

Article

Green Separation of Scandium and Titanium Using Citric Acid via Organic Complexation Scrubbing

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Abstract

Aiming at the bottleneck of the difficult scrubbing and separation of scandium and titanium in the solvent extraction process for scandium recovery, a novel strategy for scandium–titanium separation via citrate complex scrubbing is proposed based on the difference in complexation properties between scandium/titanium and hydroxycarboxylic acids. The mixed $\text{Na}_3\text{Cit} + \text{H}_2\text{O}_2$ system was screened as the optimal scrubbing agent. The effects of key parameters including dosages of Na_3Cit and H_2O_2 and phase ratio (O/A) on scrubbing performance were systematically investigated. The optimal process conditions were determined as follows: temperature of 25 °C, molar ratio $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, molar ratio $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, phase ratio (O/A) of 1:1, shaking speed of 200 r/min, and scrubbing time of 30 min. Under the optimal conditions, the titanium scrubbing efficiency reaches 97.37% with zero co-scrubbing efficiency of scandium. The separation efficiency is 14.47 times higher than that of the conventional $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$ scrubbing system, which significantly enhances the scandium–titanium separation performance. This work provides a feasible technical route for the deep separation and purification of scandium and titanium from titanium white waste acid.

Keywords: titanium white waste acid; citrate; scandium; titanium; complexation scrubbing

1. Introduction

Although scandium lacks 4f electrons and its chemical properties differ markedly from typical rare earth elements, it is conventionally grouped with yttrium and the lanthanides as a rare earth element due to its metallogenic association and partial physicochemical similarities [1]. Scandium has scattered global reserves and extremely difficult mining and refining processes. Its annual global production totals only several to tens of tons, and resource scarcity forms the core bottleneck restricting its large-scale development and extensive industrial application. Although the high market price of scandium limits its large-scale application to some extent [2], its core properties—excellent high-temperature resistance, high radiation resistance, and high-temperature insulation [3,4]—have enabled its widespread use in fields such as aerospace and high-end electronics [5–7]. Owing to its excellent physicochemical properties, it has irreplaceable applications in high-tech fields such as Al–Sc alloys, solid oxide fuel cells, high-intensity lighting materials, and



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laser materials [8–11]. Given the strategic value of scandium, several countries, including China, have classified it as a critical strategic metal affecting national security and economic development [12].

The sources of industrial scandium in China are mainly divided into two categories: primary mineral resources, such as bauxite and vanadium–titanium magnetite; and secondary resources, including red mud, tungsten residue, chlorination dust from titanium slag, and acidic hydrolysis waste liquid generated from the sulfate process titanium dioxide production (i.e., titanium white waste acid). Among these, titanium white waste acid is currently the most critical secondary resource for scandium extraction in China. Titanium white waste acid is a strong acidic, multi-component, highly impure system containing scandium, with distinct solution chemistry characteristics: the sulfuric acid concentration is as high as $200\text{--}300\text{ g}\cdot\text{L}^{-1}$, the scandium content is only $10\text{--}20\text{ mg}\cdot\text{L}^{-1}$, and it also contains large amounts of iron and titanium ions as well as small amounts of vanadium, manganese, and other impurities [13–15].

Scandium recovery from titanium white waste acid represents the most widely applied and technically mature route for scandium production in China, among which solvent extraction serves as one of the dominant industrial technologies. Taking advantage of the large reserves and high acidity of titanium white waste acid, innovative synergistic scandium enrichment strategies leaching red mud with titanium white waste acid have been developed in previous studies [16–18]. At present, the mainstream techniques for scandium recovery from titanium white waste acid mainly include solvent extraction, solid-phase adsorption, liquid membrane separation, and chemical precipitation. Benefiting from the prominent advantages of large processing capacity, simple operation, low cost, and excellent separation efficiency, solvent extraction has been widely utilized for the purification and separation of rare earth and rare metals on an industrial scale [19–21]. Although the overall solvent extraction process has been well-established, the similar physicochemical properties of scandium and titanium easily lead to co-extraction behavior during the extraction procedure. A large amount of titanium impurities is co-extracted into the organic phase together with scandium, which severely restricts the purification of scandium products. Therefore, achieving efficient separation of scandium and titanium from the loaded organic phase is the core bottleneck limiting the high-purity recovery of scandium. Focusing on this technical challenge, this study conducts in-depth research on the efficient scrubbing and separation of scandium and titanium after solvent extraction.

To address the problem of competing adsorption of scandium and titanium, researchers have conducted a large number of targeted studies. However, the existing technical solutions all have certain drawbacks to varying degrees. Traditional processes often employ multiple or excessive acid-leaching methods (e.g., using sulfuric acid and/or hydrochloric acid [22]), which suffer from limited scrubbing efficiency, high cost, and significant scandium loss. Although researchers have conducted substantial and effective work [23–29] focusing on improving solvent extraction techniques, the fundamental issue—high similarity in the solution chemistry of scandium and titanium, leading to poor separation selectivity—remains unresolved. Consequently, substantial breakthroughs in efficient Sc/Ti separation are still elusive.

To overcome the technical bottleneck of inefficient deep separation of scandium and titanium in the scandium recovery process from titanium white waste acid, this work proposes a novel strategy of hydroxycarboxylic acid complex scrubbing. This approach amplifies the differences in solution chemical characteristics between scandium and titanium, thereby achieving effective separation of the two metal ions. Among various hydroxycarboxylic acid reagents, citric acid and citrate anions exhibit superior complexing ability toward titanium ions, which have been widely employed for the wet synthesis

of diverse titanium-based functional materials and fine titanium compounds [30–33]. As Ti^{4+} possesses a high charge density and a small ionic radius of 0.68 Å, it presents strong polarization capability. No simple hydrated coordination ions of Ti exist in aqueous solution, and its hydrolysis products are dominated by octahedral mononuclear and polymeric hydroxylated species. As a polyhydroxy polycarboxylic acid, citric acid can coordinate with Ti^{4+} to form a double-bridged structure with Ti–O–C linkages (Figure 1). Given the strong complexation interaction between citrate and titanium ions, citric acid is introduced into the scrubbing process of scandium- and titanium-loaded organic phases in this study. The separation performance of the complex scrubbing technique for scandium and titanium is systematically investigated. In addition to the effective enrichment and purification of scandium, the by-product titanium citrate can be further utilized to fabricate high-value-added titanium-based materials via wet chemical processes.

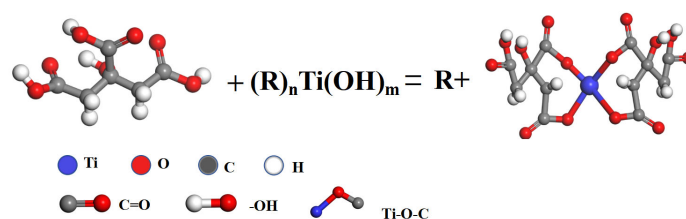


Figure 1. Formation process of titanium–citric complex.

The overall research process mainly includes preliminary screening experiments to investigate the scrubbing efficiencies of titanium and co-scrubbing efficiencies of scandium using two types of scrubbing agents: scrubbing agents prepared with various masking agents alone, and composite scrubbing agents composed of masking agents and hydrogen peroxide. Single-factor scrubbing experiments for titanium were then conducted to systematically explore the effects of sodium citrate dosage, H_2O_2 dosage, organic/aqueous phase ratio (O/A), shaking speed, scrubbing duration, reaction temperature and initial pH of scrubbing solution on the scrubbing rates of Sc(III) and Ti(IV) in the loaded organic phase. Furthermore, a novel scrubbing agent was used to replace the conventional H_2SO_4 – H_2O_2 mixture for titanium scrubbing, and a comparative study between the new and traditional scrubbing methods was carried out.

2. Experimental Section

2.1. Raw Materials and Reagents

The titanium white waste acid used in this experiment was prepared by mixing various metal sulfate solutions in specific proportions, based on the composition of titanium white waste acid from a certain enterprise. Its main components are shown in Table 1. This simulated solution was prepared based on the typical ion concentration range of industrial titanium white waste acid, which can reproduce the actual matrix environment of industrial raw materials and eliminate experimental errors arising from compositional fluctuations of real waste acid. Meanwhile, it further illustrates the necessity of developing the masking agent– H_2O_2 composite stripping system in this study to achieve selective separation of titanium and scandium. Moreover, the initial metal concentrations listed in Table 1 provide baseline data for calculating scandium recovery efficiency and evaluating the resource utilization potential of the entire process. The raw material employed in the present experiment is the loaded organic phase prepared in our previous laboratory research. This organic phase was obtained by extracting titanium dioxide waste acid with the mixed extractant consisting of P204, P507 and TBP at 25 °C. The detailed extraction conditions are specified as follows: the mole fraction of P204 is 0.7, the volume fraction of TBP is 5%, the total concentration of mixed extractants is 1.25 mol/L, the organic-to-aqueous phase ratio

(O/A) equals 1:10, the shaking speed is $150 \text{ r} \cdot \text{min}^{-1}$, and the extraction time lasts for 30 min. The elemental composition of the loaded organic phase is summarized in Table 2.

Table 1. Chemical composition analysis of titanium white waste acid.

Element	Ti	Mn	Mg	Al	Fe	H ₂ SO ₄
Concentration/ $\text{g} \cdot \text{L}^{-1}$	0.98	1.86	5.86	1.21	28.76	208.55

Table 2. Composition of loaded organic phase.

Element	Sc	Ti	Cr	V
Concentration/ $\text{mg} \cdot \text{L}^{-1}$	19.35	227.34	0.65	10.7

The core objective of the scrubbing experiment is to remove impurity components present in the loaded organic phase, thereby achieving the purpose of improving extraction and separation efficiency. The scrubbing solution is prepared, single-factor scrubbing experiments are carried out, and the scrubbing efficiency is calculated to determine the optimal composition and process conditions of the scrubbing solution.

2.2. Experimental Procedures and Measurement Methods

The loaded organic phase recovered from extraction was adopted for subsequent washing tests to remove coexisting impurities and improve the overall separation performance. All washing procedures were implemented in a thermostatted water-bath shaker, and the detailed experimental steps are described as follows:

- (1) A large amount of loaded organic phase was prepared under the optimal conditions obtained from preliminary extraction experiments, and the concentrations of Ti(IV) and Sc(III) in the organic phase were quantified;
- (2) Washing solutions were prepared at predetermined molar ratios of $n(\text{Na}_3\text{Cit})/n(\text{Ti})$ and $n(\text{H}_2\text{O}_2)/n(\text{Ti})$;
- (3) A total of 10 mL of loaded organic phase was transferred into a centrifuge tube, followed by the addition of washing solution at a fixed organic/aqueous (O/A) phase ratio. The centrifuge tube was then placed in a thermostatted water-bath oscillator;
- (4) After sufficient shaking at preset rotating speed for a given time, the mixture was kept stationary to realize phase separation.

Mass concentrations of Ti(IV) and Sc(III) in separated aqueous phases were measured via inductively coupled plasma optical emission spectrometry (ICP-OES) (HKYT-899, Beijing Huake Yitong Analytical Instrument Co., Ltd., Beijing, China). Washing ratios of all experimental groups were calculated and washing systems with high impurity removal efficiency and low co-elution loss of target metals were selected for further research.

Qualitative and quantitative detection of metallic elements is conducted by inductively coupled plasma optical emission spectrometry (ICP-OES). However, the concentration of Sc in the scrubbing solution is extremely low in this work. If its concentration falls below the instrumental limit of detection ppb, the Sc scrubbing efficiency cannot be accurately quantified under such conditions. Plasma acts as the excitation source in this technique, and multi-element quantification is realized by identifying characteristic radiation emitted by excited elemental atoms and ions and measuring corresponding spectral line intensities. An HKYT-899 instrument from Beijing Huake Yitong Analytical Instrument Co., Ltd. (Beijing, China) is applied to test metal ion concentrations of diluted aqueous samples. Fourier-transform infrared spectroscopy (FT-IR) is adopted to characterize chemical bonds and functional groups in organic phases. Structural variations are analyzed by comparing spectra of organic phases before extraction and after washing, with a Nicolet

iN10 spectrometer manufactured by Thermo Fisher Scientific, Waltham, MA, USA utilized for measurement.

2.3. Corresponding Calculation Formula

The scrubbing efficiency (denoted as S_Z^* , where Z represents the extracted species) is used to quantify the proportion of the target extracted species Z that is transferred from the loaded organic phase to the scrubbing aqueous phase during the impurity removal step of the extraction experiment. It is defined as the percentage of this transferred amount relative to the total amount of the extracted species originally contained in the loaded organic phase.

$$S_Z^* = \frac{C_a V_a}{(C_i V_i - C_j V_j)} \times 100\% \quad (1)$$

where S_Z^* —scrubbing efficiency of the extracted species Z, %; C_a —mass concentration of the extracted species Z in the loaded scrubbing solution phase, $\text{g}\cdot\text{L}^{-1}$; V_a —volume of the loaded scrubbing solution, L; C_i —mass concentration of the valuable metal element in the feed solution, $\text{mg}\cdot\text{L}^{-1}$; C_j —mass concentration of the valuable metal element in the raffinate, $\text{mg}\cdot\text{L}^{-1}$; V_i —volume of the feed solution, L; and V_j —volume of the raffinate, L.

2.4. Thermodynamic Calculation and Graphical Construction

2.4.1. Potential–pH Diagram

Detailed procedures for constructing the potential–pH diagram of the Sc–H₂O system are described below. First, analyze the dissolved species present in the Sc–H₂O system—specifically including Sc^{3+} , $\text{Sc}(\text{OH})_2^+$, ScOH^{2+} , ScOH^{3+} , $\text{Sc}(\text{OH})_4^-$, $\text{Sc}_2(\text{OH})_2^{4+}$, $\text{Sc}_3(\text{OH})_4^{5+}$, $\text{Sc}_3(\text{OH})_5^{4+}$ —as well as the solid components, including Sc, Sc_2O_3 , and $\text{Sc}(\text{OH})_3$. Next, retrieve the thermodynamic data corresponding to each species in the Sc–H₂O system potential–pH diagram, and accordingly derive the relevant equilibrium relationships. Finally, plot and analyze the diagram based on the relationship between E and pH to determine the dominant regions of each component.

Table 3 lists the chemical reactions in the Sc–H₂O system at 25 °C for the Sc–H₂O system potential–pH diagram. The expressions for the potential or pH values of each reaction can be calculated.

Table 3. Standard Gibbs energy changes in equilibrium reactions for the Sc–H₂O system at 25 °C [34].

No.	Reaction Equation	$\Delta G_T^0/\text{kJ}\cdot\text{mol}^{-1}$
1	$\text{Sc}^{3+} + 3\text{e} = \text{Sc}$	586.2
2	$\text{Sc}_2\text{O}_3 + 6\text{H}^+ + 6\text{e} = 2\text{Sc} + 3\text{H}_2\text{O}$	1107.63
3	$\text{Sc}_2\text{O}_3 + 6\text{H}^+ = 2\text{Sc}^{3+} + 3\text{H}_2\text{O}$	−64.77
4	$\text{Sc}_2\text{O}_3 + 4\text{H}^+ = 2\text{ScOH}^{2+} + \text{H}_2\text{O}$	−15.99
5	$\text{Sc}_2\text{O}_3 + 4\text{H}^+ = \text{Sc}_2(\text{OH})_2^{4+} + \text{H}_2\text{O}$	−67.74
6	$\text{Sc}_2\text{O}_3 + \text{H}_2\text{O} + 2\text{H}^+ = 2\text{Sc}(\text{OH})_2^+$	−34.352
7	$\text{ScOH}^{2+} + \text{H}^+ = \text{Sc}^{3+} + \text{H}_2\text{O}$	−24.39
8	$\text{ScOH}^{2+} + \text{H}^+ + 3\text{e} = \text{Sc} + \text{H}_2\text{O}$	561.81
9	$\text{Sc}_2(\text{OH})_2^{4+} + 2\text{H}^+ = 2\text{Sc}^{3+} + 2\text{H}_2\text{O}$	2.97
10	$\text{Sc}(\text{OH})_2^+ + 2\text{H}^+ + 3\text{e} = \text{Sc} + 2\text{H}_2\text{O}$	531.02
11	$2\text{Sc}(\text{OH})_2^+ + 2\text{H}^+ = \text{Sc}_2(\text{OH})_2^{4+} + 2\text{H}_2\text{O}$	−113.33
12	$\text{Sc}(\text{OH})_4^- + 2\text{H}^+ = \text{Sc}(\text{OH})_2^+ + 2\text{H}_2\text{O}$	−99.08
13	$2\text{Sc}(\text{OH})_4^- + 2\text{H}^+ = \text{Sc}_2\text{O}_3 + 5\text{H}_2\text{O}$	−243.75
14	$\text{Sc}(\text{OH})_4^- + 4\text{H}^+ + 3\text{e} = \text{Sc} + 4\text{H}_2\text{O}$	431.94
15	$\text{Sc}_2(\text{OH})_2^{4+} + 2\text{H}^+ + 6\text{e} = 2\text{Sc} + 2\text{H}_2\text{O}$	1175.37

The process of constructing the potential–pH diagram for the Ti–H₂O system is relatively complex. After reviewing the relevant literature, twelve chemical species have been considered. Analysis shows that the dissolved species include Ti^{2+} , Ti^{3+} , TiO^{2+} , TiO_2^{2+} , and

HTiO_3^- , while the solid species include Ti, TiO, Ti_2O_3 , $\text{Ti}(\text{OH})_3$, Ti_3O_5 , TiO_2 , and $\text{TiO}_2 \cdot \text{H}_2\text{O}$. Table 4 lists the equilibrium reactions and their Gibbs free energies for the Ti- H_2O system at 25 °C.

Table 4. Standard Gibbs energy changes in equilibrium reactions for the Ti- H_2O system at 25 °C [35].

No.	Reaction Equation	$\Delta G_T^0/\text{kJ} \cdot \text{mol}^{-1}$
1	$\text{Ti}^{2+} + 2\text{e} = \text{Ti}$	314
2	$\text{Ti}^{3+} + \text{e} = \text{Ti}^{2+}$	35.78
3	$\text{TiO} + 2\text{H}^+ = \text{Ti}^{2+} + \text{H}_2\text{O}$	−61.99
4	$\text{TiO} + 2\text{H}^+ + 2\text{e} = \text{Ti} + \text{H}_2\text{O}$	252.01
5	$\text{TiO}^{2+} + 2\text{H}^+ + \text{e} = \text{Ti}^{3+} + \text{H}_2\text{O}$	−9.58
6	$\text{TiO}^{2+} + 2\text{H}^+ + \text{e} = \text{Ti}^{2+} + \text{H}_2\text{O}$	26.2
7	$\text{TiO}_2 + 4\text{H}^+ + 2\text{e} = \text{Ti}^{2+} + 2\text{H}_2\text{O}$	100.02
8	$\text{TiO}_2 + 4\text{H}^+ + \text{e} = \text{Ti}^{3+} + 2\text{H}_2\text{O}$	64.24
9	$2\text{TiO}_2 + 2\text{H}^+ + \text{e} = \text{Ti}_2\text{O}_3 + \text{H}_2\text{O}$	107.41
10	$\text{Ti}_2\text{O}_3 + 2\text{H}^+ + 2\text{e} = 2\text{TiO} + \text{H}_2\text{O}$	216.61
11	$\text{Ti}_2\text{O}_3 + 6\text{H}^+ + 2\text{e} = 2\text{Ti}^{2+} + 3\text{H}_2\text{O}$	92.63
12	$\text{HTiO}_3^- + \text{H}^+ = \text{TiO}_2 + \text{H}_2\text{O}$	−169.69
13	$\text{HTiO}_3^- + 3\text{H}^+ = \text{TiO}^{2+} + 2\text{H}_2\text{O}$	−95.87
14	$\text{HTiO}_3^- + 5\text{H}^+ + 2\text{e} = \text{Ti}^{2+} + 3\text{H}_2\text{O}$	−69.67
a	$\text{O}_2 + 4\text{H}^+ + 4\text{e} = 2\text{H}_2\text{O}$	−474.38
b	$2\text{H}^+ + 2\text{e} = \text{H}_2$	0

2.4.2. Mole Fraction–pH Diagram

Based on the differences in the thermodynamic data of the Sc- H_2O and Ti- H_2O systems for the two metal elements (scandium and titanium) within the selected pH range, a solution thermodynamics study was conducted. The equilibrium constants and calculation formulas for each reaction ultimately determined are shown in Table 5. In addition, ion concentrations are used instead of activities in the calculations.

Table 5. Equilibrium constants and calculated equations for reactions involved (T = 25 °C).

Reaction Equation	LogK	Equation
$\text{Sc}^{3+} + 3\text{OH}^- = \text{Sc}(\text{OH})_3$	$K_{\text{sp}} = 2.2 \times 10^{-31}$	$[\text{Sc}(\text{OH})_3] = [\text{Sc}^{3+}][\text{OH}^-]^3$
$\text{Sc}^{3+} + \text{OH}^- = \text{ScOH}^{2+}$	8.9	$[\text{ScOH}^{2+}] = 10^{8.9}[\text{Sc}^{3+}][\text{OH}^-]$
$\text{Ti}^{4+} + 3\text{OH}^- = \text{Ti}(\text{OH})_3^+$	51.34	$[\text{Ti}(\text{OH})_3^+] = 10^{51.34}[\text{Ti}^{4+}][\text{OH}^-]^3$

In solution, square brackets ‘[]’ are used to denote the concentration of free ionic species (uncomplexed ions). Let $[\text{Sc}]_T$ and $[\text{Ti}]_T$ represent the total concentrations of free scandium and free titanium species in the solution, respectively. Based on the principles of equilibrium and mass conservation, the following equations can be derived:

In the Sc- H_2O system

$$[\text{Sc}]_T = [\text{Sc}^{3+}] + [\text{Sc}(\text{OH})_2^+] + [\text{ScOH}^{2+}] + 2 \times [\text{Sc}_2(\text{OH})_2^{4+}] + [\text{Sc}(\text{OH})_4^-] + [\text{Sc}(\text{OH})_{3(\text{aq})}] \quad (2)$$

In the Ti- H_2O system

$$[\text{Ti}]_T = [\text{Ti}(\text{OH})_4] + [\text{Ti}(\text{OH})_3^+] + [\text{Ti}(\text{OH})_5^-] \quad (3)$$

3. Results and Discussion

3.1. Speciation of Scandium and Titanium in Waste Acid from Titanium Dioxide Production

Because titanium white waste acid is a strongly acidic, multi-component, highly impure solution containing both Sc^{3+} and Ti^{4+} , and due to their extremely similar chemical

properties, titanium is typically co-extracted during the solvent extraction process for scandium. Therefore, the separation of scandium and titanium is a difficult and critical step in scandium extraction. Thermodynamic equilibrium studies to understand the relevant solution chemistry provide a theoretical basis for the extraction and separation of scandium and titanium from titanium white waste acid. However, comparable quantitative stability constant data for Sc-citrate species under multi-metal coexistence conditions of titanium white waste acid are still lacking. Most available Sc-citrate equilibrium parameters were acquired in simple single-scandium solution without competing metal ions, which cannot reproduce the actual competitive complexation environment in this work. Therefore, the selective separation mechanism of Ti and Sc is mainly interpreted based on the evident difference in stripping performance observed in batch experiments. Further potentiometric titration experiments will be carried out in follow-up research to determine the matrix-adapted stability constants of Sc-citrate complexes for quantitative mechanistic verification.

3.1.1. Potential-pH Diagram at 25 °C

As shown in Figure 2a, at 25 °C, Sc_2O_3 is the only confirmed stable oxide in the Sc- H_2O system. It has a face-centered cubic lattice structure and is the main stable form of scandium in the water stability region. At $\text{pH} < 3$, scandium exists as soluble $\text{Sc}^{3+}(\text{aq})$; at $\text{pH} > 3$, scandium undergoes hydrolytic precipitation to form insoluble species, mainly as Sc_2O_3 .

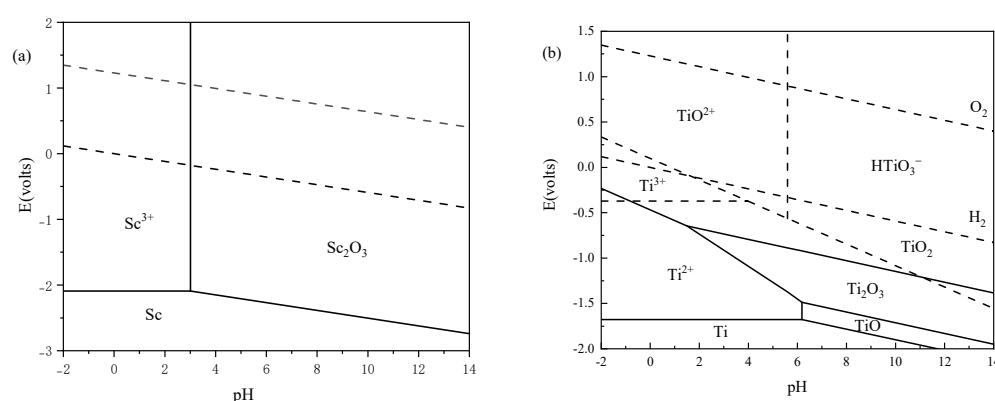


Figure 2. (a) Electric potential-pH diagram of Sc- H_2O system at 25 °C ($c(\text{Sc}) = 4.45 \times 10^{-4} \text{ M}$) (b) Electric potential-pH diagram of Ti- H_2O system at 25 °C ($c(\text{Ti}) = 0.02 \text{ M}$).

In Figure 2b, reactions of soluble titanium oxides are indicated by solid lines, while reactions of soluble titanium ions are indicated by dashed lines. At $\text{pH} < 6$, titanium exists as TiO^{2+} , Ti^{3+} , Ti^{2+} ions and solid Ti; at $\text{pH} > 6$, insoluble species such as TiO_2 and HTiO_3^- ions predominate.

3.1.2. Mole Fraction-pH Diagram of Elements at 25 °C

Figure 3a shows that in scandium solutions, the main species present are Sc^{3+} , $\text{Sc}(\text{OH})_2^+$, ScOH^{2+} , $\text{Sc}(\text{OH})_4^-$, $\text{Sc}(\text{OH})_3(\text{aq})$, and a small amount of $\text{Sc}_2(\text{OH})_2^{4+}$. At $\text{pH} = -2 \sim -1$, scandium exists entirely as Sc^{3+} . As the $\text{pH} > -1$, the mole fraction of Sc^{3+} decreases and gradually transforms into other hydroxo complexes. In the pH range of 2~2.5, Sc^{3+} is still dominant, with a small amount of ScOH^{2+} . At $\text{pH} > 2.5$, $\text{Sc}(\text{OH})_2^+$ and $\text{Sc}_2(\text{OH})_2^{4+}$ appear; at $\text{pH} > 5$, $\text{Sc}(\text{OH})_3(\text{aq})$ appears. At $\text{pH} = 6.5$, the mole fraction of $\text{Sc}(\text{OH})_2^+$ reaches 90.54%. As the pH increases above 8, $\text{Sc}(\text{OH})_4^-$ gradually forms, and at $\text{pH} > 9$, $\text{Sc}(\text{OH})_4^-$ becomes the dominant species.

Figure 3b shows that the Ti(IV) solution mainly contains $\text{Ti}(\text{OH})_4$, $\text{Ti}(\text{OH})_3^+$, and $\text{Ti}(\text{OH})_5^-$, which transform sequentially as the pH increases. In the pH range of -2 to 4, $\text{Ti}(\text{OH})_3^+$ and $\text{Ti}(\text{OH})_4$ dominate, with their mole fractions equal at about pH 2. When

pH > 4, $\text{Ti}(\text{OH})_3^+$ gradually disappears, and the mole fraction of $\text{Ti}(\text{OH})_4$ remains stable up to pH 10. When pH > 10, $\text{Ti}(\text{OH})_4$ converts to $\text{Ti}(\text{OH})_5^-$; their mole fractions are equal at about pH 12. When pH > 12, $\text{Ti}(\text{OH})_5^-$ becomes dominant.

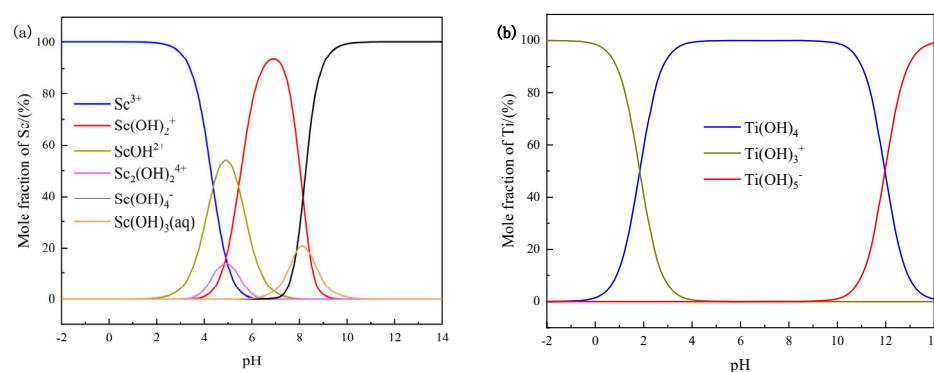


Figure 3. (a) The relationship between ion mole fraction and pH in Sc- H_2O system ($c(\text{Sc}) = 4.45 \times 10^{-4} \text{ M}$) (b) The relationship between ion mole fraction and pH in Ti- H_2O system. ($c(\text{Ti}) = 0.02 \text{ M}$) (The potential–pH diagram is entirely constructed via theoretical thermodynamic calculation rather than experimental measurement).

Therefore, the potential–pH diagrams of the Sc- H_2O and Ti- H_2O systems at 25°C indicate that scandium and titanium primarily exist in the forms of Sc(III) and Ti(IV) in titanium white waste acid. According to the thermodynamic equilibrium diagrams of Sc- H_2O , Ti- H_2O , and Sc-Ti- H_2O systems, scandium and titanium stably present as Sc(III) and Ti(IV) species within the studied system.

3.2. Preliminary Screening of Scrubbing Agents

A scrubbing solution refers to the solution added in the scrubbing stage during extraction to remove impurities or split elements from the loaded organic phase [36]. Citric acid ($\text{C}_6\text{H}_8\text{O}_7$), tartaric acid ($\text{C}_4\text{H}_6\text{O}_6$), sodium tartrate ($\text{C}_4\text{H}_4\text{Na}_2\text{O}_6$), disodium ethylenediaminetetraacetate (EDTA-2Na), lactic acid ($\text{C}_3\text{H}_6\text{O}_3$), and trisodium citrate (Na_3Cit) can complex with titanium and are commonly used as masking agents for titanium in analytical chemistry [37]. Significant differences in the molecular structures and functional groups of these carboxylic acids lead to distinct complexation abilities toward Ti^{4+} , which directly affects the titanium scrubbing efficiency and Sc-Ti separation selectivity. Compared with linear short-chain carboxylic acids such as tartaric acid and lactic acid, citrate possesses abundant hydroxyl and carboxyl functional groups, which can construct stable chelating structures with high-valent titanium ions and thus exhibits stronger and more selective complexation toward Ti. The scrubbing capacity of different scrubbing agents toward the loaded organic phase was studied, and the relevant results are presented in Figure 4. All experiments were conducted under identical conditions: reaction temperature of 25°C , molar ratio of masking agent to Ti $n(\text{masking agent})/n(\text{Ti}) = 2:1$, molar ratio of H_2O_2 to Ti $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 5:1$, phase ratio (O/A) = 1:1, shaking speed of $150 \text{ r}\cdot\text{min}^{-1}$, and scrubbing time of 30 min. The results indicate that the $\text{Na}_3\text{Cit} + \text{H}_2\text{O}_2$ composite system achieves the optimal titanium scrubbing capacity of $6.68 \text{ mg}\cdot\text{L}^{-1}$ among all tested reagents, which further confirms that citrate exhibits superior Ti-selective complexation and scrubbing performance relative to other carboxylic acids. In this paper, $n(\text{masking agent})/n(\text{Ti})$ and $n(\text{H}_2\text{O}_2)/n(\text{Ti})$ represent the molar ratio of masking agent or H_2O_2 in the aqueous phase to titanium in the organic phase. Accordingly, the $\text{Na}_3\text{Cit} + \text{H}_2\text{O}_2$ system is selected as the optimal scrubbing medium for subsequent Sc-Ti separation investigations. During the scrubbing process, citrate acts as a masking agent, and the citrate ions (Cit^{3-}) achieve selective scrubbing by exploiting the significant difference in complexation stability

between Ti(IV) and Sc(III) with citrate. H_2O_2 plays an auxiliary role in enhancing the scrubbing process. Studies have shown that in the presence of H_2O_2 , Ti(IV) can form stable peroxo-citrate–titanium complexes with citrate and peroxide, which promotes the transfer of Ti from the organic phase to the aqueous phase. The synergistic effect of citrate and H_2O_2 is the key to achieving efficient and selective scrubbing of Ti.

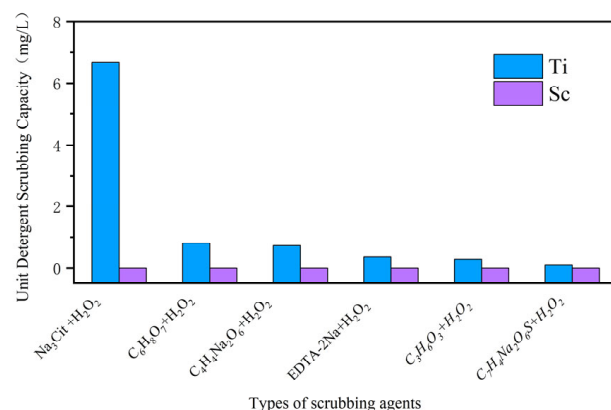


Figure 4. Scrubbing amount of loaded organic phase by different scrubbing agents.

3.3. Effects of Single Factors on Sc(III) and Ti(IV) Scrubbing Efficiency

Thermodynamic analysis verifies that scandium and titanium are the major metal species enriched in the loaded organic phase, providing a reliable theoretical foundation for the subsequent scrubbing and separation of Sc(III) and Ti(IV). Based on the above thermodynamic results, single-factor experiments for titanium scrubbing optimization were further conducted. The influences of key process parameters—including Na_3Cit dosage, H_2O_2 dosage, phase ratio (O/A), shaking speed, scrubbing time, reaction temperature, and initial pH of the scrubbing solution—on the scrubbing efficiencies of Sc(III) and Ti(IV) were systematically investigated. Throughout this paper, the phase ratio is understood as the volume-to-volume basis of the ratio of the organic phase volume to the aqueous phase volume.

Limited by the existing testing equipment, scandium in the samples cannot be detected owing to its concentration below the instrument detection limit. Hence, the separation selectivity of the system is indirectly characterized using the scrubbing efficiencies of titanium and scandium.

3.3.1. Effect of Na_3Cit Dosage on Sc and Ti Scrubbing Efficiency

Under the conditions of $25\text{ }^\circ\text{C}$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, $\text{O}/\text{A} = 1:1$, shaking speed of $200\text{ r}\cdot\text{min}^{-1}$ and scrubbing time of 30 min, the effect of Na_3Cit dosage on the titanium scrubbing efficiency and scandium co-scrubbing efficiency was investigated. As shown in Figure 5, the titanium scrubbing efficiency increased with the rise in $n(\text{Na}_3\text{Cit})/n(\text{Ti})$, while the scandium co-scrubbing efficiency remained at 0% all the time. When the molar ratio increased from 10 to 20, the titanium scrubbing efficiency rose rapidly from 3.15% to 77.10%, this phenomenon is mainly attributed to the fact that the increased sodium citrate concentration shifts the complexation equilibrium toward the formation of stable titanium–citrate complexes, thereby enhancing the driving force for the transfer of Ti(IV) from the organic phase to the aqueous phase. This is consistent with the proposed separation mechanism, which relies on the selective complexation of Ti(IV) by citrate. A further increase to 30 led to a slower growth of the scrubbing efficiency, and no obvious change was observed when the ratio exceeded 30. Considering the scrubbing performance and economic cost comprehensively, the optimal molar ratio of $n(\text{Na}_3\text{Cit})/n(\text{Ti})$ was determined to be 30:1.

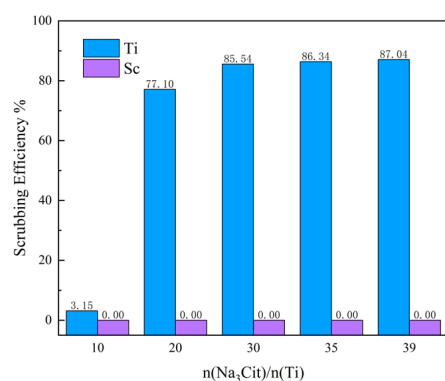


Figure 5. Effect of Na_3Cit dosage on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

3.3.2. Effect of H_2O_2 Dosage on Sc and Ti Scrubbing Efficiency

Under the conditions of $25\text{ }^\circ\text{C}$, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, phase ratio $\text{O}/\text{A} = 1:1$, shaking speed of $200\text{ r}\cdot\text{min}^{-1}$ and shaking time of 30 min, the effect of H_2O_2 dosage on the scrubbing efficiencies of titanium and scandium was investigated, and the results are shown in Figure 6. The results indicate that the scandium co-scrubbing efficiency was almost unaffected by H_2O_2 dosage, whereas the titanium scrubbing efficiency varied significantly. When $n(\text{H}_2\text{O}_2)/n(\text{Ti})$ increased from 1 to 3, the titanium scrubbing efficiency rose remarkably and reached a maximum value of 87.23% at $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$. This phenomenon is ascribed to the further reaction of TiO^{2+} with excess H_2O_2 , which leads to the generation of the peroxo-titanium species $[\text{TiO}(\text{H}_2\text{O}_2)]^{2+}$. As the molar ratio further increased to 7, the titanium scrubbing efficiency decreased slightly to 81.96%, and then rebounded moderately to 85.44% when the ratio exceeded 7. Meanwhile, the co-scrubbing efficiency of scandium remained at 0% throughout the whole process. Considering the scrubbing performance and economic cost comprehensively, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$ was selected as the optimal condition.

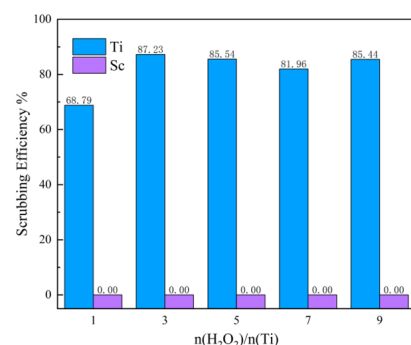


Figure 6. Effect of H_2O_2 dosage on scrubbing efficiency of Ti and the co-scrubbing efficiency of Sc.

3.3.3. Effect of Phase Ratio (O/A) on Sc and Ti Scrubbing Efficiency

Under the conditions of $25\text{ }^\circ\text{C}$, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, shaking speed of $200\text{ r}\cdot\text{min}^{-1}$ and shaking time of 30 min, the influence of phase ratio (O/A) on the scrubbing efficiencies of titanium and scandium was investigated (Figure 7). When the phase ratio decreased from 5:4 to 1:1, the titanium scrubbing efficiency increased rapidly from 63.58% to a maximum of 87.23%, which was probably attributed to the relative insufficiency of the scrubbing agent at a higher phase ratio. As the phase ratio further decreased to 2:5, the titanium scrubbing efficiency dropped to 77.66%, while the co-scrubbing efficiency of scandium remained at 0% throughout the experiment. Considering the scrubbing efficiency and reagent consumption comprehensively, the optimal phase ratio was determined to be 1:1.

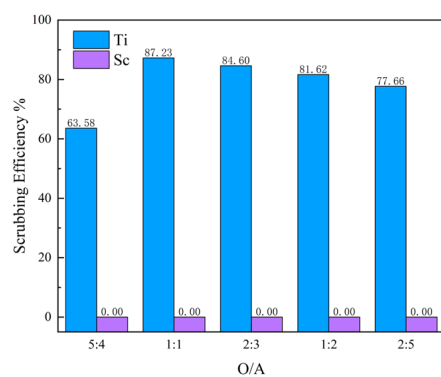


Figure 7. Effect of phase ratio (O/A) on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

3.3.4. Effect of Shaking Speed on Sc and Ti Scrubbing Efficiency

Under the conditions of 25 °C, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, $\text{O}/\text{A} = 1:1$, and scrubbing time of 30 min, the effect of shaking speed on the scrubbing rate was investigated (Figure 8). The results show that the co-scrubbing rate of scandium remained at 0% all the time, while the titanium scrubbing rate varied with shaking speed. This is because when the shaking speed is too low, the organic phase and the scrubbing phase cannot be adequately mixed, resulting in a low Ti scrubbing rate. When the rotating speed increased from 50 to 150 $\text{r}\cdot\text{min}^{-1}$, the titanium scrubbing rate rose significantly from 12.77% to 87.23%, and reached a peak of 93.37% at 200 $\text{r}\cdot\text{min}^{-1}$. This is due to the fact that an appropriate increase in shaking speed promotes adequate mixing between the organic phase and the scrubbing agent, speeds up mass transfer, and consequently enhances the scrubbing rate. Further increasing the rotating speed to 280 $\text{r}\cdot\text{min}^{-1}$ led to a slight decrease in the titanium scrubbing rate to 90.09%, and the scandium co-scrubbing rate still remained 0%. At elevated shaking speeds, mechanical foaming and the accumulation of bubbles resulting from high viscosity jointly weaken the mass transfer between the organic phase and the scrubbing solution. Taking scrubbing efficiency, energy consumption and equipment wear into comprehensive consideration, the optimal shaking speed was determined to be 200 $\text{r}\cdot\text{min}^{-1}$.

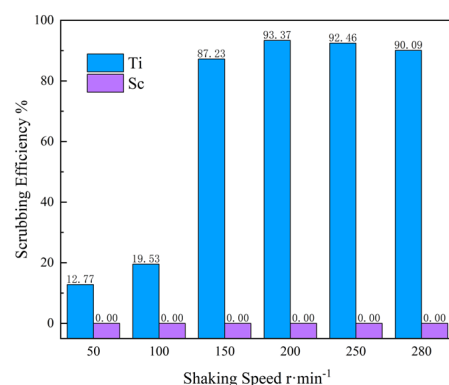


Figure 8. Effect of shaking speed on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

3.3.5. Effect of Reaction Temperature on Sc and Ti Scrubbing Efficiency

Under the conditions of $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, $\text{O}/\text{A} = 1:1$, shaking speed of 200 $\text{r}\cdot\text{min}^{-1}$ and scrubbing time of 30 min, the effect of reaction temperature on the scrubbing efficiencies of titanium and scandium was investigated (Figure 9). The results showed that the scandium co-scrubbing efficiency remained at 0% within the temperature range of 25–55 °C, while the titanium scrubbing efficiency decreased significantly from 97.37% to 77.55% with the increase in temperature. This may be attributed to the

intensification of side reactions or the reduced stability of titanium–citrate complexes at high temperatures. When the temperature exceeded 55 °C, the variation in the titanium scrubbing efficiency tended to be gentle. Comprehensive consideration indicates that the optimal reaction temperature is determined to be 25 °C.

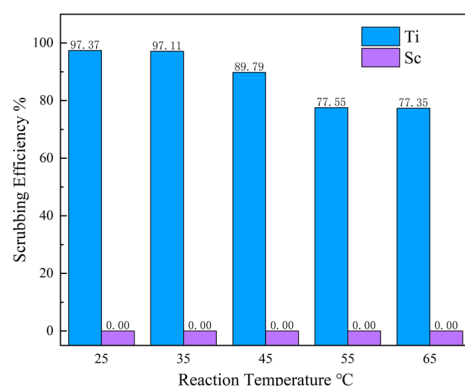


Figure 9. Effect of reaction temperature on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

3.3.6. Effect of Scrubbing Time on Ti Scrubbing Efficiency and Sc Co-Scrubbing Efficiency

Under the conditions of 25 °C, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, $\text{O}/\text{A} = 1:1$, and shaking speed of $200 \text{ r}\cdot\text{min}^{-1}$, the effect of scrubbing time on the scrubbing efficiencies of titanium and scandium was investigated (Figure 10). The scandium co-scrubbing efficiency remained at 0% and was independent of scrubbing time. The titanium scrubbing process proceeded rapidly, with the titanium scrubbing efficiency reaching 84.72% at a scrubbing time of 10 min. As the scrubbing time prolonged to 30 min, the titanium scrubbing efficiency continuously increased to 97.37%. Further extending the time to 40 min caused a slight decrease to 93.06%, which was probably due to the achievement of dynamic equilibrium. Accordingly, the appropriate scrubbing time was determined to be 30 min.

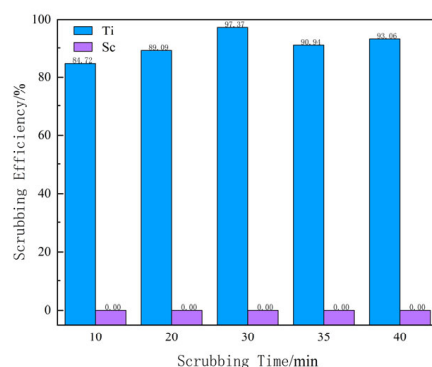


Figure 10. Effect of scrubbing time on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

This series of single-factor experiments carried out in this work provides theoretical support and experimental data for scandium recovery from titanium white waste acid and offers a novel strategy to promote the high-value utilization of scandium resources. Furthermore, the obtained aqueous titanium citrate solution can be converted into high-value-added titanium-based products via wet chemical routes. Meanwhile, scandium enriched in the organic phase can be recovered through conventional scrubbing, which effectively improves the overall resource utilization efficiency and practical application potential of the whole process.

3.4. FTIR Spectroscopy Analysis

The Fourier-transform infrared (FTIR) spectrometer used is Nicolet iN10, manufactured by Thermo Fisher Scientific, USA. FT-IR characterization was performed on the organic phase loaded with Sc (III) and Ti (IV), as well as the loaded organic phase after single-stage scrubbing with the novel detergent. The results are presented in Figure 11. The scrubbing experimental conditions were set as follows: temperature 25 °C, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, phase ratio (O/A) = 1:1, shaking speed 200 r·min^{−1}, and scrubbing time 30 min.

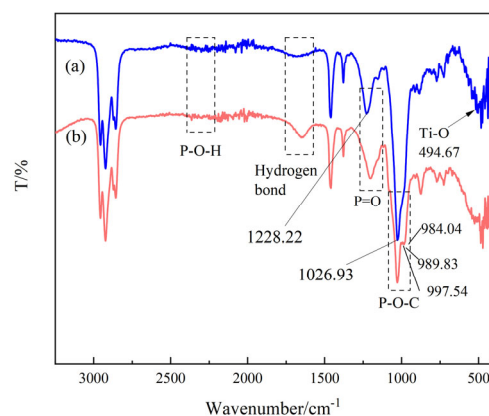


Figure 11. (a) FTIR spectrum of the loaded organic phase; (b) FTIR spectrum of the washed loaded organic phase.

For the spectrum before scrubbing (Figure 11a), the characteristic absorption peaks of the P=O bond, P–O–C bond, and Ti–O bond appeared at 1228.22 cm^{−1}, 1026.93 cm^{−1}, and 494.67 cm^{−1}, respectively. The characteristic peak of the Ti–O bond disappeared in the spectrum after scrubbing (Figure 11b), indicating that titanium was effectively removed from the organic phase. In addition, new absorption peaks emerged at 997.54 cm^{−1}, 989.83 cm^{−1} and 984.04 cm^{−1} after scrubbing, and the intensity of hydrogen bonds increased obviously, which may be related to the increase in pH in the organic phase after scrubbing [38]. The FT-IR results confirm that the novel detergent can selectively remove titanium, and neither the detergent nor its reaction products enter the organic phase.

3.5. Comparison with Traditional Scrubbing Methods

Traditional scrubbing agents are mostly composed of H₂SO₄ and H₂O₂. To compare the scrubbing performance of the novel detergent with the traditional one, the effect of H₂SO₄ concentration in the traditional detergent on the Ti scrubbing efficiency and Sc co-scrubbing efficiency was investigated under the conditions of 25 °C, $n(\text{H}_2\text{SO}_4)/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, phase ratio (O/A) = 1:1, shaking speed of 200 r·min^{−1} and scrubbing time of 30 min (Figure 12). The Ti scrubbing efficiency of the traditional method was only 6.73%, while the Sc co-scrubbing efficiency remained at 0%. The Ti scrubbing efficiency of the novel scrubbing method was 14.47 times that of the traditional one. The results clearly demonstrate the remarkable superiority of the novel detergent in scrubbing efficiency, which is favorable for the efficient separation of scandium and titanium from titanium dioxide waste acid.

The novel masking agent–H₂O₂ composite stripping agent exhibits superior separation performance compared with the conventional sulfuric acid stripping system. When applied to industrial production, this technology features mild operating conditions, and the resulting waste liquid can be neutralized with greater ease. Meanwhile, it effectively enhances the recovery rate of rare earth elements and shortens the technological process. Nevertheless, all experiments conducted in this work are batch shaking tests at the lab-

oratory scale. Further continuous countercurrent stripping scale-up experiments can be carried out to optimize the technological process.

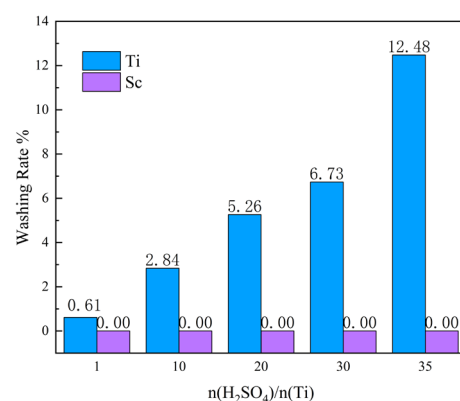


Figure 12. Effect of H_2SO_4 concentration on scrubbing efficiency of Ti and co-scrubbing efficiency of Sc.

4. Conclusions

This study focused on the efficient extraction of scandium from titanium white waste acid and the bottleneck of balancing extractability and selectivity, and was conducted by means of thermodynamic analysis and scrubbing process optimization. Thermodynamically, based on the potential–pH and equilibrium diagrams of the Sc– H_2O and Ti– H_2O systems at 25 °C, the dominant species and transformation rules of Sc (mainly Sc^{3+} and ScSO_4^+) and Ti (mainly $\text{Ti}(\text{OH})_3^+$) under different pH conditions were clarified, laying a theoretical basis for Sc–Ti extraction and separation.

The Na_3Cit – H_2O_2 composite system was screened as the optimal detergent. The effects of Na_3Cit dosage, H_2O_2 dosage and phase ratio (O/A) on scrubbing performance were systematically investigated. The optimal conditions were determined as 25 °C, $n(\text{Na}_3\text{Cit})/n(\text{Ti}) = 30:1$, $n(\text{H}_2\text{O}_2)/n(\text{Ti}) = 3:1$, O/A phase ratio of 1:1, shaking speed of 200 $\text{r}\cdot\text{min}^{-1}$ and scrubbing time of 30 min. Under these conditions, the Ti scrubbing efficiency reached 97.37% while the Sc co-scrubbing efficiency was 0%, which was 14.47 times higher than that of the traditional $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$ system and greatly improved the Sc–Ti separation efficiency. The scrubbing mechanism was preliminarily clarified via product composition analysis, offering a feasible technical route for efficient scandium recovery from titanium white waste acid. This work provides a theoretical basis and experimental data for scandium recovery from titanium white waste acid, and offers new insight to promote the high-value utilization of scandium resources.

Apart from serving as the complexing scrubbing agent in this process, sodium citrate can be utilized as desulfurizer to remove sulfide from industrial tail gas and applied for environmental remediation, relying on its complexing capacity to realize comprehensive utilization. The obtained aqueous titanium citrate can be transformed into high-value titanium-based products via two wet chemical routes: nano-titanium dioxide is obtained by pH adjustment with ammonia, evaporation drying and calcination for organic ligand removal, and titanate functional powders are synthesized through hydrothermal reaction after blending with corresponding metal salts. Scandium enriched in the organic phase can be recovered by conventional scrubbing, which effectively improves the resource utilization and practical application potential of the whole process.

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L.Z. and X.C.; visualization, W.Z.; supervision, Y.W. (Yan Wang) and Y.L.; project administration, Y.C. and Y.L.; funding acquisition, Y.C. and W.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lv, Z.J.; Zhai, X.J. *Scandium Metallurgy*; Chemical Industry Press: Beijing, China, 2015; pp. 1–50.
2. Lin, H.C. Application and market of scandium metal. *World Nonferr. Met.* **2012**, *58*, 58–59. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT92uHBEU1i6zgulvbTnPUAD8xBmTBm5NGoiZheG_LcAIOHXzjS0cdjvFjfvBl-On2qoXiv858qxU7-Ke2GeftWQjeEg6v0ODRjzYZTs2Pxr42Vev7GQgXSp_H89fmZL_6ODRYMqPtVZwTNGSBKmQ41P&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
3. Li, G.Y.; Liu, W.J.; You, C.; Cui, H.; Tian, Y. Rare earth element scandium and its applications. *Guangdong Chem. Ind.* **2013**, *40*, 108–115.
4. Fan, Y.J.; He, H.J.; Zhang, J.F.; Huang, T.Y. Study on the Process of Joint Extraction of Scandium Oxide from Titanium White Waste Acid and Red Mud. *Nonferr. Met. (Smelt. Part)* **2015**, *1*, 55–57.
5. Zhang, W.; Zhu, H.; Liu, S.F.; Ning, S.Y.; Wei, Y.Z. Scandium recovery from ion-adsorption rare earth concentrate with HEHEHP as extractant. *J. Cent. South Univ.* **2021**, *28*, 679–689. [CrossRef]
6. Zhi, W.K.; Wang, F.; Chen, X.Y.; Yang, B. Research progress on scandium resources and extraction technology. *J. Rare Earths* **2024**, *42*, 13–29. (In Chinese)
7. Li, W.; Zhu, X.B. Study on extraction of scandium from red mud by acid leaching. *Nonferr. Met. (Smelt. Part)* **2016**, 36–38. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT_e4m9H8uPW_E1S818xjvIPayikg6ZAbBRt5HLBBpa7JHHiBuwniZxZyitOpJ_vOA_X7rXezjR5Wy4SRJijHhMeTqym1kGjWowvQMb1HzUF8McvwPFXCbZGecEM9aDDS65oCum-5hgxTCIIWFK69ygUIrepKJli_qQ=&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
8. Zhang, N.; Li, H.X.; Liu, X.M. Recovery of scandium from bauxite residue—Red mud: A review. *Rare Met.* **2016**, *35*, 887–900. [CrossRef]
9. Zhang, J.Y.; Gao, Y.H.; Yang, C.; Zhang, P.; Kuang, J.; Liu, G.; Sun, J. Microalloying Al alloys with Sc: A review. *Rare Met.* **2020**, *39*, 636–650. [CrossRef]
10. Wang, Y.; Xiong, B.Q.; Li, Z.H.; Huang, S.H.; Wen, K.; Li, X.W.; Zhang, Y.A. As-cast microstructure of Al–Zn–Mg–Cu–Zr alloy containing trace amount of Sc. *Rare Met.* **2019**, *38*, 343–349. [CrossRef]
11. Liu, C.Y.; Teng, G.B.; Ma, Z.Y.; Wei, L.L.; Zhou, W.B.; Huang, H.F.; Qi, H.Q. Mechanical properties and thermal stability of 7055 Al alloy by minor Sc addition. *Rare Met.* **2020**, *39*, 725–732. [CrossRef]
12. Chakhmouradian, A.R.; Smith, M.P.; Kynicky, J. From “strategic” tungsten to “green” neodymium: A century of critical metals at a glance. *Ore Geol. Rev.* **2015**, *64*, 455–458. [CrossRef]
13. Chen, Y.D. Study on Efficient Extraction and Recovery of Scandium from Titanium White Waste Acid and Application of New Extraction Resin for Separation of Scandium and Zirconium. Master’s Thesis, Guangxi University, Nanning, China, 2022; pp. 1–3, 10.
14. Sun, S.; Sun, H.Q.; Song, J. Research progress on scandium resource status and application of solvent extraction in scandium extraction process. *Chin. J. Process Eng.* **2020**, *20*, 877–886.
15. Zhou, J.; Ning, S.Y.; Ma, S.Y.; Chen, Y.D.; Wei, Z.Y. Separation and purification of scandium from titanium white waste acid enrichment by solvent extraction. In Proceedings of the 2020 Academic Annual Meeting of the Chinese Society of Rare Earths and Jiangxi (Ganzhou) Rare Earth Resources Green Development and Efficient Utilization Conference, Ganzhou, China, 19–21 October 2020.
16. Zhou, J.; Ma, S.; Chen, Y.; Ning, S.; Wei, Y.; Fujita, T. Recovery of scandium from red mud by leaching with titanium white waste acid and solvent extraction with P204. *Hydrometallurgy* **2021**, *204*, 105724. [CrossRef]

17. Zhan, H.H.; Liang, H.L.; Fan, Y.J.; Huang, T.Y.; Guo, D.Q. Two-stage Neutralization Treatment of sulfuric acid-based titanium white waste acid and precipitation of scandium. *Nonferr. Met. (Smelt. Part)* **2014**, 45–47. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT95MLma_zJdUcQNG6mOKDqtr7oU6We68srIXQjkwNWEkKZux-2Qt7NbvvgImC2BegSj_Ed-VS6MalX2BgLghR7-dGlza8vu7CjwstEpVLGDYxpOKaNs3CZJ0-S-puYcpt5bbrN1Yyx1XsiC6Dgv-hCS&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
18. Qiu, H.; Wang, M.; Xie, Y.; Song, J.; Huang, T.; Li, X.-M.; He, T. From trace to pure: Recovery of scandium from the waste acid of titanium pigment production by solvent extraction. *Process Saf. Environ. Prot.* **2019**, 121, 118–124. [CrossRef]
19. Peng, F. Current status and research progress of solvent extraction in hydrometallurgy of scandium metal. *Metall. Mater.* **2025**, 45, 190–192.
20. Li, W.; Zhu, X.B.; Tang, S. Experiment and thermodynamic study on selective extraction and separation of scandium from acid solution. *J. Chin. Soc. Rare Earths* **2017**, 35, 755–760.
21. Liu, P.X.; Hu, G.S.; Li, H.P.; Tang, X.L.; Ma, X.H. Distribution law and inhibition method of Ce(IV) in rare earth extraction and separation process. *Nonferr. Met. (Smelt. Part)* **2024**, 83–90. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT9rDtqjGGABMj3JpjJdeV644Q6GSTjwneTq2M39-bOny9G2oh71xyHTyoZZUx8Bzn6dM-9jAqAZp43TRTjXF0lb8V_siFtCiELOyLA_3EBhskXmla4SCq3U568SoRjokU3kUywcX3x-XtigN6SNn_nUsTBhxiO-KxA=&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
22. Liu, W.; Yin, Z.F.; Li, G.G.; Yang, Y. Study on titanium removal in scandium extraction process from titanium white waste acid. *Chin. Rare Earths* **2016**, 37, 86–89.
23. Li, H.; Tong, Z.F.; Chen, Z.C.; Mao, A.Z. Improvement of scandium extraction process from titanium white waste acid. *Inorg. Salt Ind.* **2006**, 51–53. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT8VnMrwfSdRSe-4aMfjuchECIV4N3ZGIHhuWy8F2HqR0YNgwfvnBZBtLNXgwYlH0oPlx2_Odl_ThMchlVv0kQD7e9AE7ZE89il36D2clgw881SkRWFil3hCwnu2n2Uw-qyvRqUZ1dzccHRR7Zcxwflw&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
24. Li, Y.H.; Li, Q.G.; Zhang, G.Q.; Cao, Z.Y.; Guan, W.J.; Zeng, L. Recovery of scandium from titanium white hydrolysis waste acid. *CIESC J.* **2017**, 2818–2825. Available online: https://kns.cnki.net/kcms2/article/abstract?v=hiwAvoCB7A2Ip0SKR17Eyeled6ajVj0aFBA11kbEw1iGv4ewBkTKkrSKEQcnvHGQBESIEkqHB403VHYSSsOqhu3sRjJfuUYmCefywL1RhUtQS_4PsAVwrJkCqo9-FSQd1TkyEvG68gYA1RZ89MtVeeF8tpiNJJiNoKc64sEtd4btAcUchD_bA==&uniplatform=NZKPT&language=CHS (accessed on 7 March 2026). (In Chinese)
25. Li, Y.; Li, Q.; Zhang, G.; Zeng, L.; Cao, Z.; Guan, W.; Wang, L. Separation and recovery of scandium and titanium from spent sulfuric acid solution from the titanium dioxide production process. *Hydrometallurgy* **2018**, 178, 1–6. [CrossRef]
26. Man, L.M.; Fan, Y.J.; Huang, J.F.; Tian, S.C. Separation of scandium and titanium from waste acid solution by solvent extraction. *Hydrometallurgy* **2016**, 35, 231–234.
27. Luo, W.J. Study and Application of Dual Extractant Impregnated Resin for Recovery of Scandium from Titanium White Waste Acid. Master's Thesis, Sichuan University, Chengdu, China, 2004.
28. Zhang, L.; Zhang, T.; Lv, G.; Zhang, W.; Li, T.; Cao, X. Separation and Extraction of Scandium from Titanium Dioxide Waste Acid. *JOM* **2021**, 73, 1301–1309. [CrossRef]
29. Luo, Y.Z.; Xu, L.; Zeng, X.B.; Shi, G.D. Study on titanium removal from scandium enrichment. *Nonferr. Met. (Smelt. Part)* **2019**, 61–64. Available online: https://kns.cnki.net/kcms2/article/abstract?v=4Snn6dWjeT_mz1N3zN7U5w76unQC750DCBzJpJK-g6PAhBNKxpy9CErfRhAQ1CDlcO71ynZ8Y-OyXWfFa5WQQY3M00Jqisavyv_MvUxFfIJ-U9-cGEdcILWgdRy4frlYejASyZJndlJkZm--vK9uYKNZT-myTjb8sRX_o8oT_A=&uniplatform=NZKPT (accessed on 7 March 2026). (In Chinese)
30. Guo, Z.Q. Study on Synthesis Mechanism and Morphology Control of High-performance TiO₂ Assisted by Sodium Citrate. Master's Thesis, Soochow University, Suzhou, China, 2012; pp. 25–28.
31. Mo, D.H.; Ye, M.; Zhang, Y. Application of Citric Acid Dissociated Titanium Coordination Complex Drugs in 4AA Preparation. *Chem. Ind. Manag.* **2020**, 101–103. Available online: https://kns.cnki.net/kcms2/article/abstract?v=hiwAvoCB7A3jqhAthkYISVZDgF5tGrgDXCrwE8Ic4ic2lSbCuCuaptQi_E4lkUyfhcg59IvNcU6X-z6UeB05PEjrVrOIMbtzmWkbZLs-TEbxtRgptTdLlpKPpi1xi9ocdqm36VGXi9XtnumrRzB5YNP86JNQMTq-wn1X47BpJCC=&uniplatform=NZKPT (accessed on 7 March 2026).
32. Yang, J.W. Development of Li₄Ti₅O₁₂-Based Anode Materials for Hybrid Supercapacitors and Related Mechanism Research. Ph.D. Thesis, Central South University, Changsha, China, 2005; pp. 32–38.
33. Deng, Y.F.; Zhou, Z.H.; Wan, H.L. pH-Dependent Isolations and Spectroscopic, Structural, and Thermal Studies of Titanium Citrate Complexes. *Inorg. Chem.* **2004**, 43, 6266–6273. [CrossRef] [PubMed]
34. Nikolaychuk, P.A. The revised potential-pH diagram of Sc-H₂O system. *Научные Ведомости* **2016**, 25, 72–77.
35. Mu, W.-Z.; Zhang, T.-A.; Dou, Z.-H.; Lü, G.-Z.; Liu, Y. φ-pH diagram of V-Ti-H₂O system during pressure acid leaching of converter slag containing vanadium and titanium. *Trans. Nonferr. Met. Soc. China* **2011**, 21, 2078–2086. [CrossRef]
36. Yu, H.Y. Study on Separation of Scandium from Titanium White Waste Acid. Master's Thesis, University of Jinan, Jinan, China, 2023.

37. Deng, X.J. Application of Masking Agents in Metal Analysis. *Metall. Anal.* **1985**, 44–51.
38. Zhang, W.; Zhang, T.-A.; Lv, G.; Zhou, W.; Cao, X.; Zhu, H. Extraction Separation of Sc(III) and Fe(III) from a Strongly Acidic and Highly Concentrated Ferric Solution by D2EHPA/TBP. *JOM* **2018**, *70*, 2837–2845. [[CrossRef](#)]

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