

Article

Study of the Electrochemical Oxidation Process of Vanadium

Saltanat Jumankulova ^{*}, Zhaksylyk Alybayev and Gulnara Moldabayeva 

O.A. Baikonurov Mining and Metallurgical Institute, Department of Metallurgy and Mineral Processing, K.I. Satbayev Kazakh National Research Technical University, 22 Satpayev St., Almaty 050013, Kazakhstan; zh.alybayev@satbayev.university (Z.A.); gulnara.moldabayeva@satbayev.university (G.M.)

^{*} Correspondence: s.jumankulova@satbayev.university

Abstract

The article presents experimental data on the electrochemical oxidation of vanadium-bearing ore with the aim of increasing the efficiency of vanadium extraction during subsequent hydrometallurgical processing. Three different charge compositions were studied during the preliminary oxidative roasting stage, differing in the type of oxidizers used: calcined soda, sodium chloride, and their mixture in a mass ratio of 9:1. Electrochemical oxidation was carried out in a sulfuric acid medium using a membrane electrolysis cell equipped with an MK-40 type diaphragm. Experimental studies were conducted by varying key technological parameters: H_2SO_4 concentration (5–15%), solid-to-liquid phase ratio (1:2–1:5), temperature (25–85 °C), process duration (0.5–3 h), and current density (100–1000 A/m²). It was found that preliminary roasting promotes the conversion of vanadium into higher oxidation states, predominantly V^{5+} , which significantly increases its solubility during subsequent electrochemical treatment. For the first time, the kinetic patterns of electrochemical vanadium leaching were identified, as well as the limiting mechanism of the process, associated with the formation of poorly soluble oxide films on the ore surface. Optimization of the electrochemical oxidation parameters allowed us to achieve vanadium extraction into solution up to 92%.

Keywords: vanadium-bearing ore; Balasauskandyk and Kurumsak deposits; roasting; leaching; electrochemical oxidation; concentration; duration; solid-to-liquid phase ratio; temperature; current density



Academic Editor: Angeles Sanroman Braga

Received: 3 September 2025

Revised: 1 October 2025

Accepted: 6 October 2025

Published: 13 October 2025

Citation: Jumankulova, S.; Alybayev, Z.; Moldabayeva, G. Study of the Electrochemical Oxidation Process of Vanadium. *Appl. Sci.* **2025**, *15*, 10976. <https://doi.org/10.3390/app152010976>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Vanadium is a strategically important metal due to its unique physicochemical properties, such as high strength, corrosion resistance, and the ability to enhance the characteristics of alloys.

The main application of vanadium is in the production of high-strength steels, as well as its use in catalysts and the chemical industry. In recent years, its role in the development of energy storage technologies has attracted significant attention, particularly in the production of vanadium redox flow batteries (VRFBs). These batteries, known for their long service life and fast charging capabilities, are considered a promising solution for large-scale energy storage, which is driving increased demand for the metal in the energy sector [1].

According to the International Energy Agency (IEA, 2023), global vanadium consumption continues to grow steadily, with China remaining the leading consumer, accounting for more than half of the world's vanadium use—primarily for steel production. Significant consumption is also observed in the United States, Europe, Japan, and developing Asian

countries such as India and South Korea. Vanadium mining and processing play a key role in the global market and are primarily concentrated in China, Russia, South Africa, and Brazil. In addition to primary extraction, the processing of secondary resources and industrial waste is gaining increasing importance, helping to ensure supply stability amid geopolitical risks and demand fluctuations. According to several studies [2–13], further growth in vanadium consumption will be driven by the development of the metallurgical, construction, and automotive industries, as well as the adoption of innovative technologies for metal extraction and application in energy and environmental protection.

Against the backdrop of a steady increase in global vanadium demand and expanding areas of application, the strategic importance of this metal for the economy of the Republic of Kazakhstan is also growing. This importance is due to vanadium's unique physicochemical properties—high mechanical strength, corrosion resistance, and the ability to modify the structure and properties of metal alloys. These characteristics determine its wide range of applications, from metallurgy and the chemical industry to modern energy storage technologies [3].

The main vanadium reserves in the Republic of Kazakhstan are concentrated in the Karatau vanadium basin, which includes the Balasauskandyk and Kurumsak deposits. The Balasauskandyk deposit, which accounts for about 65% of Kazakhstan's total vanadium reserves, is among the largest in the world in terms of mineral resource volume [14]. However, the industrial development of these deposits is significantly constrained by the lack of efficient processing and extraction technologies, which results in a large portion of the resources being classified as subeconomic ore (subeconomic ore refers to ore whose metal content or mining conditions do not currently permit economically viable extraction) [15]. The future development of Kazakhstan's vanadium industry directly depends on the implementation of innovative ore beneficiation methods, as well as investment attraction to enhance the industrial exploitation of this strategically important raw material [16–19].

The aim of this study is to determine the optimal conditions for the electrochemical oxidation of vanadium-bearing ore after preliminary oxidative roasting with different charge compositions, as well as to establish the kinetic patterns and mechanisms of vanadium leaching in a sulfuric acid medium, in order to increase the efficiency of its extraction during hydrometallurgical processing.

A review of the literature [20–22] shows that traditional methods of processing vanadium-bearing ores—including acid leaching without roasting or with low-temperature roasting (up to 700 °C)—are insufficiently effective for extracting vanadium from the Balasauskandyk and Kurumsak deposits. This is due to the complex mineralogical form in which vanadium occurs in the ore—as sulfides, hydroxides, as part of micas (in the form of isomorphic substitution), and in anionic complexes. Despite the implementation of pyrometallurgical, hydrochemical, and sorption technologies at the industrial pilot site of Balasaus LLP, they do not ensure complete oxidation of vanadium to V^{5+} , which significantly reduces the efficiency of its extraction. In addition, there is no integrated processing scheme in place that would allow for the recovery of other valuable components, particularly uranium and rare earth elements (REEs).

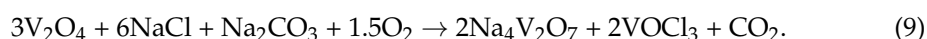
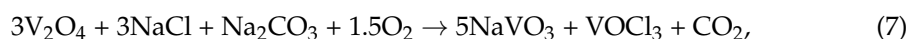
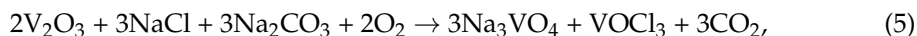
In this context, the application of the electrochemical processing method appears to be a promising direction. This approach combines three processes in the anode region: vanadium oxidation, its leaching, and solution activation under the influence of direct electric current. The use of electrochemical oxidation can significantly improve vanadium recovery rates and ensure comprehensive processing of vanadium-bearing ores from the Greater Karatau region, including the extraction of accompanying elements. Conducting such research is of high scientific and practical relevance, as it contributes to the creation of a national production base for vanadium and associated rare metals.

Currently, there is no available literature on the electrochemical oxidation of vanadium directly from natural mineral raw materials, which emphasizes that the presented experimental studies on the electrochemical oxidation of vanadium from ore materials have been conducted for the first time [23–29].

2. Materials and Methods

The original composition of vanadium-bearing ores from the Balasauskandyk and Kurumsak deposits was studied using chemical analysis methods in the laboratory of the K.I. Satpayev Institute of Geological Sciences.

To carry out the oxidative roasting of powdered vanadium-bearing ore, three charge compositions were used. In the first variant, the charge consisted of a mixture of vanadium-bearing ore and calcined soda (GOST 83-79) in a mass ratio of 1:1. In the second variant, sodium chloride (GOST 4233-77) was used as the oxidizing agent, also in a 1:1 ratio with the ore. The third variant of the charge included a mixture of calcined soda and sodium chloride in a mass ratio of 9:1. The specified sodium salts and their mixture were introduced with a 20% excess relative to the stoichiometrically required amount [30]. Oxidative roasting was carried out at a temperature of 700–850 °C. The possible reactions occurring during the roasting process were determined based on thermodynamic calculations performed using the HSC Chemistry 7.1 software package:



Thermodynamic calculations using HSC Chemistry 7.1 were performed to predict the stability of various forms of vanadium during electrochemical oxidation. These calculations allowed us to confirm the possibility of the formation of target compounds and compare theoretical data with experimental results.

Methodology for Conducting Experiments on Roasting Vanadium-Bearing Ores

During roasting, a crucial condition was the regular stirring of the charge to prevent its sintering. The air flow rate supplied as the oxidizer was approximately 0.107 m³ per 100 g of ore. The roasting temperature was maintained within the range of 700–850 °C, with a total process duration of 2 h. Upon completion of the roasting, the resulting calcines were cooled, ground, and subjected to semi-quantitative X-ray phase analysis at the laboratory of the K.I. Satpayev Institute of Geological Sciences.

Methodology for experiments on electrochemical oxidation and leaching of vanadium

During the experimental studies, the optimal type of electrochemical cell (electrolysis bath) was first selected, after which the main parameters affecting the degree of vanadium oxidation and its transition into solution were determined, including the type and concentration of the electrolyte, anode material, and process temperature. The ore was ground to a particle size of 10 microns. Sulfuric acid at concentrations of 5%, 10%, and 15% was

chosen as the most suitable electrolyte. The ore sample was mixed with the electrolyte in solid-to-liquid ratios (S:L) of 1:2, 1:3, 1:4, and 1:5, at temperatures of 25, 45, 65, and 85 °C, durations of 0.5, 1, 1.5, 2, 2.5, and 3 h, and current densities from 100 to 1000 A/m², and then subjected to electrochemical oxidation in an electrolyzer equipped with an MK-40 membrane separating the anode and cathode chambers.

Before starting the process, a mixture of ore and electrolyte was introduced into the anode compartment of the electrolyzer and stirred using a mixer at 120–150 rpm, while only acid was poured into the cathode compartment. During electrolysis, vanadium oxidation reactions occur in the anode chamber, while water decomposition with hydrogen evolution takes place at the cathode according to the following reaction:



It should be noted that gaseous oxygen, produced at the anode as a result of the discharge of water molecules or hydroxyl ions, can further participate in the vanadium oxidation process.

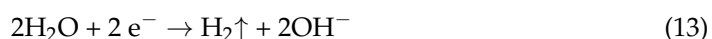
In such electrolyzers, where the anode and cathode chambers are separated by an MK-40 membrane, redox reactions occur, accompanied by changes in the oxidation states of individual ions:



In the conducted studies, a lead plate was used as the anode, and titanium served as the cathode. It is known that increasing the current density at the electrodes leads to an increase in their electrode potential, which in turn enhances the reducing or oxidizing properties of the respective electrode. This enables the realization of redox processes that are otherwise difficult to achieve. However, excessive current density reduces current efficiency, as a significant portion of the electrical energy is consumed by side reactions such as oxygen or hydrogen evolution.

On the other hand, the use of electrolyzers with a separating partition (membrane) permeable to ions allows for the production of alkali in the cathode compartment of the electrolyzer.

At the cathode, the water reduction reaction takes place:



In traditional sorption technology for processing productive solutions, alkali can be used in the neutralization processes of commercial regenerates prior to vanadium precipitation.

For electrochemical oxidation, the use of a special electrolyzer has been proposed, in which a strongly oxidizing environment is created in the anode chamber due to oxygen generated from a component of the electrolyte.

All experiments were carried out three times. The values presented are averages.

3. Results

The results of the chemical analysis of the original ore samples are presented in Tables 1 and 2.

Table 1. Results of the chemical analysis of the original ore (Balasauskandyk deposit), wt.%.

Elements	Fe	Mg	Al	Si	P	S	K	Ca	Ti	V	Cr	O ₂ and Others
Sample 1	2.37	0.52	6.85	35.24	0.38	0.37	3.10	0.57	0.33	0.64	0.24	49.39
Sample 2	1.61	0.43	7.28	33.70	0.19	0.34	3.76	0.46	0.48	0.71	0.17	50.87
Sample 3	1.76	0.54	6.48	33.63	0.42	0.53	3.23	0.30	0.48	0.77	0.17	51.69
Sample 4	1.42	0.47	5.19	28.73	0.32	0.26	2.74	0.39	0.24	0.61	0.23	59.40
Sample 5	1.43	0.40	5.77	28.86	0.35	0.50	2.76	0.39	0.21	0.62	0.25	58.46
Sample 6	1.63	0.64	6.31	26.35	0.28	0.38	3.09	0.38	0.30	0.85	0.24	59.55
Average	1.70	0.50	6.31	31.08	0.32	0.40	3.11	0.41	0.34	0.70	0.22	54.89

Table 2. Results of the chemical analysis of the original ore (Kurumsak deposit), wt.%.

Elements	Fe	Mg	Al	Si	P	S	K	Ca	V	Ba	O ₂ and Others
Sample 1	7.07	-	6.93	37.74	1.14	3.49	2.32	0.15	0.97	8.15	32.04
Sample 2	4.47	-	5.56	37.53	0.42	2.73	2.31	0.55	1.04	7.61	37.78
Sample 3	4.28	-	6.90	34.42	0.61	3.53	2.60	0.36	1.37	7.93	38.00
Sample 4	2.40	0.07	1.74	27.21	0.35	1.09	0.53	0.03	0.28	1.21	65.09
Sample 5	2.64	0.12	1.70	23.74	0.28	1.25	0.56	0.12	0.22	1.32	68.05
Sample 6	1.58	0.20	3.03	28.29	0.28	1.37	1.01	-	0.51	2.57	61.16
Average	3.74	0.065	4.31	31.49	0.51	2.24	1.55	0.20	0.73	4.80	50.35

Oxidative roasting was carried out in a muffle furnace SNOL-1.4/2.5/1.2/12.5—I1 (Figure 1) with the supply of an oxidizing gas (air) passing through the filtering layer of the powdered charge.

**Figure 1.** Muffle furnace SNOL-1.4/2.5/1.2–12.5—I1.

A special electrolyzer was designed for conducting the electrochemical oxidation process (Figures 2 and 3).

The material flows of the roasting process of vanadium-containing ore from the Balasauskandyk and Kurumsak deposits in the presence of a mixture of sodium salts are presented below (Tables 3 and 4).



Figure 2. Electrolyzer for electrochemical oxidation of vanadium-containing ores.

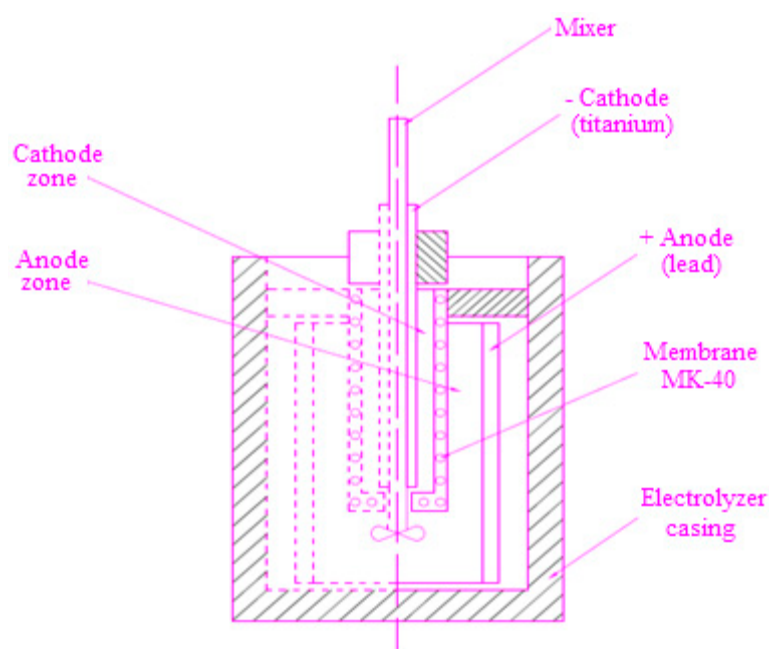


Figure 3. Diagram of the electrolyzer for carrying out the electrochemical oxidation of vanadium-containing ores.

Effect of sulfuric acid concentration on vanadium extraction into solution

As the concentration of sulfuric acid increases from 5% to 15%, the vanadium extraction rate rises from 68.96–70.14% to 90.91–92.19%, respectively, during the leaching of both unroasted and roasted vanadium-containing ores (Table 5, Figure 4).

Table 3. Material balance of the roasting of vanadium-containing ore from the Balasauskandyk deposit in the presence of a mixture of sodium salts.

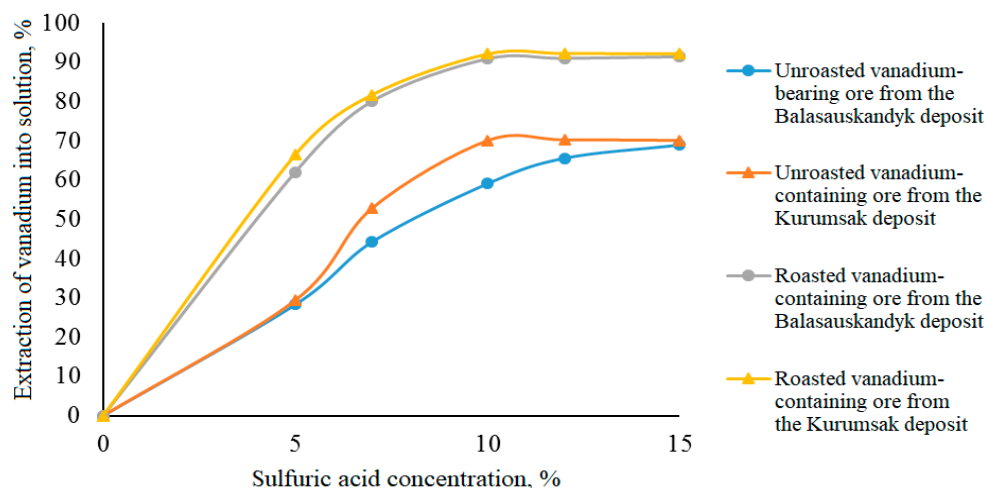
Materials Input	Total, g	Products Obtained	Total, g
Ore from the Balasauskandyk deposit	100	Clinker	59.186
Na ₂ CO ₃	0.7	Gases	191.805
NaCl	0.07	Discrepancy	−0.221
Air	150		
Total	250.77	Total	250.77

Table 4. Material balance of the roasting of vanadium-containing ore from the Kurumsak deposit in the presence of a mixture of sodium salts.

Materials Input	Total, g	Products Obtained	Total, g
Ore from the Kurumsak deposit	100	Clinker	55.434
Na ₂ CO ₃	0.7	Gases	195.392
NaCl	0.07	Discrepancy	−0.056
Air	150		
Total	250.77	Total	250.77

Table 5. Effect of sulfuric acid concentration on the vanadium extraction rate into solution.

H ₂ SO ₄ Concentration, %	5	7	10	12	15
Unroasted ore from the Balasauskandyk deposit					
Concentration in solution, g/dm ³	0.218	0.341	0.455	0.505	0.531
Extraction into solution, %	28.31	44.28	59.09	65.58	68.96
Concentration in the residue, g/dm ³	0.552	0.429	0.315	0.265	0.239
Unroasted ore from the Kurumsak deposit					
Concentration in solution, g/dm ³	0.403	0.724	0.960	0.963	0.961
Extraction into solution, %	29.42	52.85	70.07	70.29	70.14
Concentration in the residue, g/dm ³	0.967	0.646	0.410	0.407	0.409
Roasted ore from the Balasauskandyk deposit					
Concentration in solution, g/dm ³	0.478	0.617	0.700	0.701	0.704
Extraction into solution, %	62.08	80.13	90.91	91.03	91.43
Concentration in the residue, g/dm ³	0.292	0.153	0.070	0.069	0.066
Roasted ore from the Kurumsak deposit					
Concentration in solution, g/dm ³	0.911	1.120	1.262	1.264	1.263
Extraction into solution, %	66.50	81.75	92.12	92.26	92.19
Concentration in the residue, g/dm ³	0.459	0.250	0.108	0.106	0.107

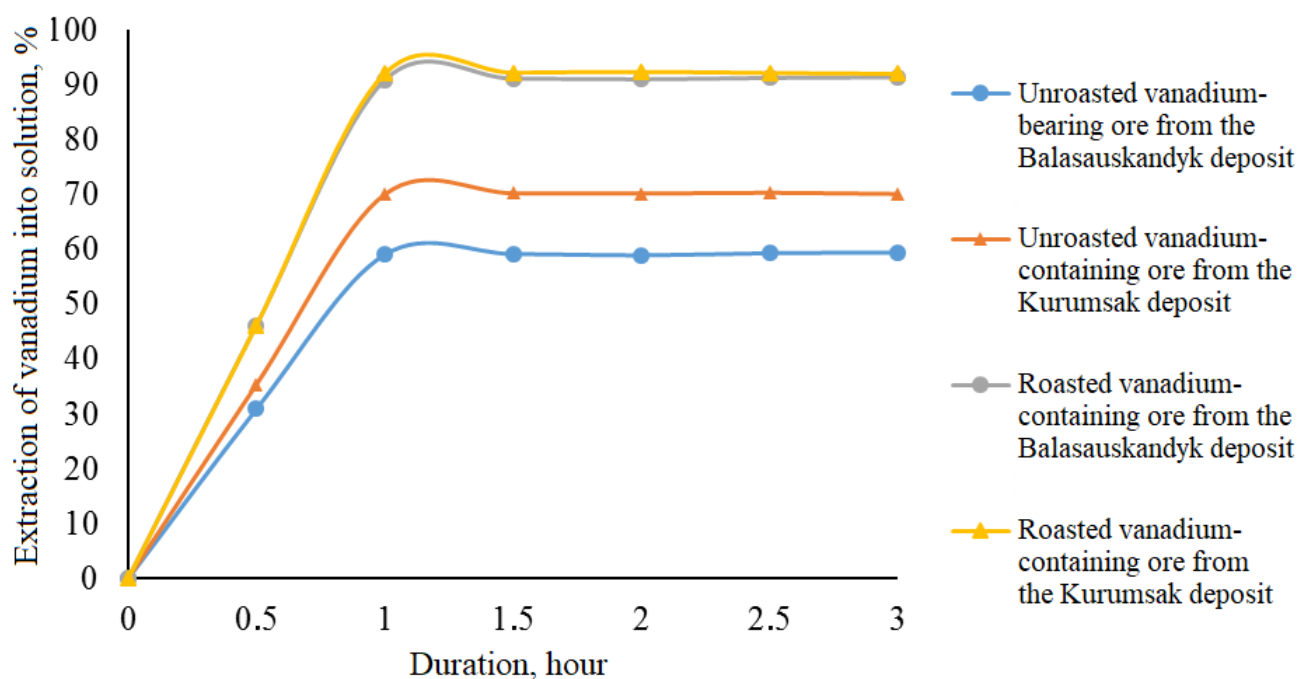
**Figure 4.** Dependence of vanadium extraction rate into solution on sulfuric acid concentration.

Effect of electrochemical oxidation duration on vanadium extraction into solution

Experiments to determine vanadium extraction into solution depending on the duration of electrochemical oxidation were conducted at the following time intervals: 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 h. The obtained results are presented in Table 6 and Figure 5.

Table 6. Effect of electrochemical oxidation duration on the vanadium extraction rate into solution.

Duration, Hours	0.5	1	1.5	2	2.5	3
Unroasted ore from the Balasauskandyk deposit						
Concentration in solution, g/dm ³	0.238	0.455	0.456	0.454	0.457	0.458
Extraction into solution, %	30.91	59.09	59.22	58.96	59.35	59.48
Concentration in the residue, g/dm ³	0.532	0.315	0.314	0.316	0.313	0.312
Unroasted ore from the Kurumsak deposit						
Concentration in solution, g/dm ³	0.485	0.960	0.963	0.962	0.964	0.961
Extraction into solution, %	35.40	70.07	70.29	70.22	70.36	70.14
Concentration in the residue, g/dm ³	0.885	0.410	0.407	0.408	0.406	0.409
Roasted ore from the Balasauskandyk deposit						
Concentration in solution, g/dm ³	0.356	0.700	0.702	0.701	0.703	0.704
Extraction into solution, %	46.23	90.91	91.17	91.04	91.30	91.43
Concentration in the residue, g/dm ³	0.414	0.070	0.068	0.069	0.067	0.066
Roasted ore from the Kurumsak deposit						
Concentration in solution, g/dm ³	0.633	1.262	1.264	1.266	1.263	1.261
Extraction into solution, %	46.20	92.12	92.26	92.41	92.19	92.04
Concentration in the residue, g/dm ³	0.737	0.108	0.106	0.104	0.107	0.109

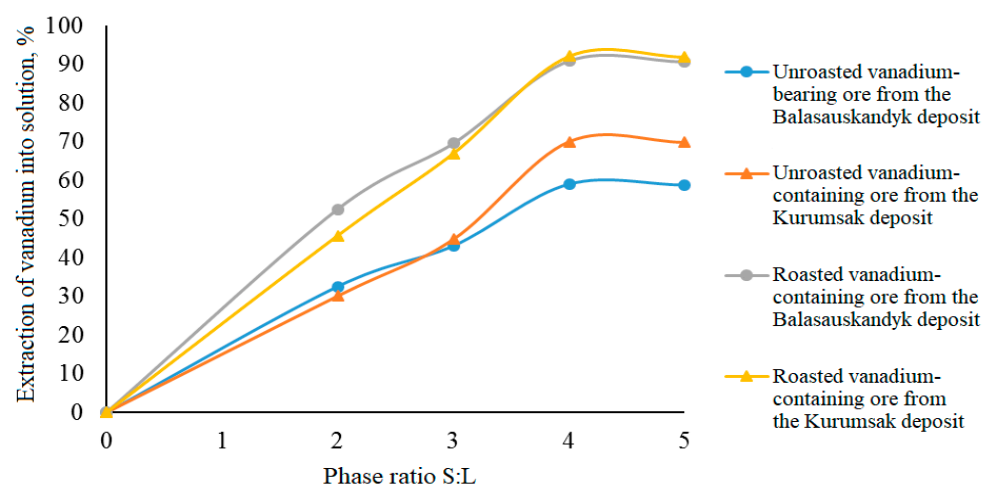
**Figure 5.** Dependence of vanadium extraction rate into solution on the duration of electrochemical oxidation.

Effect of solid-to-liquid phase ratio on vanadium extraction into solution

In this series of experiments, the solid-to-liquid (S:L) ratio varied from 1:2 to 1:5 (Table 7, Figure 6). The other parameters under investigation remained unchanged and corresponded to the conditions of the previous experimental series.

Table 7. Study of the effect of solid-to-liquid phase ratio on the vanadium extraction rate into solution.

S:L Ratio	1:2	1:3	1:4	1:5
Unroasted ore from the Balasauskandyk deposit				
Concentration in solution, g/dm ³	0.251	0.332	0.455	0.453
Extraction into solution, %	32.60	43.12	59.09	58.83
Concentration in the residue, g/dm ³	0.519	0.438	0.315	0.317
Unroasted ore from the Kurumsak deposit				
Concentration in solution, g/dm ³	0.413	0.614	0.960	0.957
Extraction into solution, %	30.14	44.82	70.07	69.85
Concentration in the residue, g/dm ³	0.957	0.756	0.410	0.413
Roasted ore from the Balasauskandyk deposit				
Concentration in solution, g/dm ³	0.405	0.536	0.700	0.698
Extraction into solution, %	52.60	69.61	90.91	90.65
Concentration in the residue, g/dm ³	0.365	0.234	0.070	0.072
Roasted ore from the Kurumsak deposit				
Concentration in solution, g/dm ³	0.627	0.918	1.262	1.259
Extraction into solution, %	45.77	67.01	92.12	91.90
Concentration in the residue, g/dm ³	0.743	0.452	0.108	0.111

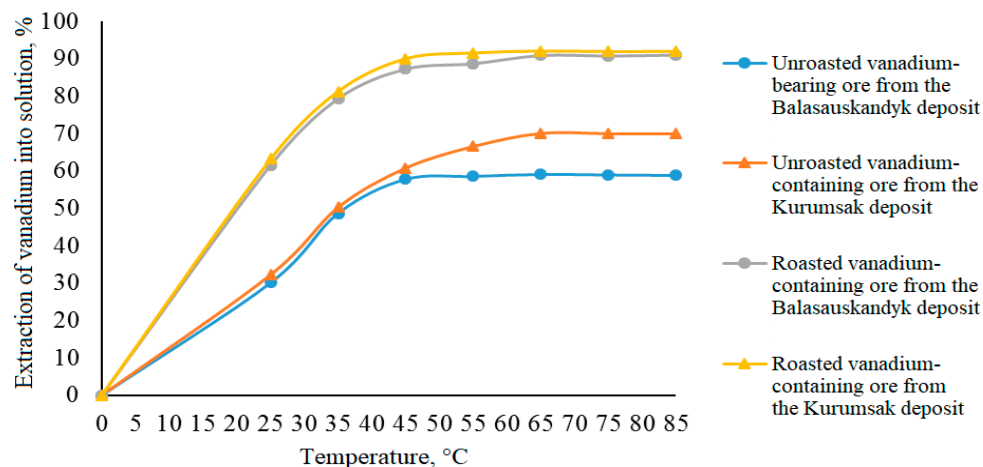
**Figure 6.** Dependence of vanadium extraction rate into solution on the solid-to-liquid (S:L) phase ratio.

Effect of electrochemical oxidation temperature on vanadium extraction into solution

In these experiments, the temperature varied from 25 to 85 °C while keeping other parameters constant (sulfuric acid concentration, duration, and solid-to-liquid ratio). The results are presented in Table 8 and Figure 7.

Table 8. Investigation of the effect of temperature on the degree of vanadium extraction into solution.

Temperature, °C	25	35	45	55	65	75	85
Unroasted ore from the Balasauskandyk deposit							
Concentration in solution, g/dm ³	0.232	0.375	0.445	0.451	0.455	0.454	0.453
Extraction into solution, %	30.13	48.70	57.79	58.57	59.09	58.96	58.83
Concentration in the residue, g/dm ³	0.538	0.395	0.325	0.319	0.315	0.316	0.317
Unroasted ore from the Kurumsak deposit							
Concentration in solution, g/dm ³	0.442	0.689	0.833	0.912	0.960	0.959	0.958
Extraction into solution, %	32.26	50.29	60.80	66.57	70.07	70.00	69.93
Concentration in the residue, g/dm ³	0.928	0.681	0.537	0.458	0.410	0.411	0.412
Roasted ore from the Balasauskandyk deposit							
Concentration in solution, g/dm ³	0.474	0.611	0.672	0.683	0.700	0.699	0.701
Extraction into solution, %	61.56	79.35	87.27	88.70	90.91	90.78	91.04
Concentration in the residue, g/dm ³	0.296	0.159	0.098	0.087	0.070	0.071	0.069
Roasted ore from the Kurumsak deposit							
Concentration in solution, g/dm ³	0.866	1.114	1.234	1.255	1.262	1.260	1.261
Extraction into solution, %	63.21	81.31	90.07	91.60	92.12	91.97	92.04
Concentration in the residue, g/dm ³	0.504	0.256	0.136	0.115	0.108	0.110	0.109

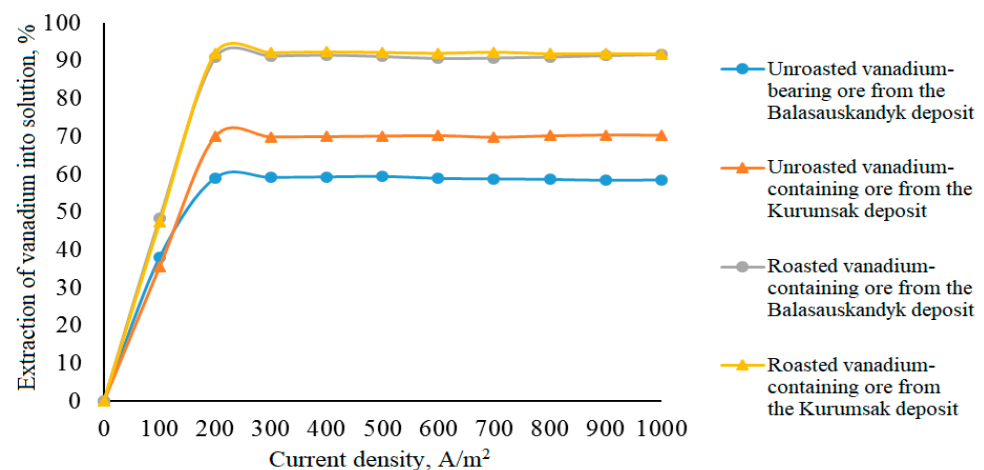
**Figure 7.** Dependence of the vanadium extraction rate into solution on temperature.

Effect of current density on vanadium leaching efficiency

Experiments to determine the dependence of vanadium leaching efficiency on current density were conducted in the range of 100–1000 A/m². All other studied parameters were kept constant and were similar to those in the previous series. The obtained results are presented in Table 9 and Figure 8.

Table 9. Influence of current density on the degree of vanadium extraction into the solution.

Current Density, A/m ²	100	200	400	800	1000
Unroasted ore from the Balasauskandyk deposit					
Concentration in solution, g/dm ³	0.293	0.455	0.457	0.452	0.451
Extraction into solution, %	38.05	59.09	59.35	58.70	58.57
Concentration in the residue, g/dm ³	0.477	0.315	0.313	0.318	0.319
Unroasted ore from the Kurumsak deposit					
Concentration in solution, g/dm ³	0.487	0.960	0.959	0.962	0.964
Extraction into solution, %	35.55	70.07	70.00	70.22	70.36
Concentration in the residue, g/dm ³	0.883	0.410	0.411	0.408	0.406
Roasted ore from the Balasauskandyk deposit					
Concentration in solution, g/dm ³	0.372	0.700	0.705	0.701	0.706
Extraction into solution, %	48.31	90.91	91.56	91.04	91.69
Concentration in the residue, g/dm ³	0.398	0.070	0.065	0.069	0.064
Roasted ore from the Kurumsak deposit					
Concentration in solution, g/dm ³	0.648	1.262	1.266	1.259	1.258
Extraction into solution, %	47.30	92.12	92.41	91.90	91.82
Concentration in the residue, g/dm ³	0.722	0.108	0.104	0.111	0.112

**Figure 8.** Dependence of the degree of vanadium extraction into the solution on current density.

Based on the conducted comprehensive studies, a conceptual technological flowsheet for the processing of hard-to-treat vanadium-bearing ores has been developed, as shown in Figure 9.

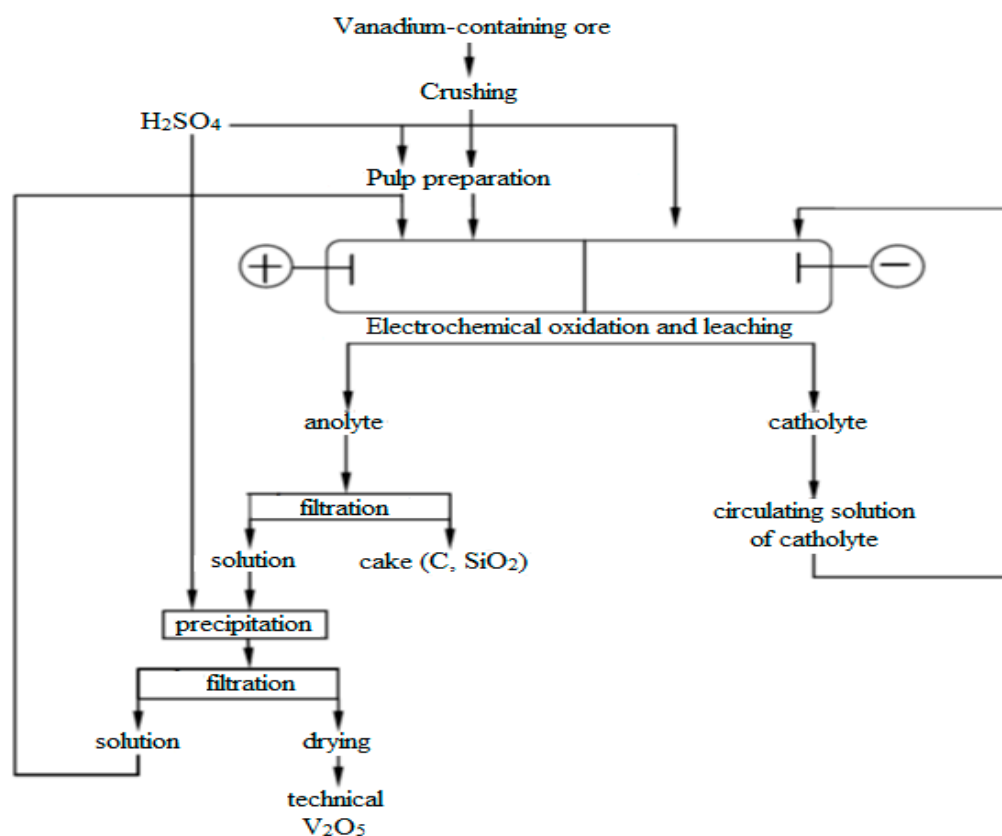


Figure 9. Principal technological scheme for the processing of refractory vanadium-bearing ores.

4. Discussion

The analysis of the data presented in Tables 1 and 2 shows an uneven distribution of vanadium in the ores from the Balasauskandyk and Kurumsak deposits. At the same time, in some ore samples from the Kurumsak deposit, the vanadium content exceeds its concentration in the ores of Balasauskandyk.

Oxidative roasting of vanadium-containing ore in the presence of alkali metal salts at temperatures ranging from 700 to 850 °C, with a holding time of 2 h at the given temperature, promotes the conversion of vanadium to a higher oxidation state (Tables 3 and 4).

From the data in Table 5 and Figure 4, it follows that during electrochemical oxidation with sulfuric acid of both unroasted and roasted vanadium-containing ores, the maximum degree of vanadium extraction into the solution is achieved at an acid concentration of 10 g/dm³. The highest vanadium extraction efficiency is observed during the electrochemical oxidation of pre-roasted ore (up to 92.12%) compared to the leaching of unroasted ore (only about 70.1%).

From Table 6 and Figure 5, it follows that increasing the duration of electrochemical oxidation of both unroasted and roasted vanadium-containing ores positively affects the dissolution of vanadium into the solution. During the first 0.5 h, vanadium extraction increases from 30.91–35.40% to 46.20–46.23%, and in the following 0.5 h, the extraction rates further increase from 59.09–70.07% to 90.91–92.12%. Extending the process duration from 1.0 to 3.0 h does not have a significant impact on the degree of vanadium extraction into the solution.

From Table 7 and Figure 6, it can be seen that increasing the solid-to-liquid ratio (S:L) from 1:2 to 1:4 raises the vanadium extraction into the solution from 30.14–32.60% to 59.09–70.07% and from 45.77–52.60% to 90.91–92.12%, respectively, during electrochemical oxidation of unroasted and roasted vanadium-containing ores. Further increasing the S:L ratio from 1:4 to 1:5 has practically no effect on vanadium extraction efficiency.

As shown by the data in Table 8 and Figure 7, the degree of vanadium extraction into the solution increases as the temperature rises from 25 to 65 °C. The maximum vanadium extraction reaches 70.07% from unroasted vanadium-containing ore and 92.12% from roasted ore. Increasing the temperature from 65 to 85 °C has practically no effect on vanadium extraction rates.

Analysis of the results showed that for more complete vanadium extraction into the solution from both unroasted and roasted vanadium-containing ores, it is advisable to conduct the leaching process at a temperature not lower than 65 °C. It was found that increasing the temperature positively affects the electrolyte's conductivity and promotes the intensification of the electrochemical oxidation process. At the same time, raising the temperature can cause indirect effects, including changes in overpotential during gas evolution (H_2 , O_2) as well as an increase in side reactions.

It was also established that the concentration of the initial solution influences the course of the electrochemical oxidation process. If the solution concentration is low and the process is carried out at high current densities to achieve a high potential, conditions in the near-electrode layer may lead to hydrogen or oxygen evolution at the respective electrodes due to insufficient diffusion of ions undergoing discharge, which reduces the current efficiency of the target product.

From Table 9 and Figure 8, it can be seen that increasing the current density during the electrochemical oxidation of unroasted and roasted vanadium-containing ores positively affects the transfer of vanadium into the solution. At a current density of 100 A/m², vanadium extraction ranged from 35.55–38.05% to 47.30–48.31%. When the current density was doubled, vanadium extraction from unroasted and roasted ores increased, respectively, from 59.09–70.07% to 90.91–92.12%. Further increasing the current density from 200 to 1000 A/m² did not have a significant effect on the degree of vanadium extraction into the solution.

One of the important characteristics of the electrochemically activated solution is the oxidation–reduction potential (ORP). ORP was measured using a platinum reference electrode relative to a silver chloride standard electrode, model ESL-15-11, with a high-impedance millivoltmeter model pH-150, which had a measurement error of 0.1 mV.

The current load was regulated by a B5-70 DC power supply, operating in voltage stabilization and current stabilization modes. Voltage and current were measured using a multimeter.

In the experiments, the optimal sulfuric acid concentration was 10% with an anode current density of 200 A/m², a temperature of 65 °C, an electrochemical oxidation process duration of 1 h, and a solid-to-liquid ratio of 1:4. At the end of the experiment, the solution was filtered, and then the vanadium content in the solution and residue was determined.

The degree of vanadium extraction into the solution during electrochemical oxidation was 59–70.1% for unroasted vanadium-containing ores from these deposits, and 90.9–92.1% for pre-roasted ores.

A comparative analysis of vanadium extraction methods is given in Table 10.

A comparative analysis of vanadium extraction methods (Table 10) shows that the electrochemical method combines high efficiency with a more favorable environmental profile and the potential to reduce energy consumption while optimizing parameters.

Table 10. Comparative analysis of vanadium extraction methods.

Criterion	Electrochemical Method	Acid Leaching	Roasting Followed by Leaching
Recovery efficiency	High (≈ 90 – 92%)	Medium–high (70 – 85%)	High (85 – 90%)
Energy consumption	Moderate: electricity required for electrolysis, but no roasting	Low: moderate temperatures, but high reagent consumption	High: roasting at 700 – 900 °C
Environmental impact	Relatively low: minimization of wastes and emissions	Significant: generation of acidic effluents	High: SO_2 and CO_2 emissions, slag formation
Advantages	Flexible process control, environmentally friendly	Simplicity, well-established technology	High recovery, applicable to refractory ores
Disadvantages	Requires electricity supply, electrolyte management	Large reagent consumption, wastewater treatment issues	High energy demand, significant pollution

5. Conclusions

The conducted studies showed the possibility of effective electrochemical oxidation of vanadium and confirmed the prospects of the proposed method for extracting metal from solutions. The development of effective technologies for processing vanadium-containing ores from the Balasauskandyk and Kurumsak deposits, characterized by a complex mineralogical structure, has acquired special importance. Thermodynamic modeling serves as a justification for the choice of experimental conditions and confirms their correctness. It was shown that preliminary oxidative roasting of ore with the addition of sodium salts at temperatures of 700 – 850 °C promotes the conversion of vanadium into readily soluble forms with a high degree of oxidation, which significantly increases the efficiency of subsequent electrochemical leaching.

Experimental data demonstrated the high effectiveness of the electrochemical method, especially when processing pre-roasted material, from which the degree of vanadium extraction into the solution reaches 90.9 – 92.1% , compared to 59 – 70.1% for unroasted ore. Optimal technological parameters were identified: sulfuric acid concentration of 10% , temperature of 65 °C, duration of 1 h, solid-to-liquid ratio of $1:4$, and current density of 200 A/m². It was established that increasing the temperature and current density up to certain limits contributes to the intensification of the electrochemical process; however, excessive increases lead to a rise in side reactions and a decrease in efficiency.

The obtained results have important scientific and practical significance, as the electrochemical oxidation of vanadium directly from natural mineral raw materials has been realized for the first time. This opens opportunities for creating highly efficient and environmentally safe technologies for the comprehensive processing of vanadium-containing ores in Kazakhstan, involving subeconomic ore reserves in economic turnover and extracting valuable associated components such as uranium and rare earth elements.

Author Contributions: Conceptualization, S.J.; data processing, G.M.; formal analysis, G.M. and Z.A.; research, S.J. and Z.A.; methodology, Z.A.; project administration, S.J.; resources, G.M. and Z.A.; software, S.J. and G.M.; visualization, S.J., Z.A. and G.M.; Writing—original draft preparation, S.J.; writing—review and editing, S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the governmental institution “Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan” within the framework of project AP22683893, entitled “Hydrometallurgical Processing Technology for Refractory Vanadium-Bearing Ores of Kazakhstan to Obtain the Target Product—Vanadium Pentoxide (V_2O_5)”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data to support the results of this study are included in this article.

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

References

1. Vanadium Market Report 2025. Available online: https://www.researchandmarkets.com/report/vanadium?srsId=AfmBOOpJFi4Yd3D8d_GezaG1LT4BsTTn3XSJzboWVmqMQSE7qMYopCV08 (accessed on 10 March 2025).
2. Vanadium—Mineral Commodity Summaries 2024—USGS.gov. Available online: <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-vanadium.pdf> (accessed on 10 March 2025).
3. Roskill—Vanadium: Outlook to 2030. Available online: <https://www.woodmac.com/reports/metals-roskill-vanadium-outlook-to-2030-545713/> (accessed on 10 March 2025).
4. Nasimifar, A.; Mehrabani, J.V. A review on the extraction of vanadium pentoxide from primary, secondary, and co-product sources. *Int. J. Min. Geo-Eng.* **2022**, *56*, 361–382. [\[CrossRef\]](#)
5. Mineral Commodity Summaries 2023. Available online: <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf> (accessed on 10 March 2025).
6. Zhang, W.; Li, X.; Zhu, Y.; Sun, K.; Zhang, W. Rapid Vanadium Extraction from Roasted Vanadium Steel Slag via a H₂SO₄–H₂O₂ System. *ACS Omega* **2022**, *7*, 32429–32438. [\[CrossRef\]](#)
7. Li, H.; Ren, Q.; Tian, J.; Tian, S.; Wang, J.; Zhu, X.; Shang, Y.; Liu, J.; Fu, L. Efficient recovery of vanadium from calcification roasted-acid leaching tailings enhanced by ultrasound in H₂SO₄–H₂O₂ system. *Miner. Eng.* **2024**, *205*, 108492. [\[CrossRef\]](#)
8. Kologrieva, U.; Volkov, A.; Zinoveev, D.; Krasnyanskaya, I.; Stulov, P.; Wainstein, D. Investigation of Vanadium-Containing Sludge Oxidation Roasting Process for Vanadium Extraction. *Metals* **2021**, *11*, 100. [\[CrossRef\]](#)
9. Yang, J.; Wang, Y.; Gao, X.; Zuo, R.; Song, L.; Jin, C.; Wang, J.; Teng, Y. Vanadium: A Review of Different Extraction Methods to Evaluate Bioavailability and Speciation. *Minerals* **2022**, *12*, 642. [\[CrossRef\]](#)
10. Liu, S.; Wang, L.; Chen, J.; Ye, L.; Du, J. Research progress of vanadium extraction processes from vanadium slag: A review. *Sep. Purif. Technol.* **2024**, *342*, 127035. [\[CrossRef\]](#)
11. Yuan, J.; Cao, Y.; Fan, G.; Du, H.; Dreisinger, D.; Han, G.; Li, M. Study on the mechanisms for vanadium phases' transformation of vanadium slag non-salt roasting process. In *Book Rare Metal Technology*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 235–242.
12. Liu, S.; Wang, L.; Chou, K.-C. Innovative method for minimization of waste containing Fe, Mn and Ti during comprehensive utilization of vanadium slag. *Waste Manag.* **2021**, *127*, 179–188. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Liu, S.; Wang, L.; He, X.; Chou, K.-C. Insight into the oxidation mechanisms of vanadium slag and its application in the separation of V and Cr. *J. Clean. Prod.* **2023**, *405*, 136981. [\[CrossRef\]](#)
14. Wikipedia. Karatau Vanadium Basin. Available online: https://ru.wikipedia.org/wiki/Каратауский_ванадиевый_бассейн (accessed on 10 March 2025).
15. Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan. State Register of Mineral Reserves. 2022. Available online: <https://kz.kursiv.media/2011-09-01/pri-lyubom-sprose-rm-i-rzm-ne-uydut-v-oblast-nerentabelnosti> (accessed on 12 March 2025).
16. Vanadium Mining Technology in Kyzylorda Region Has Not Been Developed. Available online: https://forbes.kz/news/newsid_28719 (accessed on 12 March 2025).
17. Volkov, A.I. State and prospects of the use of rare metals in ferrous metallurgy. *Razved. Okhr. Nedr.* **2020**, *3*, 11–18. (In Russian)
18. Silin, I.; Gürsel, D.; Kremer, D.; Hahn, K.; Wotruba, H. Production of Vanadium Concentrate from a Small-Scale Lead Vanadate Deposit by Gravity Concentration: A Pilot Plant Study. *Minerals* **2020**, *10*, 957. [\[CrossRef\]](#)
19. Gao, L.; Gao, B.; Xu, D.; Liu, L. DGT: A promising technology for in-situ measurement of metal speciation in the environment. *Sci. Total Environ.* **2020**, *715*, 136810. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Krashenin, A.G.; Vatolin, N.A.; Khalezov, B.D.; Zayakin, O.V.; Sychev, A.V.; Zhuchkov, V.I. Technology for Comprehensive Processing of Vanadium Metallurgical Slags. In Proceedings of the International Congress “Fundamentals of Processing and Recycling of Technogenic Wastes”, New Delhi, India, 24–28 September 2012; UIPC LLC: Ekaterinburg, Russia, 2012; pp. 438–441.
21. Chepushtanova, T.; Yulusov, S.; Baygengzhenov, O.; Khabiev, A.; Merkibayev, E.; Mishra, B. Review of Methods for Processing Vanadium-Bearing Ores. *Eng. J. Satbayev Univ.* **2024**, *146*, 15–22. [\[CrossRef\]](#)
22. Baygengzhenov, O. Review of Methods for Processing Technogenic Vanadium-Bearing Materials. *Bull. EKSTU* **2024**, *2*. Available online: <https://vestnik.ektu.kz/index.php/vestnik/article/view/843> (accessed on 12 March 2025).
23. Cai, J.J.; Zhou, M.H.; Zhang, Q.Z.; Tian, Y.S.; Song, G. The radical and non-radical oxidation mechanism of electrochemically activated persulfate process on different cathodes in divided and undivided cell. *J. Hazard. Mater.* **2021**, *416*, 125804. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Song, H.R.; Yan, L.X.; Wang, Y.W.; Jiang, J.; Ma, J.; Li, C.P.; Wang, G.; Gu, J.; Liu, P. Electrochemically activated PMS and PDS: Radical oxidation versus nonradical oxidation. *Chem. Eng. J.* **2020**, *391*, 123560. [\[CrossRef\]](#)

25. Zou, J.P.; Chen, X.; Liu, S.S.; Xing, Q.J.; Dong, W.H.; Luo, X.B.; Dai, W.L.; Xiao, X.; Luo, J.M.; Crittenden, J. Electrochemical oxidation and advanced oxidation processes using a 3D hexagonal Co₃O₄ array anode for 4-nitrophenol decomposition coupled with simultaneous CO₂ conversion to liquid fuels via a flower-like CuO cathode. *Water Res.* **2019**, *150*, 330–339. [[CrossRef](#)] [[PubMed](#)]
26. Song, H.R.; Yan, L.X.; Jiang, J.; Ma, J.; Zhang, Z.X.; Zhang, J.M.; Liu, P.X.; Yang, T. Electrochemical activation of persulfates at BDD anode: Radical or nonradical oxidation? *Water Res.* **2018**, *128*, 393–401. [[CrossRef](#)] [[PubMed](#)]
27. Liu, Z.; Ding, H.J.; Zhao, C.; Wang, T.; Wang, P.; Dionysiou, D.D. Electrochemical activation of peroxymonosulfate with ACF cathode: Kinetics, influencing factors, mechanism, and application potential. *Water Res.* **2019**, *159*, 111–121. [[CrossRef](#)] [[PubMed](#)]
28. Zhang, Y.; Kang, V.D.; Yu, H.T.; Chen, S.; Kuan, H. Electrochemical Activation of Peroxymonosulfate in Cathodic Micro-Channels for Effective Degradation of Organic Pollutants in Wastewater. *J. Hazard. Mater.* **2020**, *398*, 122879. [[CrossRef](#)] [[PubMed](#)]
29. Alybayev, Z.; Boshkayeva, L.; Bekenova, G.; Dzhumankulova, S. Studying the process of vanadium leaching from vanadium ores of Big Karatau (Southern Kazakhstan) by chemical and electrochemical oxidation methods. In Proceedings of the International Conference “Scientific Research of the SCO Countries: Synergy and Integration”, Beijing, China, 14–15 June 2018; pp. 228–236.
30. Jumankulova, S.K.; Alybayev, Z.A.; Zhuchkov, V.I.; Boshkayeva, L.T. Oxidative Roasting of Vanadium-Bearing Ore with Alkali Metal Salts. *Complex Use Miner. Resour.* **2018**, *3*, 37–45. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.