

Article

Investigation of the Electrodialysis of Sodium Tungstate Solutions for the Production of Tungstic Acid

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Abstract

Industrial technologies for processing tungsten concentrates using soda roasting or autoclave leaching are based on the production of alkaline sodium tungstate solutions that contain impurities such as silicon, phosphorus, arsenic, and others. The purification of these solutions from impurities requires the neutralization of excess soda or alkali with inorganic acids, which leads to the formation of chloride and sulfate effluents that are subsequently discharged into waste repositories. An analysis was carried out on existing methods for the production and processing of sodium tungstate solutions using HNO_3 and NH_3 , as well as extraction and sorption techniques involving anion exchange resins. Currently, processes such as nanofiltration, reverse osmosis, and electrodialysis are being applied for water purification and the treatment of sulfate and chloride effluents. These processes employ various types of industrially manufactured membranes. For the purpose of electrodialysis, a two-compartment electrodialyzer setup was employed using cation-exchange membranes of the MK-40 (Russia) and EDC1R (China) types. The composition and structure of sodium tungstate, used as the starting reagents, were analyzed. Based on experiments conducted on a laboratory-scale unit with continuous circulation of the catholyte and anolyte, dependencies of various parameters on current density and process duration were established. Stepwise changes in the anolyte pH were recorded, indirectly confirming changes in the composition of the Na_2WO_4 solution, including the formation of polytungstates of variable composition and the production of H_2WO_4 via electrodialysis at $\text{pH} < 2$. The resulting tungstic acid solutions were also analyzed. The conducted studies on the processing of sodium tungstate solutions using electrodialysis made it possible to obtain alkaline solutions and tungstic acid at a current density of $500\text{--}1500\text{ A/m}^2$, without the use of acid for neutralization. Yellow tungstic acid was obtained from the tungstic acid solution by evaporation.

Keywords: sodium tungstate; tungstic acid; purification; electrodialysis; membrane processes



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1. Introduction

The primary method for processing tungsten raw materials in countries such as China [1,2], Russia [3,4], the Democratic Republic of the Congo, Canada, and the USA [5] is the roasting of concentrates with Na_2CO_3 followed by the leaching of the calcined product. Another widely used method is the autoclave leaching of the concentrate with an alkaline solution to produce soluble sodium tungstate (Na_2WO_4) [6]. Further processing of the

sodium tungstate solution [7–9] involves the sequential removal of impurities through the formation of insoluble compounds, which are subsequently separated by filtration. In China and Russia, this method [2,8] is the main approach used for extracting tungsten from ores containing molybdenum and other metals.

The conventional scheme for processing sodium tungstate solutions [10,11] includes the following stages:

- Sequential removal of sodium salt impurities, such as silicon, phosphorus, molybdenum, arsenic, and additional silicon;
- Precipitation of calcium tungstate (CaWO_4 , synthetic scheelite) [12], followed by acid decomposition of the precipitate to produce H_2WO_4 ;
- Dissolution of tungstic acid in aqueous ammonia [7,13], evaporation of the resulting solution, and crystallization of ammonium paratungstate (APT) [14–16];
- The final stage of the process involves the calcination of ammonium paratungstate to obtain high-purity tungsten trioxide.

Ammonium paratungstate can also be directly recovered from sodium tungstate solutions via extraction [17] or ion-exchange conversion of Na_2WO_4 solutions into $(\text{NH}_4)_2\text{WO}_4$. In [18], the authors present results on the processing of sodium tungstate solutions obtained by the autoclave leaching of wolframite concentrate with soda. The study investigated parameters such as solution acidity, type of mineral acid, and the presence of complexing and seeding agents. The sodium tungstate solution was acidified with concentrated nitric acid in a molar ratio of $\text{HNO}_3:\text{W} = 12:1$. The use of nitric acid enables a high degree of tungsten precipitation in the temperature range of 75–95 °C.

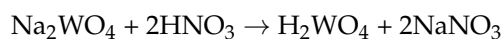
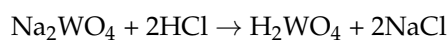
In [19], a technology for processing tungsten-containing waste with subsequent production of sodium tungstate solutions is presented. The waste underwent mechanical treatment and was leached with the addition of sodium hydroxide. The productive solution was then directed to the impurity removal stage. The sorption process was carried out using the anion exchanger MP–62, followed by washing with nitric acid, while extraction purification was performed using an ammonia solution.

The study [20] describes a method for investigating the sorption recovery of tungsten from tungsten-containing solutions using a flocculant (polyacrylamide) and the anion exchanger AV–17–8 in a ratio of 1:8 (ion exchanger to solution) in pressure sorption columns.

In the work by the authors [21,22], a method is described for obtaining sodium tungstate by smelting a charge composed of wolframite, Na_2CO_3 , and SiO_2 at a temperature of 1100–1300 °C. After smelting, sodium tungstate was separated from the slag, which contained excess sodium oxide, flux, and unreacted wolframite. The slag was additionally subjected to leaching to extract the remaining sodium tungstate. The resulting product contained 78% WO_3 and was presumed to be subsequently directed for electrolysis.

In industrial processing, tungsten concentrates are sintered with sodium carbonate (Na_2CO_3), followed by the aqueous leaching of the sintered mass. This yields alkaline sodium tungstate (Na_2WO_4) solutions containing 110–150 g/L WO_3 and exhibiting a high pH in the range of 12–14 [11].

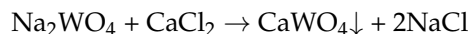
Tungstic acid (H_2WO_4) can be directly precipitated from sodium tungstate solutions via acidification with mineral acids such as hydrochloric or nitric acid, according to the following reactions:



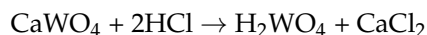
Despite the apparent simplicity of these reactions, this method is seldom employed industrially due to significant challenges in removing residual sodium ions from the

precipitate. The presence of sodium in the final tungsten trioxide product must be strictly limited, complicating purification.

More commonly, calcium tungstate (CaWO_4) is initially precipitated by introducing a calcium chloride (CaCl_2) solution at elevated temperatures (80–90 °C), resulting in the formation of a fine white crystalline precipitate:



The CaWO_4 precipitate, typically obtained as a pulp or paste, is subsequently decomposed by hydrochloric acid at approximately 90 °C:



According to stoichiometric calculations, the production of 249.85 kg of tungstic acid requires approximately 73 kg of hydrochloric acid. Furthermore, the actual acid consumption often exceeds this amount due to the necessity of neutralizing residual sodium carbonate (Na_2CO_3) or sodium hydroxide (NaOH), which are present in solutions derived from roasting and autoclave leaching technologies, respectively.

The use of inorganic acids in tungstic acid production also leads to the generation of significant volumes of saline effluents (e.g., NaCl or Na_2SO_4), contributing to environmental pollution and necessitating costly wastewater treatment processes.

The aim of the present study was to investigate the feasibility of producing tungstic acid from sodium tungstate solutions via a membrane-based electrodialysis process. This approach employs insoluble platinum anodes and cation exchange membranes, offering a potential alternative that eliminates the need for mineral acids and avoids the formation of saline waste streams. The specific objectives included the selection of suitable ion-exchange membranes and electrode materials, as well as the evaluation of key electrodialysis parameters and their effects on process efficiency and product quality.

Electrodialysis is currently widely applied in technologies for the decomposition and concentration of aluminate solutions [23,24], the processing of binary solutions containing sodium and zinc [25,26], the treatment of industrial wastewater and seawater desalination [27,28], the removal of nickel ions from solutions [29], and the recovery of acids and alkalis from sodium sulfate solutions [30].

One study [31] focused on exploring the electrodialysis behavior of sodium tungstate solutions, describing an experimental method for removing impurities from these solutions. The author proposes conducting electrodialysis of Na_2WO_4 in a two-compartment electrodialyzer using a cation-exchange membrane to separate the anode and cathode chambers. This investigation was carried out with small quantities of sodium tungstate to determine the fundamental feasibility of producing tungstic acid via electrodialysis.

2. Materials and Methods

Sodium tungstate solutions were prepared using the reagent $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$ (sodium tungstate dihydrate) of analytical grade, in accordance with standard 18289–78 [32], with the composition shown in Table 1.

Sodium tungstate (Na_2WO_4) is a white powder, soluble in water, and may contain impurities such as N, SO_4 , Cl, Fe, Mo, As, and Pb not exceeding 0.01%. The density at a concentration of 38% and a temperature of 20 °C is 3.00 g/cm³. The pH value is between 9 and 11. The electrical conductivity of the sodium tungstate solution depends on the concentration and temperature of the solution. For a solution with a concentration of 0.1 mol/L, the conductivity is 0.01–0.1 S/m [33].

According to literature sources, the formation of sodium paratungstates in solutions is possible during the electrodialysis process.

Table 1. Composition of the initial sodium tungstate.

Indicator Name	Mass %
Mass fraction of $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$, %, not less than	99.0
Mass fraction of water-insoluble substances, %, not more than	0.01
Mass fraction of nitrogen (N) from nitrates, nitrites, etc., %, not more than	0.01
Mass fraction of sulfates (SO_4), %, not more than	0.01
Mass fraction of chlorides (Cl), %, not more than	0.003
Mass fraction of iron (Fe), %, not more than	0.0005
Mass fraction of molybdenum (Mo), %, not more than	0.002
Mass fraction of arsenic (As), %, not more than	0.0005
Mass fraction of heavy metals (Pb), %, not more than	0.001
pH of a 5% solution of the reagent	8–10

Sodium paratungstate is an inorganic substance, a complex salt of sodium and tungstic acid with the formula $\text{Na}_5[\text{HW}_6\text{O}_{21}]$. Under normal conditions, it is a white crystalline substance, soluble in water, and poorly soluble in organic solvents. A crystalline hydrate with the formula $\text{Na}_5[\text{HW}_6\text{O}_{21}] \cdot 13.5\text{H}_2\text{O}$ exists and is stable in air [33].

The initial reagent $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$ was analyzed using an X-ray diffractometer X, Pert MPD PRO (PANalytical, Singapore), and JED-2300 AnalysisStation JEOL (Singapore). The results of the analyses are shown in Figure 1.

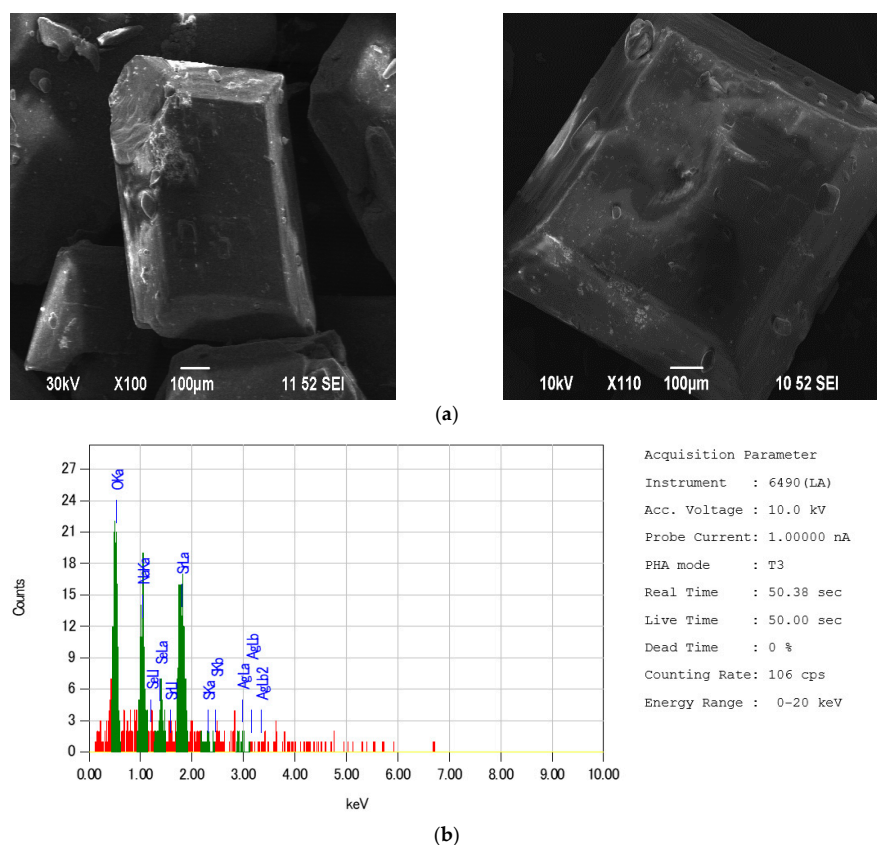


Figure 1. Images of $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$ obtained using X-ray diffractometer X (a) and spectrum from JED-2300 AnalysisStation JEOL (b).

A simplified scheme of an electrochemical cell (Figure 2) was used to carry out the electrodialysis of sodium tungstate solutions for the purpose of producing tungstic acid and regenerating the NaOH solution.

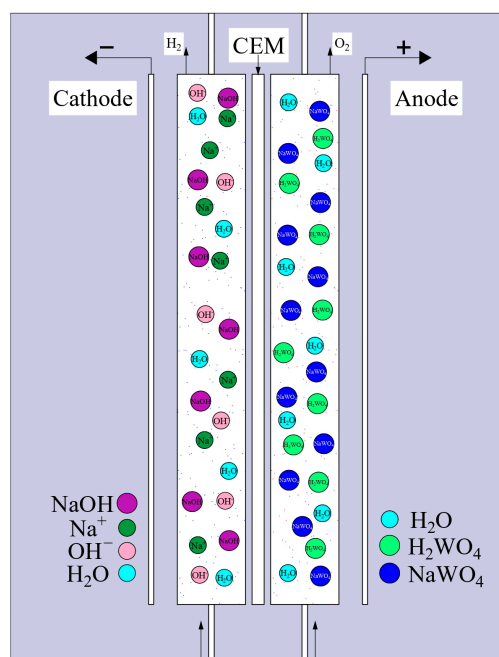


Figure 2. Diagram of a 2-compartment electrodialyzer.

The electrodialyzer unit was constructed from rectangular plates and frames made of plexiglass. The installation parameters of the electrodialyzer are shown in Table 2.

Table 2. Parameters of the electrodialyzer unit.

Parameter	Unit	Value
External dimensions of the cell	mm	100 × 180 × 8
Internal dimensions of the cell	mm	70 × 140 × 8
Cathode—stainless steel	mm	100 × 182 × 1
Effective surface area of the cathode	cm ²	98
Surface area of the cation-exchange membrane	cm ²	98
Surface area of the platinized anode	cm ²	50
Distance from cathode to membrane	cm	2.0
Volume of the cathode compartment	mL	98
Distance from anode to membrane	cm	2.0
Volume of the anode compartment	mL	98

Cation-exchange membranes of the MK-40 (Russia) [34] and EDC1R (China) [35] brands were used. According to the manufacturers, the electrical resistance of the membranes is $R_{avg} = 10.0 \, \Omega \cdot \text{cm}^2$ for MK-40 and $R_{avg} = 5.0 \, \Omega \cdot \text{cm}^2$ for EDC1R.

Figure 3 shows the electrodialyzer setup with the solution circulation and pH control of the resulting tungstic acid (H_2WO_4) solution.

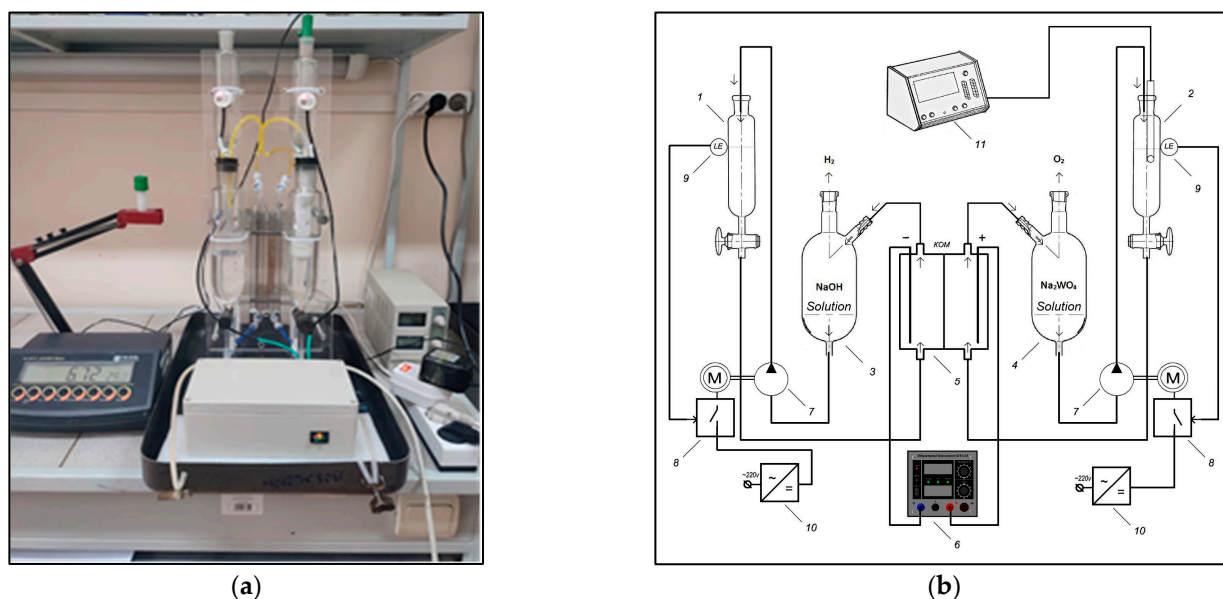


Figure 3. Electro dialysis setup for Na₂WO₄ solution (a) and diagram of the experimental setup (b). 1—Pressure vessel for NaOH solution; 2—Pressure vessel for Na₂WO₄ solution; 3—Recirculation vessel for NaOH solution with H₂ separation; 4—Recirculation vessel for Na₂WO₄ solution with O₂ separation; 5—Two-section electro dialyzer; 6—Power supply with current and voltage control; 7—Membrane pumps; 8—Electronic power supply switches; 9—Electronic level sensors; 10—Power supply units for pumps; 11—pH meter.

The pH of the anolyte solution was measured using the HANNA HI 2213 pH/ORP Meter (Singapore). The circulation speed of the electrolytes was regulated by the power supply voltage of the membrane pumps and the electrolyte levels in the pressure vessels. The density of the Na₂WO₄ (H₂WO₄) and NaOH solutions was measured using the digital densitometer D6 Excellence.

Figure 4 shows the dependencies of the voltage at the electro dialysis unit and the electrical conductivity of the cell on the current density from 50 to 200 A/m².

Electro dialysis was carried out with the current density at the electrodes as follows: cathodic current density $d(k)$ ranging from 25.51 to 523.56 A/m² and anodic current density $d(a)$ ranging from 50 to 1333.33 A/m². The graphs show that as the current increases, the voltage across the electro dialysis system and the conductivity of the solutions consistently rise.

The volumes of solutions in the pressure vessels for the cathodic and anodic compartments were $V(\text{Na}_2\text{WO}_4) = 500\text{--}600$ mL and $V(\text{NaOH}) = 500\text{--}600$ mL, with the circulation rate of the solutions in the chambers ranging from 5 to 8 L/hour.

Experiments on the electro dialysis of sodium tungstate solutions were carried out using the method of probabilistically deterministic experiment planning [36] (an analog of Desing Expert 7.0). The following process factors were taken into account: duration, current density, and concentration of Na₂WO₄. The temperature of the solution, the circulation rate, the pH of the solution, and the density of tungstate and alkali solutions were monitored. The accepted significance level is 0.05 or a 95% confidence probability of the results.

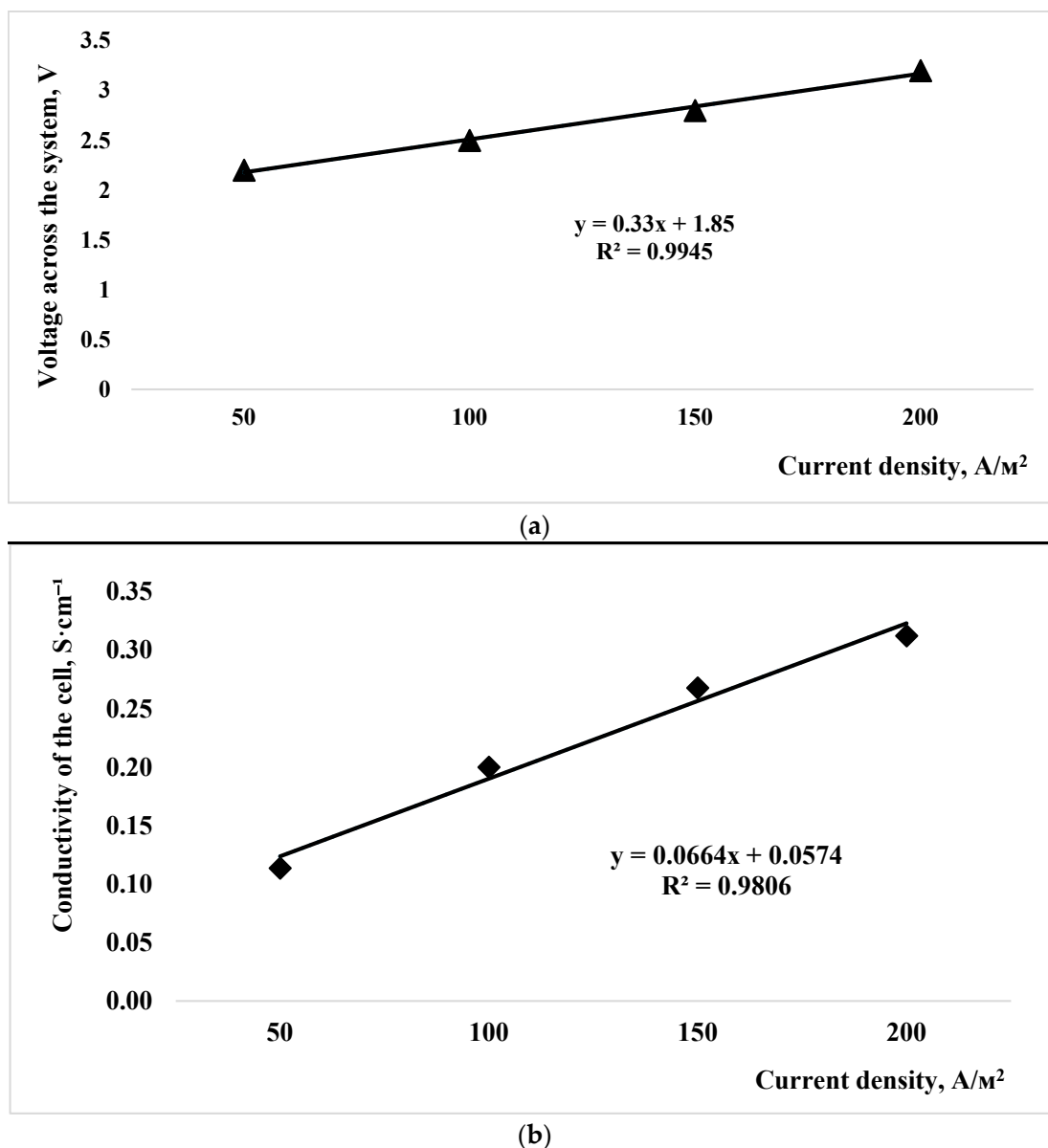


Figure 4. Dependence of the voltage (a) and cell conductivity (b) on the current density electrodia-lysis.

3. Results and Discussion

The schemes of a multi-chamber electrodialyzer employing cation-exchange, anion-exchange, and bipolar membranes are primarily used for water desalination [37]. These configurations are also applicable for the concentration of salt solutions such as NaCl, Na₂SO₄, and others, where salts dissociate in water to form mobile cations and anions.

However, this conventional multi-chamber electrodialyzer design—with ion-selective and bipolar membranes—is not suitable for the electrodialysis of sodium tungstate solutions. In alkaline media (pH > 8), sodium tungstate undergoes dissociation according to the following reaction scheme:



During the dissociation of sodium tungstate, mobile Na⁺ ions and relatively immobile WO₄^{2−} ions are formed. Moreover, as the pH of the solution decreases, polyoxotungstates (polytungstates) begin to form. In a multi-chamber system, the equivalent transfer of WO₄^{2−} anions through the anion-exchange membrane does not occur efficiently, and the

observed current is largely attributed to the migration and discharge of H_3O^+ and OH^- ions at the electrodes.

The overall reaction for the production of tungstic acid via electrodialysis from a sodium tungstate solution can be represented by the following equation:



According to the literature [38], the speciation and degree of polymerization of tungstate ions in solution depend strongly on the pH of the medium:

- Sequential removal of sodium salt impurities, such as silicon, phosphorus, molybdenum, arsenic, and additional silicon;
- In alkaline solutions up to $\text{pH} \approx 8$, normal (monomeric) tungstate ions predominate;
- In the pH range from 8 to approximately 6, hexatungstate ions ($\text{HW}_6\text{O}_{21}^{5-}$) are formed;
- With a further decrease in pH, particularly in highly dilute solutions, the monohydrogen hexatungstate ion ($\text{HW}_6\text{O}_{21}^{5-}$) is converted into the trihydrogen form ($\text{H}_3\text{W}_6\text{O}_{21}^{3-}$);
- Upon the gradual neutralization of alkaline sodium tungstate solutions to $\text{pH} \approx 5$, a precipitate of sodium paratungstate ($\text{Na}_{10}\text{W}_{12}\text{O}_{41} \cdot 28\text{H}_2\text{O}$) is formed;
- Normal alkaline tungstates are highly soluble, whereas paratungstates exhibit significantly lower solubility;
- At $\text{pH} < 4$, metatungstate aquapolyions are formed, typically with a $\text{Me}_2\text{O}:\text{WO}_3$ ratio of 1:4 (e.g., $\text{Na}_2\text{W}_2\text{O}_7$). The number of coordinated water molecules in isopoly and heteropoly tungstate species varies depending on temperature and concentration, which in turn influences the physicochemical properties of the resulting salts.

Figure 5 illustrates the variation in the acidity of the anolyte during the electrodialysis of a sodium tungstate solution with an initial concentration of 135 g/L, carried out at an anodic current density of 666.7 A/m^2 .

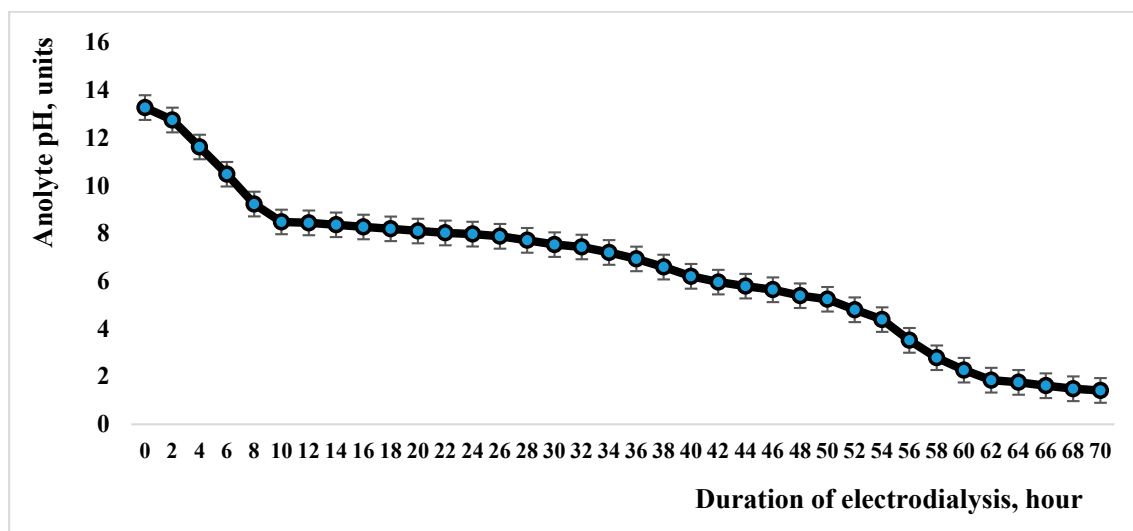


Figure 5. Change in the pH of the tungstate solution from the duration of electrodialysis at $d_a = 666.7 \text{ A/m}^2$.

As seen from the pH of the sodium tungstate solution in Figure 5, distinct regions of stepwise changes in composition can be identified, which are consistent with previously reported data. The final segment of the curve, corresponding to the pH decrease from 4.0 to 1.42, reflects the progressive removal of sodium ions from metatungstate species such as

Na_2WO_7 and the subsequent formation of hydrated compounds, including $\text{WO}_3 \cdot 2\text{H}_2\text{O}$ or $\text{H}_2\text{WO}_4 \cdot \text{H}_2\text{O}$ (commonly referred to as white tungstic acid).

At elevated solution temperatures above 30°C , further dehydration leads to the formation of $\text{WO}_3 \cdot \text{H}_2\text{O}$ or H_2WO_4 (yellow tungstic acid). At low current densities, the temperature of the circulating anolyte and catholyte remained between 25 and 28°C , resulting in the formation of a gel-like white tungstic acid. In contrast, higher current densities led to electrolyte heating above 30 – 35°C , promoting the formation of dispersed particles of yellow tungstic acid.

Furthermore, during sodium ion removal from solutions containing Na_2WO_7 -type compounds, the transient formation of intermediate hydrated tungstate species, such as H_2WO_7 , is also possible.

Figure 6 shows that as sodium ions are removed from the anolyte and the pH of the sodium tungstate solution decreases pH to the formation of polyoxotungstates and tungstic acid in the pH range of 8 to 7—the resistance of the electro dialysis cell increases. This is attributed to a reduction in the electrical conductivity of the tungstate solution.

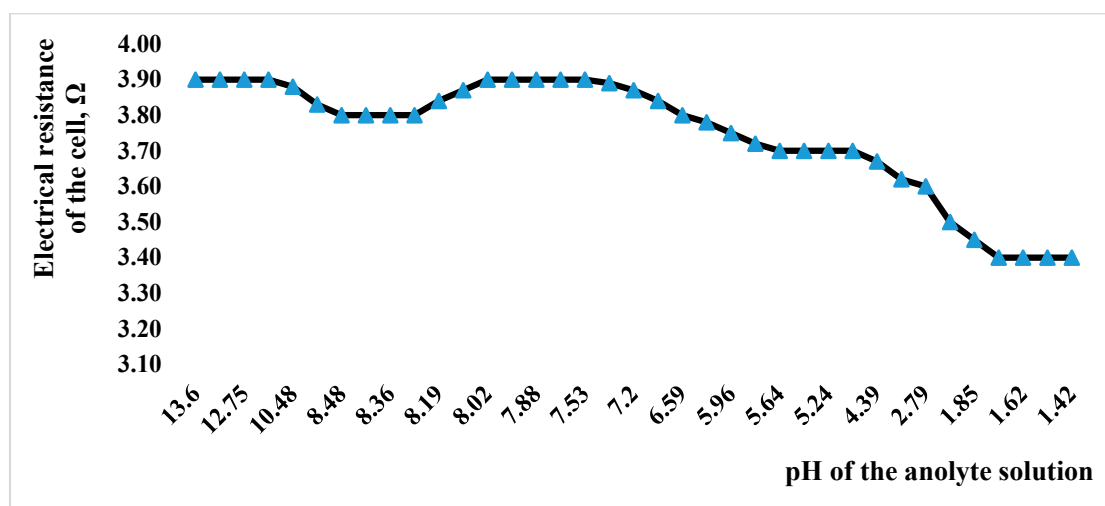


Figure 6. Dependence of solution pH on total cell resistance of electro dialysis at $da = 666.7 \text{ A/m}^2$.

As the acidity further increases, with the pH decreasing from approximately 7 to 1.42, the cell resistance decreases in a stepwise manner. This also supports the occurrence of compositional changes in the anolyte during the electro dialysis process.

One of the key indicators determining the feasibility of using the electro dialysis of sodium tungstate solutions for tungstic acid production and for reducing the consumption of inorganic acids in tungsten processing technologies is the energy consumption per unit mass of tungstate.

Based on the results of electro dialysis experiments conducted at various current densities, the dependence shown in Figure 7 was obtained.

With an increase in both anode and cathode current densities above 200 A/m^2 , the specific energy consumption per unit mass of sodium tungstate increases significantly. At the same time, the proportion of energy directed toward the electrode reactions—namely, the formation of tungstic acid and oxygen in the anode compartment, and alkali and hydrogen in the cathode compartment—decreases from 61.5–69.4% to 24.8–30.3%. As the current density rises, electrical losses due to heat generation and electrolyte heating also increase.

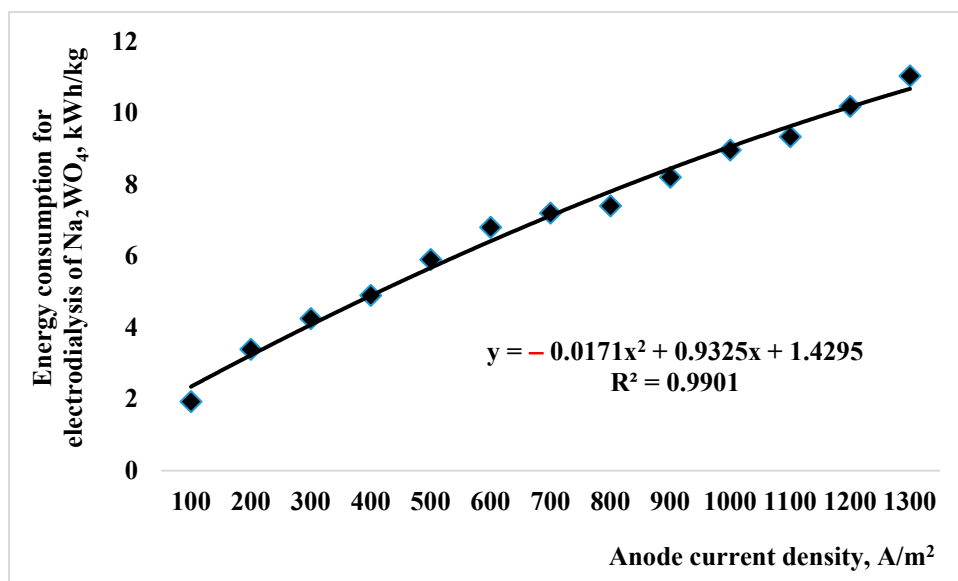


Figure 7. Dependence of energy consumption during electroanalysis of Na_2WO_4 on anodic current density.

Process efficiency can be enhanced by reducing the interelectrode gap and implementing bipolar electrolyzers equipped with titanium electrodes featuring unilateral platinum coating. However, scaling up the process is limited by the available size of platinum-coated electrodes. Currently, insoluble titanium-based anodes with a platinum layer thickness of 1 to 2.5 microns and plate dimensions ranging from 50×100 mm to 310×500 mm are manufactured in the Russian Federation.

The resulting tungstic acid solutions were evaporated in a SNOL drying oven at a temperature of 120°C to obtain solid precipitates of tungstic acid and sodium paratungstate. A photograph of the obtained samples is presented in Figure 8.



Figure 8. Photographs of solid samples obtained by evaporating tungstic acid solutions at 120°C : yellow tungstic acid and sodium paratungstate.

The phase composition of the tungstic acid powders was analyzed using an X-ray diffractometer X'Pert MPD PRO (PANalytical) and a JED-2300 Analysis Station (JEOL).

The results of the structural and elemental analyses are presented in Figures 9 and 10.

During the electroanalysis of sodium tungstate solutions at pH 4–5, a small amount of insoluble white precipitate of sodium paratungstate may form. A micrograph and corresponding spectrogram of this compound are presented in Figure 10. Sodium paratungstate is separated from the tungstic acid solution by filtration.

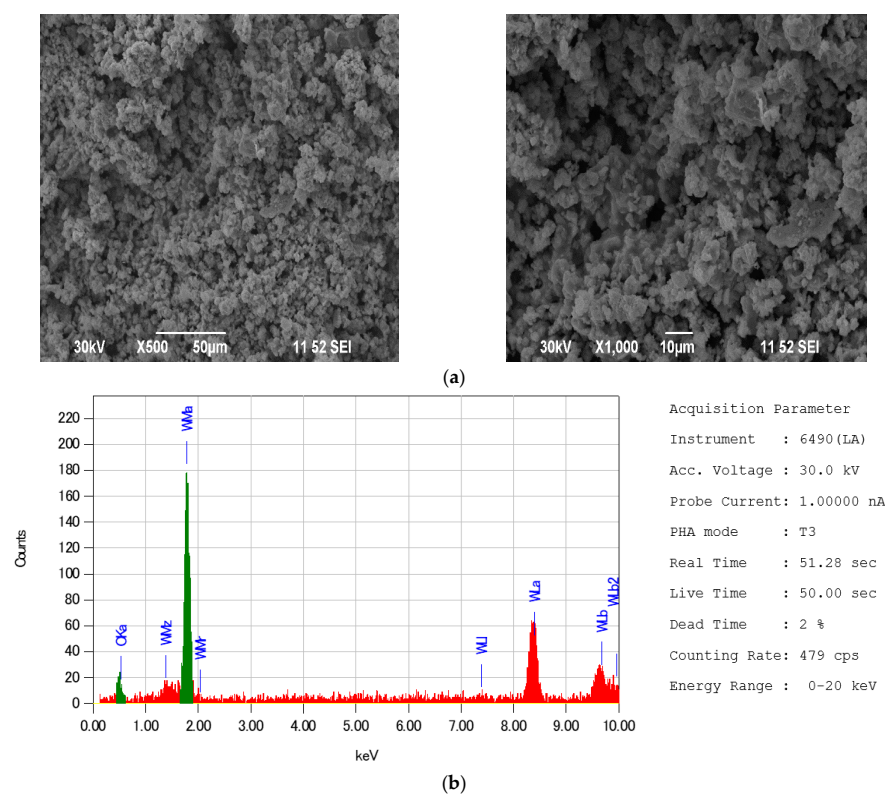


Figure 9. X-ray diffraction pattern of tungstic acid obtained using the X'Pert MPD PRO diffractometer (a), and energy-dispersive X-ray spectrogram obtained with the JED-2300 Analysis Station (JEOL) (b).

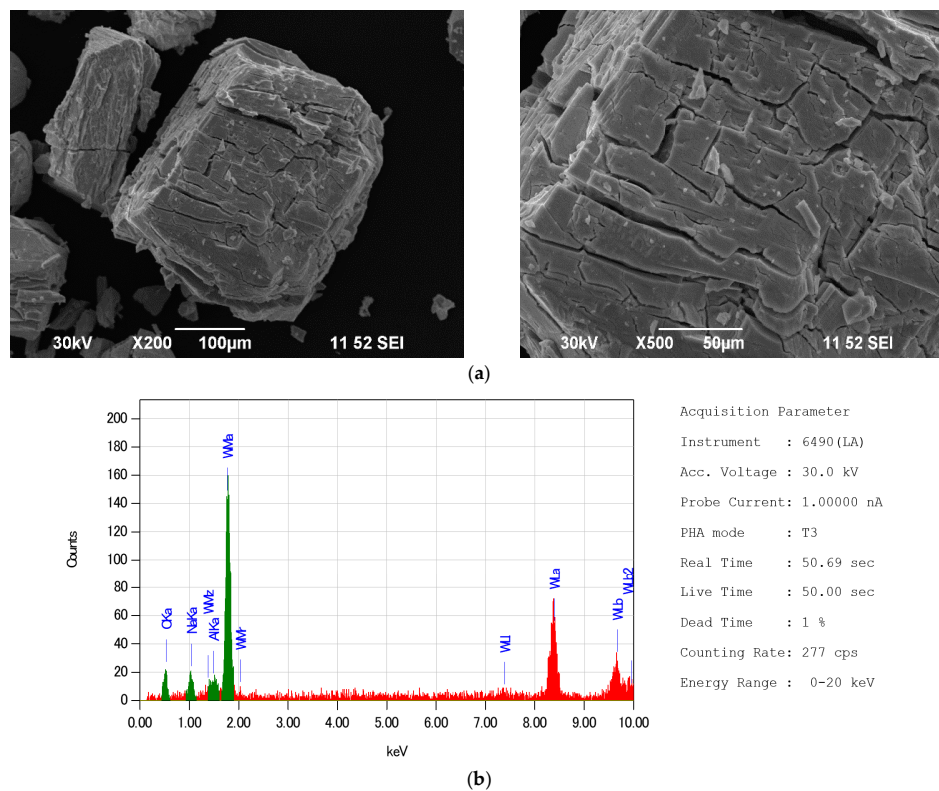


Figure 10. X-ray diffraction pattern of the insoluble sodium paratungstate precipitate obtained using the X'Pert MPD PRO diffractometer (a), and energy-dispersive X-ray spectrogram acquired with the JED-2300 Analysis Station (JEOL) (b).

4. Conclusions

Existing technologies for the production and processing of sodium tungstate solutions are accompanied by the use of a significant number of auxiliary reagents, including ammonia, sulfuric acid, hydrochloric acid, nitric acid, and anionites, which complicates the technological process and leads to the formation of sulfate and chloride effluents.

Currently, membrane technologies of electrodialysis, cations, and anions are increasingly being used for water and wastewater treatment. However, the scheme of a multi-chamber electrodialyzer with ion-selective and bipolar membranes is not applicable for the electrodialysis of solutions of sodium tungstate, which in alkaline solutions forms mobile Na^+ cations and sedentary WO_4^{2-} anions, and when the pH of the solution decreases, polyvolframates are formed.

In a multi-chamber apparatus, there is no transfer of an equivalent amount of WO_4^{2-} anions through the anion exchange membrane, and the magnitude of the flowing current is due to the discharge of H_3O^+ and OH^- anions at the cathode. This work uses a two-chamber electrodialysis unit with solution circulation and anolyte pH control, with separation of cathode and anode volumes by MK-40 (RF) and EDC1R (PRC) cation exchange membranes.

A characteristic feature is the dependence of the pH change in the sodium tungstate solution on the duration of the process; the curve exhibits distinct regions of stepwise compositional changes, corresponding to the formation of intermediate polyoxotungstate species, which is consistent with previously reported data.

At low current densities, the temperature of the circulating anolyte and catholyte remained within 25–28 °C, resulting in the formation of a gel-like white tungstic acid. In contrast, at higher current densities, the electrolytes were heated to temperatures exceeding 30–35 °C, leading to the formation of dispersed particles of yellow tungstic acid.

The electrodialysis of sodium tungstate solutions for the production of tungstic acid offers a significant reduction in the consumption of inorganic acids typically required for the neutralization and purification of alkaline solutions.

Process efficiency can be further improved by reducing the interelectrode gap and employing bipolar electrolyzers equipped with titanium electrodes featuring unilateral platinum coating. However, the scalability of the process is currently constrained by the available size of platinum-coated electrodes. In the Russian Federation, insoluble titanium-based plates are produced with platinum layer thickness ranging from 1 to 2.5 microns and plate dimensions ranging from 50 × 100 mm to 310 × 500 mm.

Author Contributions: Conceptualization, A.D. and B.B.; data curation, Y.T.; formal analysis, A.D.; investigation, A.D. and B.B.; methodology, G.M.; project administration, Y.T.; resources, G.M.; software, Y.T.; visualization, A.D. and B.B.; writing—original draft, B.B.; writing—review and editing, A.D. and B.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

References

1. Tang, L.; Wang, P.; Graedel, T.E.; Pauliuk, S.; Xiang, K.; Ren, Y.; Chen, W.-Q. Refining the understanding of China's tungsten dominance with dynamic material cycle analysis. *Resour. Conserv. Recycl.* **2020**, *158*, 104829. [CrossRef]
2. Wang, X.; Qin, W.; Jiao, F.; Dong, L.; Guo, J.; Zhang, J.; Yang, C. Review of tungsten resource reserves, tungsten concentrate production and tungsten beneficiation technology in China. *Trans. Nonferrous Met. Soc. China* **2022**, *32*, 2318–2338. [CrossRef]
3. Khatkov, V.Y.; Boyarko, G.Y. The current state of the Russian tungsten industry. Proceedings of Tomsk Polytechnic University. *Georesource Eng.* **2019**, *330*, 124–137. [CrossRef]
4. Kraydenko, R.I.; Perederin, Y.V.; Filatov, D.S.; Manucharyan, A.B.; Karpov, A.G.; Vasilishin, M.S. Tungsten mining technology: The current state of technology. *Polzunovsky Bull.* **2015**, *2*, 135–139.
5. Tungsten–2020 U.S. Geological Survey Minerals Yearbook. Available online: <https://pubs.usgs.gov/myb/vol1/2020/myb1-2020-tungsten.pdf> (accessed on 5 May 2025).
6. Zaitsev, V.P.; Markin, O.V.; Kholkin, A.I.; Chudinov, E.G.; Bobkov, A.V.; Kuznetsov, I.P. The Method of Processing Solutions of Sodium Tungstate. RF Patent No. 96123057/25, 20 January 1998.
7. Belsky, S.S. Processing of scheelite concentrate to produce tungsten trioxide. *Bulletin* **2015**, *12*, 204–208.
8. Peganov, V.A.; Shatalov, V.V.; Molchanov, T.V.; Medvedev, A.S.; Molchanov, S.A.; Adosik, G.M.; Kursinov, I.; Popov, G.; Mikhailovsky, V.G. Method of Hydrometallurgical Processing of Tungsten Concentrates. RF Patent No. 98123867/02, 28 December 1998.
9. Bogacheva, L.M.; Akbarov, U.; Ismatov, H.R.; Pirmatov, E.A.; Sidiyakin, V.V.; Edunov, I.A. Method of Purification of Sodium Tungstate Solutions from Impurities. USSR Patent No. 4722840/02, 30 January 1992.
10. Baimbetov, B.; Moldabayeva; Yeleuliyeva, A.; Jumankulova, S.; Taimassova, A.; Adilzhan, Z.; Baisultanov, R.; Yakob, E.; Serikbayev, V. Prospects of Processing Tungsten Ores from the Akchatau Deposit. *Processes* **2024**, *12*, 77. [CrossRef]
11. Zelikman, A.N.; Korshunov, B.G. Metallurgy of rare metals. In *Textbook for Universities, 2nd Edition, Revised and Expanded*; Metallurgiya: Moscow, Russia, 1991; 432p, Available online: <https://reallib.org/reader?file=412937> (accessed on 10 March 2025).
12. Sipenko, A.V.; Sotnikov, A.A. Research on the decomposition of artificial scheelite by sintering with ammonium chloride. *Notes Min. Inst.* **2009**, *181*, 158–160.
13. Verevkin, G.V.; Kulmukhamedov, G.K. Method of Obtaining Ammonium Paravolframate. RF Patent No. 96122224/02, 9 October 1998.
14. Doronin, A.V. Method of Obtaining Pure Tungstic Acid. Patent of the Russian Federation No. 2014135710/02, 9 February 2014.
15. Zhang, L.; Shen, L.; Zhou, Q.; Qi, T.; Peng, Z.; Liu, G.; Li, X. Green and low-carbon preparation of ammonium paratungstate by adding ammonia to ammonium metatungstate solution. *Hydrometallurgy* **2023**, *2221*, 106196. [CrossRef]
16. Erdoğan, M.; Karakaya, İ. Electrochemical Reduction of Tungsten Compounds to Produce Tungsten Powder. *Metall. Mater. Trans. B* **2010**, *41*, 798–804. [CrossRef]
17. Orefice, M.; Nguyen, V.T.; Raiguel, S.; Jones, P.T.; Binnemans, K. Solvometallurgical Process for the Recovery of Tungsten from Scheelite. *Ind. Eng. Chem. Res.* **2022**, *61*, 754–764. [CrossRef]
18. Shoinbaev, A.T. Processing of sodium tungstate solutions obtained after leaching of sintering products of tungstite concentrate with sodium carbonate. *Izvestiya NAS RK* **2006**, *4*, 72–77.
19. Mirzaev, D.; Parmanova, S.T.; Ulugova, D.G. Processing of Tungsten—About a Year of Waste to Equalize the Content of Obtaining Tungsten. *Universum: Technical Sciences: Electronic. Scientific Chide.* **2023**, Volume 10, pp. 19–21. Available online: <https://7universum.com/ru/tech/archive/item/16175> (accessed on 10 March 2025).
20. Chegrintsev, S.N.; Dyachenko, A.N.; Kraydenko, R.I. Sorption extraction of tungsten from a solution of sodium tungstate. *Chem. Interests Sustain. Dev.* **2013**, *21*, 345–348. Available online: https://www.elibrary.ru/title_about_new.asp?id=7582 (accessed on 13 March 2025).
21. Xu, L.; Zhao, B. A Fundamental Study on the Preparation of Sodium Tungstate from Wolframite via the Smelting Process. *Metals* **2024**, *14*, 299. [CrossRef]
22. Xiao, L.; Wang, W.; Zhang, Q.; Gong, B.; Cao, J. Electrode selection of electrolysis with membrane for sodium tungstate solution. *J. Cent. South Univ. Technol.* **1999**, *6*, 107–110. [CrossRef]
23. Vasiunina, N.; Dubova, I.; Druzhinin, K.; Ghilmanshina, T. Processing of Sludge Water from Alumina Production by Electrodialysis. *Ecol. Ind. Russia* **2024**, *28*, 28–32. [CrossRef]
24. Melnikov, S.S.; Mugtamtov, O.A.; Zabolotsky, V.I. Study of electrodialysis concentration process of inorganic acids and salts for the two-stage conversion of salts into acids utilizing bipolar electrodialysis. *Sep. Purif. Technol.* **2020**, *235*, 116198. [CrossRef]
25. Kemerovo, M.A. Electrodialysis of a binary solution containing sodium and zinc ions using MK-100 M membranes. *Electron. Process. Mater.* **2019**, *55*, 73–78. [CrossRef]

26. Sadyrbaeva, T.J. Electrodialysis extraction of zinc (II) by liquid membranes based on di-(2-ethylhexyl) phosphoric acid. *Electrochemistry* **2019**, *55*, 609–618. [CrossRef]
27. Dzhubari, M.K.; Alekseeva, N.V. Efficiency of electrodialysis in industrial wastewater treatment. *Bull. Technol. Univ.* **2020**, *23*, 33–39.
28. Krasnova, T.A. The Experience of Using Electrodialysis for Processing Wastewater from Organic Industries. *Sorpt. Chromatogr. Process.* **2012**, *12*, 419–427. Available online: http://www.chem.vsu.ru/sorbcr/images/pdf/2012/3/2012_03_12.pdf (accessed on 13 March 2025).
29. Gonova, V. Experimental investigation of the purification of solutions from nickel ions by electrodialysis. Modern high-tech technologies. *Reg. Appl.* **2023**, *73*, 37–41. [CrossRef]
30. Niftaliev, S.I.; Kozaderova, O.A.; Kim, K.B.; Velho, F. The use of electrodialysis to produce acid and alkali from a concentrated solution of sodium sulfate. *Bull. Voronezh State Univ. Eng. Technol.* **2014**, *4*, 175–178. [CrossRef]
31. Islamov, K.B. Research and Modeling of the Electrodialysis Process of Sodium Tungstate Solutions: Dis. Mr. of Technical Sciences. 06/08/2022/Islamov K.B., Almaty, 2022; 88p. Available online: <https://official.satbayev.university/download/document/25720/2022%20%D0%9C%D0%90%D0%93%20%D0%98%D1%81%D0%BB%D0%B0%D0%BC%D0%BE%D0%B2%20%D0%9A.%D0%91..pdf> (accessed on 4 April 2025).
32. *Standard 18289-78*; The State Standard of the USSR. Reagents. Sodium Tungstate Is 2-Aqueous. Publishing House of Standards: Moscow, Russia, 1979. Available online: <https://files.stroyinf.ru/Data2/1/4294834/4294834827.pdf> (accessed on 4 April 2025).
33. Zefirov, N.S.; Knunyants, I.L.; Kulov, N.N. (Eds.) *Chemical Encyclopedia*; Soviet Encyclopedia: Moscow, Russia, 1988; Volume 1, 625p, Available online: <https://www.geokniga.org/books/10851> (accessed on 22 April 2025).
34. Shokhaksimova, A.A. Study of heterogeneous cation exchange membranes based on inert polymers Universum: Technical sciences: Electron. *Sci. J.* **2022**, *1*, 39–42. Available online: <https://7universum.com/ru/tech/archive/item/12989> (accessed on 22 April 2025).
35. Wang, W.; Zhang, Y.; Yang, X.; Sun, H.; Wu, Y.; Shao, L. Monovalent Cation Exchange Membranes with Janus Charged Structure for Ion Separation. *Engineering* **2023**, *25*, 204–213. [CrossRef]
36. Malyshev, V.P. *Probabilistic Deterministic Experiment Planning*; Nauka: Almaty, Kazakhstan, 1981; p. 115.
37. Komarova, L.F.; Somin, V.A.; Lapshin, D.A. Desalination of groundwater using membrane technologies. *Polzunovskiy Vestnik.* **2023**, *1*, 200–206. [CrossRef]
38. Chemistry and Technology of Rare and Scattered Elements. Part III. Edited by K.A. Bolshakov. Textbook for Universities. 2nd Edition, Revised. and Additional M., “Higher School”. 1976; 320p. Available online: <https://djvu.online/file/MtJa8NuNRaVvc> (accessed on 22 April 2025).

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