrate appears interwoven, primarily composed of aluminum, silicon, and oxygen, indicating a silicate mineral composition. Additionally, scanning electron microscopy and energy dispersive spectrometer (SEM-EDS) analysis in Fig. 9(b) detected Scandium content in a single mineral, consistent with the composition of diopside ($\text{CaMgSi}_2\text{O}_6$). These elemental components are in agreement with the results of the main scandium-containing minerals presented in Table 3. The results confirm that the main Scandium-bearing minerals were successfully concentrated through the combined beneficiation process, which is to concentrate a certain amount of scandium containing mineral and discard most of the gangue.

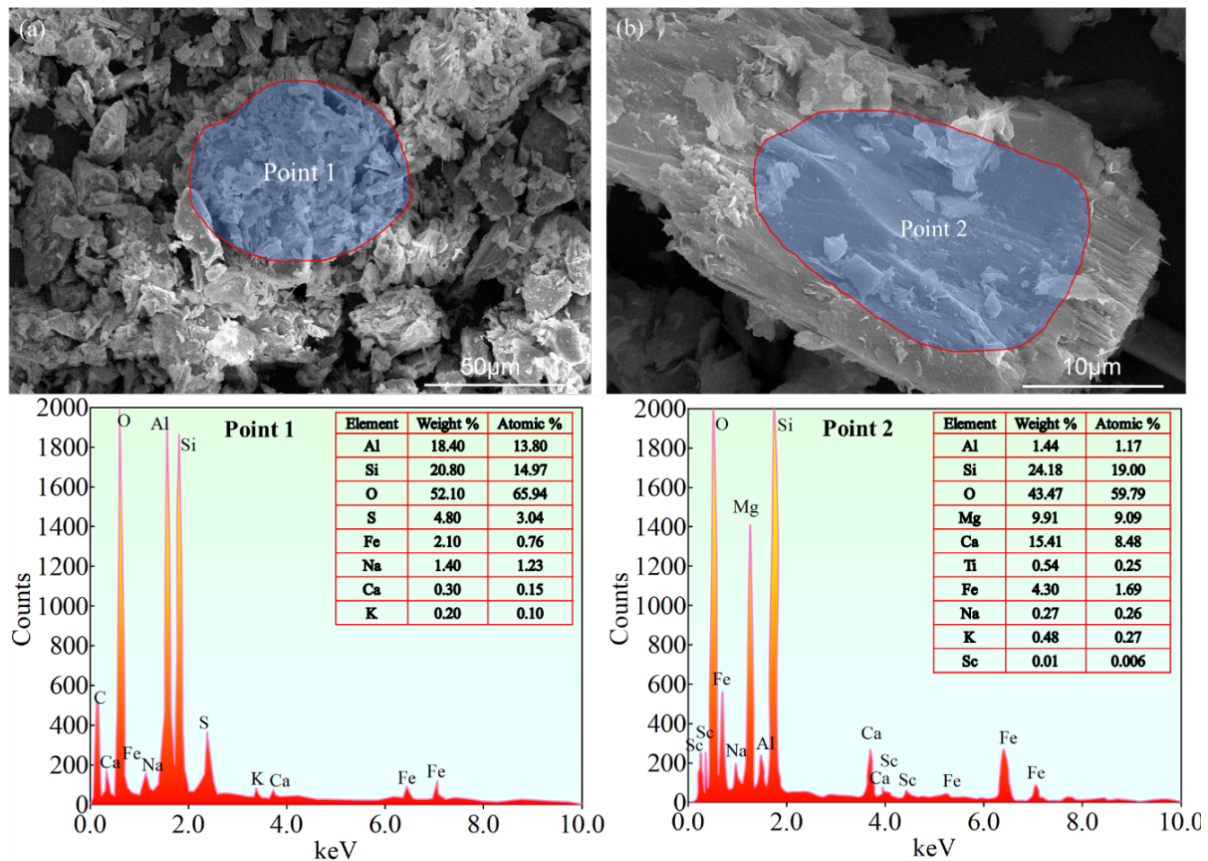


Fig. 9. SEM micrograph and EDS elements analysis of the scandium concentrate sample: (a) concentrate, (b) single mineral

4. Conclusions

- (1) The principal economically element extracted from this mine is Scandium, present at a concentration of $87.8 \times 10^{-4} \text{ wt. \%}$. This element occurs within silicate minerals via isomorphous substitution. Mineralogical analysis reveals that the majority of plagioclase, amphibole, and diopside minerals in the ore display semi-euhedral to euhedral crystal morphologies, resulting in a semi-euhedral granular texture.
- (2) A combined test based on the proposed processing flow sheet was carried out to assess the feasibility and reliability of the beneficiation method. Under specific operating conditions, low-intensity magnetic separation at 0.40 T and high-intensity magnetic separation at 1.40 T, a scandium concentrate was produced with a scandium content of $122.0 \times 10^{-4} \text{ wt. \%}$, a recovery rate of 57.94%, and a yield of 41.70%. These outcomes are considered satisfactory for subsequent leaching treatment, which the iron was recovered and the gangue minerals was removed in the previous pre-enrichment stage.
- (3) In light of these results, it can be concluded that the proposed beneficiation process of “low intensity magnetic separation -graded shaker separation-high intensity magnetic separation”, constitutes a viable strategy for the pre-concentration of this complex Silicate ore.

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