Dissolution behavior of representative elements from red mud (RM) by leaching with titanium white waste acid (TWWA)

Xiaobo Zhu

Henan Polytechnic University

Chen Ma

Henan Polytechnic University

Wang Li (✉ liwang0805@126.com)

Henan Polytechnic University

Research Article

Keywords: Dissolution behavior, Representative elements, Leaching, RM, TWWA

Posted Date: February 4th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1265756/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

The leaching parameters on the leaching efficiency of representative elements (Na, Sc and Al) were investigated. XRD and SEM-EDS were used to analyze the phase change of RM and leaching residue, and the leaching kinetics characteristics difference of Na, Sc and Al from RM was analyzed by the unreacted shrinking core model (USCM). The results show that the dealkalization efficiency was close to 100%, and the leaching efficiency of Sc and Al was 82% and 75%, respectively. The cancrinite was dissolved from RM by TWWA, and then the elements such as Na, Al and Ca also reacted with H_2SO_4 of TWWA. Sodium existed in the leaching liquor in the form of ions, and calcium reacted with sulfuric acid to form anhydrite and existed in leaching residue. The particles of RM became smaller and dispersed with each other after leaching. The apparent activation energy of Na, Sc and Al leaching was 4.947 kJ/mol, 6.361 kJ/mol and 31.666 kJ/mol, respectively. The kinetic equation of Na leaching was $1-(1-a)^{2/3}=0.084\cdot\exp[-595.05/T]\cdot t$ controlled by external diffusion. The kinetic equation of Sc leaching was $1-2a/3-(1-a)^{2/3}=0.021\cdot\exp[-765.16/T]\cdot t$ controlled by internal diffusion. The kinetic equation of Al leaching was $\ln(1-a)/3+(1-a)^{-2/3}-1=67.12\cdot\exp[-3808.8/T]\cdot t$ controlled by joint action, respectively.

1. Introduction

Red mud (RM) is a strong alkaline solid waste discharged from alumina production of bauxite, which is called RM because of its large amount of iron oxide. About 1.0-1.8 tons of RM would be discharged for per ton of alumina production. China discharges 100 million tons of RM every year as a large alumina production country (Jin et al., 2021; Xu et al., 2021; Wang et al., 2021). At present, the accumulated total amount of RM has exceeded 400 million tons. RM is also a kind of harmful pollution source because of its high content of sodium. It is urgent to make full use of RM with the increasing storage of RM and the increasingly serious pollution to the environment (Liu et al., 2014; Smiciklas et al., 2013). According to the physical and chemical properties of RM, the current research mainly focuses on the preparation of building materials, adsorption materials and the recovery of valuable metals (Bao et al., 2021; Li et al., 2021; Lyu et al., 2021; Wu et al., 2021; Zhang et al., 2020). The recovery of valuable elements has been attracted more and more attention from RM, which was as secondary resources containing a lot of aluminum, iron and trace of scandium and vanadium (Li et al., 2021; Xu et al., 2020; Deng et al., 2017). The technology of hydrometallurgy was mainly applied for the recovery of valuable metals, especially rare metals from RM. The acid leaching process (including sulfuric acid, hydrochloric acid, oxalic acid, etc.) was usually used for the dissolution of metals, and then the solvent extraction was applied for separation and purification of metals from the acid leaching solution, in which a lot of acid could be consumed (Wang et al., 2021; Zhang et al., 2021; Li et al., 2021).

Titanium white waste acid (TWWA) is the hydrolytic waste liquid produced in the production of titanium dioxide by sulfuric acid method, which is highly acidic and rich in many metal ions. Approximately 5-6 tons of TWWA with concentration of 20% would be produced for per ton of titanium dioxide production. The direct discharge of TWWA can not only affect the water quality, acidify the soil and break the

ecological balance, but also restrict the development of agriculture and infringe the safety of drinking water (Li and Dai, 2014; Song et al., 2019; Feng et al., 2018). At present, the treatment methods of TWWA were mainly neutralization method and comprehensive method. Neutralization process was to neutralize the wastewater with alkaline substances and then it was discharged at pH value of 6-8, in which the alkaline substances included lime, limestone, soda, caustic soda, etc. The comprehensive method is an integral solution based on the comprehensive treatment and resource utilization of TWWA (Hu et al., 2020). For example, the extraction method was used for recovery of scandium, vanadium and other rare metals, and the crystallization method was used for recovery of iron, aluminum and titanium (Zhou et al., 2020; Song et al., 2021; Feng et al., 2016). However, the strong acidity of TWWA limited the comprehensive utilization of solvent extraction and crystallization, in which a large amount of alkali was needed to adjust the pH value of the solution to meet the operation requirements of extraction and crystallization. The scholar has put forward a research idea, in which the recovery of vanadium was carried from vanadium-bearing steel slag by acid leaching by TWWA (Zhang et al., 2021).

However, TWWA was different from the pure solution of sulfuric acid, which also contained a large number of iron ions and aluminum ions, as well as a certain amount of rare metal ions such as titanium, vanadium and scandium. Whether the existence of these metal ions could affect the dissolution of elements from red mud was still worth studying and analyzing. Therefore, an idea of “treating waste with waste” was put forward in this paper, where the leaching process of RM was carried out by using TWWA as the leaching agent. The dissolution behavior and leaching kinetics characteristics of representative elements in RM were investigated. Structural sodium was the main alkaline pollution source in the RM, in which aluminum belonged a non-ferrous metal with high content, and scandium was a rare metal with strategic value. Therefore, the three elements were selected as the representative elements. The investigation may provide a new idea and method for effective comprehensive utilization of RM and TWWA.

2. Experimental

2.1. Materials

The sample of RM was collected from Henan province, China. The particle size of RM was less than 30 μm accounted for 100%. The RM was analyzed by using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and Fourier Transform Infrared (FT-IR). The results are shown in Table 1, and Fig. 1, respectively.

Table 1
Composition and content of red mud(wt.%)

Composition	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	CaO	Na ₂ O	TiO ₂	K ₂ O	MgO	Sc ₂ O ₃
Content	28.05	26.28	16.05	15.68	5.26	4.39	1.21	0.87	0.02

The RM mainly included silicon, iron, aluminum, titanium, calcium and sodium with 0.02% scandium from Table 1.

It can be seen from Fig. 1 that there were some obvious absorption peaks near 3445 cm⁻¹, 1630 cm⁻¹, 1420 cm⁻¹, 1113 cm⁻¹, 1004 cm⁻¹, 866 cm⁻¹, 680 cm⁻¹, 620 cm⁻¹ and 566 cm⁻¹ in the red mud sample. The broad absorption band at 3445 cm⁻¹ in the spectrum was caused by the contraction vibration of O-H bond in water molecules in various states (mainly adsorbed water and crystal water), and which may also be the stretching vibration of -OH bond in the gibbsite (Al(OH)₃). The absorption peak at 1630 cm⁻¹ was caused by the vibration of Si-O-Si, and the absorption band at 1420 cm⁻¹ was caused by the stretching vibration of CO₃²⁻. The bending vibration of -OH in gibbsite resulted in the absorption band at 1004 cm⁻¹, and the absorption band at 620 cm⁻¹ and 566 cm⁻¹ was caused by the vibration of diaspor except for -OH.

The sample of TWWA was collected from Henna province, in which the main composition and concentration are shown in Table 2.

Table 2

Composition and concentration of TWWA

Composition	H ₂ SO ₄	Fe	Al	Ti	V	Sc
Concentration	198.6 g/L	23.9 g/L	3.3 g/L	2.3 g/L	116 mg/L	20 mg/L

2.2. Methods

The RM of 50 g with a certain volume of TWWA were placed into the beaker according to different liquid to solid ratio (e.g., 3 mL/g, 5 mL/g, 7 mL/g, 9 mL/g), and then heated on the magnetic stirrer. Some experiments were carried out under different conditions of stirring speed (e.g., 100 r/min, 200 r/min, 300 r/min, 400 r/min, 500 r/min), reaction temperature (e.g., 25 °C, 50 °C, 75 °C, 100 °C) and reaction time (e.g., 0.5 h, 1.0 h, 1.5 h, 2.0 h). The leaching solution and leaching residue were obtained by filtration. The leaching efficiency of metals can be expressed as follows.

$$a = (mq - np) / mq \times 100\% \quad (1)$$

Where a represents the leaching efficiency of metals (%), m represents the weight of RM sample (g), q represents the grade of metals in the RM (%), n represents weight of leaching residue (g), p represents the grade of metals in the leaching residue (%).

2.3. Analytical methods

The component of elements in RM and leaching residue was analyzed by ICP-AES (ICAP6300, America). The XRD analysis (D8ADVANCE, Germany) was carried out for the RM and leached residue. The SEM-EDS analysis (JSM-5600LV and IE 300 X, Japan) of RM and leaching residue was used. The FT-IR

(Spectrum100, America) was used for the analysis of RM. The theoretical analysis of acid leaching was carried out by leaching kinetics with unreacted shrinking core model (USCM).

3. Results And Discussions

3.1. leaching parameters

The effects of leaching temperature, liquid to solid ratio, stirring speed and reaction time on the dissolution of sodium, scandium and aluminum in RM were investigated, and the results are shown in Fig. 2.

The dissolution efficiency of Sc, Al, and Na showed an increasing trend by increasing reaction temperature, while the Al increased significantly than Sc and Na (Fig. 2(a)). And the dealkalization efficiency of RM presented by Na leaching efficiency could reach 99% at 100 °C, with the recovery of Sc and Al of 82% and 73%, respectively. It is because that the leaching process between RM and TWWA belongs a chemical reaction of acid and base. Thus, the rate constant of chemical reaction and diffusion process could be greater with a higher temperature (Pasechnik et al., 2021). Since the liquid to solid ratio directly affected the pulp viscosity and acid content of the solid-liquid system (Abhilash et al., 2021). Therefore, the higher was the liquid-solid ratio, the lower was the pulp viscosity and the higher was the acid content, in which the solubility of Na, Sc and Al was better from RM with TWWA (Fig. 2(b)). It was difficult to stir evenly due to the high viscosity with the stirring speed of 100 r/min, in which the Na removal efficiency was lower than 60%, and the leaching efficiencies of Sc and Al were lower than 40% (see Fig. 2(c)). It reveals that the mixing of solid and liquid was more uniform at higher stirring speed (i.e., 400 r/min), so the chemical reaction accelerated with the diffusion rate of the two phases increasing (Zhu et al., 2015). In Fig. 2(d), the dealkalization efficiency of RM increased from 72–99% with an increase of leaching time from 0.5 h to 1.0 h, so as Sc (from 71–82%) and Al (from 55–73%). It indicates that the reaction of components in the RM was more sufficient with a longer leaching time.

3.2. Leaching mechanism analysis

The dissolution of Na, Sc and Al was carried out from RM by using TWWA. In order to further explore the dissolution process of these elements, it was necessary to analyze the phase of RM and leaching residue. Under the conditions of 100 °C, 6 mL/g 400 r/min and 1.0 h, the RM was leached with TWWA to obtain the leaching residue. The phase analysis and morphology analysis of RM and the leaching residue were detected by using X-ray diffraction (XRD) and Scanning Electron Microscope-Energy Dispersive Spectrometer (SEM-EDS), and the results are shown in Fig. 3 and Fig. 4, respectively.

It can be seen from Fig. 3(a) that the main mineral phases of RM included hematite, perovskite, gibbsite, cancrinite, quartz, calcite, etc. Furthermore, there were also some minerals which did not show their characteristic peaks. Some minerals were difficult to distinguish because of the little content and the overlapping spectral lines of the characteristic peaks. In a word, the minerals in RM were rich, and the occurrence state of metals was also very complex, which was not in the form of a single mineral, but a

variety of minerals coexist. The iron and aluminum mainly existed in the form of hematite (Fe_2O_3), and gibbsite ($\text{Al}(\text{OH})_3$), respectively. However, the titanium mainly existed in perovskite (CaTiO_3) and brookite (TiO_2). Cancrinite ($\text{Na}_6\text{Ca}_2[\text{AlSiO}_4]_6[\text{CO}_3, \text{SO}_4](\text{OH})_2$) was a mineral with many elements including sodium, calcium, aluminum, silicon, etc. The rare earth element of scandium mainly existed in the minerals of hematite and gibbsite (Agrawal and Dhawan, 2021). Fig. 3 (b) that the phase composition of RM has been obviously changed. The diffraction peaks of hematite, perovskite, gibbsite and cancrinite in leaching residue were weakened, which indicates that these minerals could be dissolved into the TWWA. The increase of the diffraction peak of quartz indicates that quartz was formed in the leaching process. And the emergence of a new phase of anhydrite existed in the leaching residue. The lattice of cancrinite was destroyed resulting in the separation of silicon, aluminum, sodium, calcium and other oxides from the minerals. The oxides of sodium and calcium were easy to react with TWWA resulting in the existence of sodium ions in the leaching solution, while the calcium and sulfate in TWWA formed anhydrite and existed in the leaching residue. Furthermore, the titanium in perovskite and the iron in hematite were also leached.

As shown in Fig. 4 (a), the surface morphology of RM could be observed directly by using SEM. The result shows that the red mud was mainly composed of multi-component granular or irregular block structure, which was disorderly distributed. The microstructure was relatively loose and the particles constituted a larger specific surface area of RM. The small particles were the main parts, while the larger particles may be the calcite (CaCO_3), which constituted the framework of RM. Furthermore, it can be seen from the energy spectrum that the composition analysis results of RM are reliable with the result of ICP-AES. However, the scandium was not detected by using EDS due to its low content in the RM. It can be seen from Fig. 4 (b) that the RM particles became smaller and nearly spherical with leaching by TWWA, and the particles were separated from each other. The energy spectrum analysis also shows that the content of silicon in the leaching residue increased, and the sodium was not detected, which indicates that the dealkalization process was more complete. In addition, the content of calcium was not reduced compared with red mud, which once again verifies the existence of anhydrite calcium sulfate in the leaching residue. Therefore, the leaching mechanism of red mud by TWWA may be summarized as follows (see Fig. 5).

The minerals of cancrinite, hematite, perovskite and gibbsite were existed in the red mud, in which the elements of Na, Sc and Al was in the lattice of these minerals. The lattice of these minerals could be destroyed in red mud by acid leaching with TWWA resulting in the dissolution of some elements (Na, Sc, Al, Fe, Ti, V, etc.) into the leaching solution. Quartz was one of the products from lattice destruction of cancrinite in the leaching residue, and anhydrite was produced by the reaction of calcium oxide from cancrinite and sulfuric acid from TWWA.

3.3. Leaching kinetics

In order to further explain the dissolution characteristics of Na, Sc and Al from RM, it is necessary to investigate the leaching kinetics. The leaching process of RM with TWWA is essentially a heterogeneous

liquid-solid reaction. Combined with the analysis of SEM, the unreaction shrinking core model (USCM) can be used to describe and analyze the leaching process. The acid leaching process of RM mainly included the following five processes (Sun et al., 2021).

- (A) The leaching agent moved from TWWA to the surface of RM particles (external diffusion);
- (B) The leaching agent diffused to the reaction interface through the solid product layer (internal diffusion);
- (C) Leaching agent reacted with unreacted RM at the reaction interface (chemical reaction);
- (D) The reaction products diffused from the reaction interface to the boundary layer of solid particles (internal diffusion);
- (E) The reaction products diffused from the surface of solid particles to the leaching solution (external diffusion).

The kinetics characteristic equations of the above different control steps are shown as follows.

$$1-(1-a)^{2/3}=k_1t \quad (2)$$

$$1-(1-a)^{1/3}=k_2t \quad (3)$$

$$1-2a/3-(1-a)^{2/3}=k_3t \quad (4)$$

$$\ln(1-a)/3+(1-a)^{-2/3}-1=k_4t \quad (5)$$

Where a is the leaching efficiency of metals (%); t is the reaction time (min); k_1 , k_2 , k_3 and k_4 is the rate constants of external diffusion control, chemical reaction control, internal diffusion control and mixed control, respectively (min^{-1}).

The dealkalization efficiency, leaching efficiency of Sc and Al from RM are respectively substituted into the kinetics control equations in Formulas (2) - (5) under different reaction temperatures. The results are shown in Fig. 6, Fig. 7 and Fig. 8, respectively.

It can be seen from Fig. 6 that among the four kinetic models, the fitting degree with external diffusion and chemical reaction control was greater than 0.98. It can be seen from Fig. 7 that the fitting degree of Sc leaching process with internal diffusion and joint control was greater than 0.99. Fig. 8 shows that the fitting degree of Al leaching process in red mud with internal diffusion and joint control was greater than 0.99. In order to further determine the kinetic equation of dissolution reaction of Na, Sc and Al from RM, the kinetic data of the model with high fitting degree at corresponding temperature are listed in Table 2.

Table 2
Kinetic model and parameters on leaching of Na, Sc and Al from red mud

Species	Models	Parameters	Temperature (°C)			
			25	50	75	100
Na	$1-(1-a)^{2/3}$	k_1	0.0114	0.0135	0.0152	0.0171
		R^2	0.9962	0.9990	0.9986	0.9975
	$1-(1-a)^{1/3}$	k_2	0.0070	0.0080	0.0104	0.0134
		R^2	0.9886	0.9874	0.9953	0.9828
Sc	$1-2a/3-(1-a)^{2/3}$	k_3	0.0016	0.0021	0.0024	0.0027
		R^2	0.9990	0.9979	0.9954	0.9918
	$\ln(1-a)/3-(1-a)^{-1/3}-1$	k_4	0.0017	0.0027	0.0032	0.0041
		R^2	0.9916	0.9869	0.9933	0.9939
Al	$1-2a/3-(1-a)^{2/3}$	k_3	0.0003	0.0007	0.0012	0.0022
		R^2	0.9960	0.9991	0.9953	0.9871
	$\ln(1-a)/3-(1-a)^{-1/3}-1$	k_4	0.0002	0.0005	0.0010	0.0028
		R^2	0.9916	0.9905	0.9988	0.9995

According to the kinetic data in Table 2, the leaching process of RM was further analyzed by Arrhenius equation (see equation 6) (Lin et al., 2021).

$$k = A \cdot \exp[-E_a/(RT)] \quad (6)$$

Where k is the rate constant, A is the pre-exponential factor, and E_a is the apparent activation energy of leaching reaction (kJ/mol), and R is the molar gas constant ($J \cdot mol^{-1} \cdot K^{-1}$). The relationship between $\ln k$ and $1/T$ is constructed by taking the logarithm on both sides of Arrhenius equation (see Fig. 9).

According to the leaching kinetics theory, while the apparent activation energy was less than 11 kJ/mol, it was mainly controlled by diffusion steps. While the apparent activation energy was greater than 38 kJ/mol, it was mainly controlled by chemical reaction. The leaching process was jointly controlled by the two steps as the apparent activation energy was 11-38 kJ/mol (Zhou et al., 2020). It can be seen from Fig. 9 (a) that the apparent activation energy of dealkalization with the control of external diffusion was 4.947 kJ/mol, while the apparent activation energy under the control of chemical reaction was 7.781 kJ/mol. Therefore, it is determined that the dealkalization process of RM was controlled by external diffusion, and its kinetic equation is $1-(1-a)^{2/3}=0.084 \cdot \exp[-595.05/T] \cdot t$. Fig. 9 (b) shows that the apparent

activation energy of Sc leaching was 10.479 kJ/mol under the combined control, while it was 6.361 kJ/mol under internal diffusion control. Therefore, it is determined that Sc leaching was controlled by internal diffusion, and its kinetic equation was $1-2a/3-(1-a)^{2/3}=0.021 \cdot \exp[-765.16/T] \cdot t$. It can be seen from Fig. 9 (c) that the apparent activation energy of Al leaching was 24.145 kJ/mol under internal diffusion control, but the apparent activation energy was 31.666 kJ/mol under combined control. Therefore, it is determined that Al leaching was jointly controlled, and the kinetic equation is $\ln(1-a)/3+(1-a)^{-2/3}-1=67.12 \cdot \exp[-3808.8/T] \cdot t$. In addition, the apparent activation energy could also explain the difficulty of chemical reaction. The result of E_a of dealkalization process $< E_a$ of Sc leaching $< E_a$ of Al leaching was obtained according to the results of leaching kinetics analysis. It is indicated that the dealkalization process was easier to carry out than the leaching of Sc and Al, which was consistent with the experimental results of the leaching of Na, Sc and Al from RM with TWWA.

4. Conclusions

TWWA could be used as the leaching agent for dissolution of elements from red mud according to the idea of "treating waste with waste". The leaching behavior of Na, Sc and Al was analyzed from RM with TWWA, in which the alkali mainly existed in the form of structural sodium in cancrinite of red mud. The Al and Sc were dispersed in other mineral compositions of gibbsite and hematite of red mud. The dealkalization efficiency of RM was close to 100%, and the leaching efficiency of Sc and Al is 82% and 75%, respective under the conditions of leaching temperature of 100 °C, liquid to solid ratio of 6 mL/g, stirring speed of 300 r/min and reaction time of 1.0 h. It is important for practical significance on dealkalization of RM and recovery of valuable metals. The mineral composition of RM was obviously changed by leaching with TWWA, in which the destruction of cancrinite crystal lattice containing Na, Al and Ca was the premise of dealkalization and elements dissolution. The particles of RM became smaller after leaching, and the leaching kinetics can be analyzed with USCM. The dealkalization process of RM was controlled by external diffusion and the apparent activation energy was only 4.947 kJ/mol, which indicates that the dissolution of sodium was easy to occur. The kinetic equation of dealkalization was $1-(1-a)^{2/3}=0.084 \cdot \exp[-595.05/T] \cdot t$. The apparent activation energy of Sc leaching was 6.361 kJ/mol, and the kinetic equation was $1-2a/3-(1-a)^{2/3}=0.021 \cdot \exp[-765.16/T] \cdot t$ controlled by internal diffusion. The apparent activation energy of Al leaching was 31.666 kJ/mol, and the kinetic equation was $\ln(1-a)/3+(1-a)^{-2/3}-1=67.12 \cdot \exp[-3808.8/T] \cdot t$ controlled by diffusion and chemical reaction. The different leaching characteristics of Na, Sc and Al from RM were obtained with TWWA, which can provide the experimental basis and theoretical guidance for effective comprehensive utilization of RM and TWWA.

Declarations

Ethical Approval and Consent to Participate: Not applicable

Consent to Publish: Not applicable

Authors Contributions: Xiaobo Zhu: Methodology, Software, Writing; Chen Ma: Data curation, Writing-Original draft preparation; Wang Li: Investigation, Writing-Reviewing and Editing.

Funding: the research is financially supported by the National Natural Science Foundation of China (51904097 and 51804103), the training program for young backbone teachers in Colleges and universities of Henan Province (2019GGJS056), Open Foundation of State Environmental Protection Key Laboratory of Mineral Metallurgical Resources Utilization and Pollution Control (HB202106), Scientific and Technological Project of Henan Province (202102310548), Program for Innovative Research Team in the University of Henan Province (21IRTSTHN006).

Competing Interests: we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and company.

Availability of data and materials: Not applicable

References

1. Abhilash., Hedrich S, Schippers A (2021) Distribution of scandium in red mud and extraction using *Gluconobacter oxydans*. *Hydrometallurgy* 202:105621
2. Agrawal S, Dhawan N (2021) Microwave acid baking of red mud for extraction of titanium and scandium values. *Hydrometallurgy* 204:105704
3. Bao SX, Qin L, Zhang YM, Luo YP, Huang XL (2021) A combined calcination method for activating mixed shale residue and red mud for preparation of geopolymer. *Construction and Building Materials* 297:123789
4. Deng B, Li GH, Luo J, Ye Q, Jiang T (2017) Enrichment of Sc_2O_3 and TiO_2 from bauxite ore residues. *Journal of Hazardous Materials* 331:71–80
5. Feng X, Jiang LY, Song Y (2016) Titanium white sulfuric acid concentration by direct contact membrane distillation. *Chemical Engineering Journal* 285:101–111
6. Feng X, Wu P, Jiang LY (2018) Titanium white waste acid concentration by DCMD: Wetting, crystallization, and fouling. *Desalination* 440:161–174
7. Hu B, Ouyang JT, Jiang LY (2020) Influence of flocculant polyacrylamide on concentration of titanium white waste acid by direct contact membrane distillation. *Chin J Chem Eng* 28:2483–2496
8. Jin JP, Liu X, Yuan S, Gao P, Li YJ, Zhang H, Meng XZ (2021) Innovative utilization of red mud through co-roasting with coal gangue for separation of iron and aluminum minerals. *J Ind Eng Chem* 98:298–307
9. Li JK, Dai J (2014) Research on treatment and utilization of “Three Wastes” of titanium dioxide production by sulfuric acid process. *Environmental Science* 33:63–66
10. Li SC, Zhang J, Li ZF, Liu C, Chen JP (2021) Feasibility study on grouting material prepared from red mud and metallurgical wastewater based on synergistic theory. *Journal of Hazardous Materials*

11. Li SW, Pan J, Zhu DQ, Guo ZQ, Shi Y, Dong T, Lu SH, Tian HY (2021) A new route for separation and recovery of Fe, Al and Ti from red mud. *Resources, Conservation and Recycling*. 168, 105314
12. Li W, Yan XD, Niu ZP, Zhu XB (2021) Selective recovery of vanadium from red mud by leaching with using oxalic acid and sodium sulfite. *Journal of Environmental Chemical Engineering* 9:105669
13. Lin LQ, Lu ZM, Zhang W (2021) Recovery of lithium and cobalt from Lithium-Ion batteries using organic aqua regia (OAR): Assessment of leaching kinetics and global warming potentials. *Resources, Conservation and Recycling*. 167, 105416
14. Liu YJ, Naidu R (2014) Hidden values in bauxite residue (red mud): Recovery of metals. *Waste Manag* 34:2662–2673
15. Lyu F, Niu SL, Wang L, Liu RQ, Sun W, He DD (2021) Efficient removal of Pb(II) ions from aqueous solution by modified red mud. *Journal of Hazardous Materials* 406:124678
16. Pasechnik LA, Skachkov VM, Chufarov AY, Suntsov AY, Yatsenko SP (2021) High purity scandium extraction from red mud by novel simple technology. *Hydrometallurgy* 202:105597
17. Smičiklas I, Smiljanič S, Perič-Grujič A, Šljivič-Ivanovič M, Antonovič D (2013) The influence of citrate anion on Ni(II) removal by raw red mud from aluminum industry. *Chemical Engineering Journal* 214:327–335
18. Song YW, Wang HR (2019) Using polyvinyl alcohol to improve the deacidification performance of titanium white waste acid: Pilot tests. *Waste Manag* 87:13–20
19. Song YW, Wang HE, Wang R, Zhou JC (2021) Novel approach for high-efficiency recovery of titanium dioxide, hydrochloric acid, and organic solvents from titanium white waste acid. *J Clean Prod* 315:128105
20. Sun BB, Liu J, Zhang YQ, Leungb KMY, Zeng EY (2021) Leaching of polybrominated diphenyl ethers from microplastics in fish oil: Kinetics and bioaccumulation. *Journal of Hazardous Materials* 406:124726
21. Wang F, Xu J, Yin HL, Zhang YH, Pan H, Wang L (2021) Sustainable stabilization/solidification of the Pb, Zn, and Cd contaminated soil by red mud-derived binders. *Environmental Pollution* 284:117178
22. Wang SH, Jin HX, Deng Y, Xiao YD (2021) Comprehensive utilization status of red mud in China: A critical review. *Journal of Cleaner Production* 289:125136
23. Wu WY, Chen Z, Huang Y, Li JW, Chen DY, Chen N, Su MH (2021) Red mud for the efficient adsorption of U(VI) from aqueous solution: Influence of calcination on performance and mechanism. *Journal of Hazardous Materials* 409:124925
24. Xu YP, Chen CY, Lan YP, Wang LZ, Li JQ (2020) Desilication and recycling of alkali-silicate solution seeded with red mud for low-grade bauxite utilization. *Journal of Materials Research and Technology* 9:7418–7426
25. Xu ZM, Lu ZY, Zhang LS, Fan HY, Wang YF, Li JW, Lin YL, Liu H, Guo SH, Xu MY, Wang JF (2021) Red mud based passivator reduced Cd accumulation in edible amaranth by influencing root organic

- matter metabolism and soil aggregate distribution. *Environmental Pollution* 275:116543
26. Zhang J, Li SC, Li ZF, Liu C, Gao YF, Qi YH (2020) Properties of red mud blended with magnesium phosphate cement paste: Feasibility of grouting material preparation. *Construction and Building Materials* 260:119704
 27. Zhang WG, Zhang TG, Li TT, Lv GZ, Cao XJ (2021) Basic research on the leaching behavior of vanadium-bearing steel slag with titanium white waste acid. *Journal of Environmental Chemical Engineering* 9:104897
 28. Zhang YW, Qian WM, Zhou PX, Liu Y, Lei XL, Li B, Ning P (2021) Research on red mud-limestone modified desulfurization mechanism and engineering application. *Sep Purif Technol* 272:118867
 29. Zhou J, Yu Q, Huang J, Meng JJ, Chen YD, Ning SY, Wang XP, Wei YZ, Yin XB, Liang J (2020) Recovery of scandium from white waste acid generated from the titanium sulphate process using solvent extraction with TRPO. *Hydrometallurgy* 195:105398
 30. Zhou JF, Zhao JH, Yang F, Wang TL, Du F, Qin YH, Ma JY, Wu ZK, Wang CW (2020) Leaching kinetics of potassium and aluminum from phosphorus-potassium associated ore in HCl-CaF₂ system. *Sep Purif Technol* 253:117528
 31. Zhu XB, Li W, Guan XM (2015) An active dealkalization of red mud with roasting and water leaching. *Journal of Hazardous Materials* 286:85–91

Figures

Figure 1

Infrared spectrum of red mud.

Figure 2

Effect of leaching parameters on the dissolution of Na, Sc and Al from the red mud.

Figure 3

XRD pattern of red mud and leaching residue.

Figure 4

SEM-EDS of red mud and leaching residue.

Figure 5

Schematic diagram on leaching process of red mud with TWWA.

Figure 6

Fitting results of dealkalization kinetic model.

Figure 7

Simulation results of Sc leaching kinetic model.

Figure 8

Simulation results of Al leaching kinetic model.

Figure 9

Apparent activation energy characteristic curve of Na, Sc and Al leaching from red mud.