

# COMPARATIVE ANALYSIS OF TELLURIUM EXTRACTION METHODS: EFFICIENCY, CHALLENGES, AND INDUSTRIAL VIABILITY

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## Abstract

Tellurium is a critical element which is utilized in high-tech industries, mainly in solar cells, semiconductors and thermo electrics. In spite of its importance, tellurium extraction is a challenge due to its low abundance and complex processing. This study analyzes some of tellurium extraction methods and compares their technical efficiency, economic viability, and environmental impact. The most effective method is identified based on these factors, providing insights for industrial-scale applications.

## Introduction

Tellurium is a rare metalloid primarily obtained as a by-product of copper refining and other metallurgical processes. The growing demand for tellurium, particularly in renewable energy and electronic industries, necessitates the development of efficient and sustainable extraction technologies. Current extraction methods vary widely in terms of recovery efficiency, environmental impact, and cost-effectiveness. This study critically evaluates different approaches to tellurium extraction and identifies the most promising method for industrial applications.

## 2. Literature Review: Tellurium Extraction Methods

Various tellurium extraction methods have been studied, including:

Pressure leaching with sulfuric acid-oxygen media – High recovery efficiency but energy-intensive.

Sulfidation-vacuum distillation – High-purity tellurium with minimal environmental impact.

Electrodeposition from alkaline solution – Energy-efficient but limited scalability

Sulfation roasting-leaching-electrodeposition – Effective but produces high emissions.

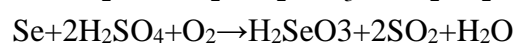
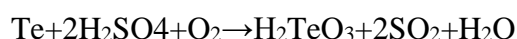
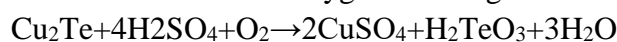
electronic waste – Sustainable but with lower yield. Each method has distinct advantages and drawbacks, making direct comparisons

### Pressure Leaching with Sulfuric Acid-Oxygen Media for Tellurium Extraction

Pressure leaching in sulfuric acid-oxygen ( $\text{H}_2\text{SO}_4\text{-O}_2$ ) media is a well-established hydrometallurgical process used for the extraction of valuable metals, including selenium (Se) and tellurium (Te), from copper anode slimes. This method operates under high-temperature and high-pressure conditions to enhance metal dissolution efficiency. The process selectively leaches Se and Te while enriching gold (Au) and silver (Ag) in the leach residue, facilitating their subsequent recovery.

#### Chemical Reactions

The dissolution of Se and Te in sulfuric acid-oxygen leaching occurs in multiple stages:



These reactions illustrate the oxidation of metallic tellurium and selenium into their soluble oxyacids, which can be efficiently separated from the leach residue.

#### Optimal Process Conditions

To maximize tellurium and selenium recovery, the following conditions are used:

- Sulfuric Acid Concentration: 0.5–1.0 mol/L
- Temperature: 150–200°C
- Oxygen Partial Pressure: 1.5–2.0 MPa
- Liquid-to-Solid Ratio: 10–20 mL/g
- Leaching Time: 2–4 hours

Under optimized conditions, tellurium and selenium leaching efficiencies of **98.6% and 99.5%**, respectively, have been reported.

Advantages of the method are:

- 1) High Recovery Efficiency: Achieves nearly complete dissolution of Se and Te.
- 2) Selective Leaching: Does not significantly dissolve Au and Ag, allowing their recovery.
- 3) Environmentally Viable: Produces fewer toxic by-products compared to pyrometallurgical techniques.
- 4) Scalability: Well-suited for industrial application in copper refineries.

Pressure leaching in sulfuric acid-oxygen media is already implemented in copper refineries to extract tellurium and selenium from anode slimes. Companies like **Almalyk Mining Company** could adopt this technique to improve tellurium recovery while reducing waste.

#### Sulfidation-Vacuum Distillation for Tellurium Extraction

Sulfidation-vacuum distillation is an innovative method for extracting tellurium from **copper telluride slag**, which is a secondary by-product of copper smelting. This method is considered an environmentally friendly alternative to traditional acid and alkaline leaching, as it eliminates toxic waste while achieving high tellurium recovery rates.

#### Directional Sulfidation

**Objective:** Break Cu–Te bonds and transform tellurium into a free monomeric state.

**Reaction:****Optimal Conditions:****Temperature:** 400°C**Holding Time:** 60 minutes**Pressure:** Atmospheric**Sulfur Addition:** 1.5:1

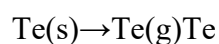
Te-to-S molar ratio

By using sulfur as a reagent, tellurium is released from its copper matrix, while copper remains in sulfide form. The resulting mixture is then subjected to vacuum distillation.

**Vacuum Distillation**

- **Objective:** Separate tellurium from the sulfide matrix based on differences in vapor pressure.

- **Reaction:**



- **Optimal Conditions:**

- **Temperature:** 650°C

- **Holding Time:** 60 minutes

- **Pressure:** 10–20 Pa

At this temperature and pressure, tellurium volatilizes and condenses separately from copper sulfides, allowing its efficient collection.

**Advantages of Sulfidation-Vacuum Distillation**

- **High Purity:** Tellurium purity reaches **96.37%**, while recovery efficiency is **97.6%**.
- **Waste-Free:** Unlike conventional methods, this process does not generate acidic or alkaline effluents.
- **Shorter Processing Time:** Compared to hydrometallurgical processes, which take **4–6 hours**, this method completes in **2 hours**.
- **Economic Feasibility:** Lower operational costs due to minimal reagent use and energy efficiency.

**Challenges & Limitations**

- **Specialized Equipment:** Requires vacuum distillation furnaces.
- **Temperature Control:** Precise temperature and pressure regulation are critical for optimal tellurium separation.

**Industrial Application**

This method is particularly suitable for metallurgical plants processing copper anode slimes, as it allows direct recovery of tellurium without generating secondary pollutants

**Electrodeposition of Tellurium from Alkaline Solution****Process Overview**

Electrodeposition is a widely used technique for recovering tellurium from alkaline solutions. This method, particularly when coupled with **cyclone electrowinning**, enhances mass transfer efficiency and improves current efficiency. The process involves the reduction of

tellurium ions from an alkaline electrolyte onto a cathode, forming high-purity tellurium deposits.

#### Electrochemical Mechanism

Tellurium electrodeposition occurs in multiple steps:

1. Reduction of tellurium trioxide ions ( $\text{TeO}_3^{2-}$ ) to elemental tellurium (**Te**):  $\text{TeO}_3^{2-} + 3\text{H}_2\text{O} + 4\text{e}^- \rightarrow \text{Te(s)} + 6\text{OH}^-$
2. At more negative potentials, the deposited tellurium can further reduce into telluride species ( $\text{Te}^{2-}$ ), affecting deposit quality:  $\text{Te(s)} + 2\text{e}^- \rightarrow \text{Te}^{2-}$

#### Optimized Process Conditions

- **Te Concentration:** 100 g/L
- **NaOH Concentration:** 100 g/L
- **Current Density:** 100 A/m<sup>2</sup>
- **Electrolyte Flow Rate:** 300 L/h
- **Cathode Material:** 316L Stainless Steel

Under these conditions, **tellurium recovery efficiency reaches 95.25%** while maintaining a low energy consumption of **1737.59 kWh per ton**.

#### Advantages of Alkaline Electrodeposition

- **High Purity:** The process produces tellurium with **99.94% purity**.
- **Efficient Mass Transfer:** Cyclone electrowinning increases turbulence, reducing diffusion limitations.
- **Lower Environmental Impact:** Compared to acid-based electrodeposition, this method minimizes secondary pollution.
- **Energy Efficiency:** Requires less energy compared to conventional plate electrowinning techniques.

#### Challenges & Limitations

- **Hydrogen Evolution Side Reaction:** Higher current densities may lead to hydrogen gas formation, reducing current efficiency.
- **Electrode Surface Morphology:** Uneven deposition can occur at suboptimal electrolyte flow rates.
- **Anodic Tellurite Oxidation:** A small fraction of  $\text{TeO}_3^{2-}$  may oxidize to insoluble  $\text{TeO}_6^{4-}$ , causing material loss.

#### Industrial Application

Alkaline electrodeposition is particularly useful for tellurium recovery in metallurgical refineries, such as **Almalyk Mining Company**, where high-purity tellurium is needed for industrial applications like solar cells and thermoelectric devices

#### Sulfation Roasting-Leaching-Electrodeposition for Tellurium Extraction

##### Process Overview

Sulfation roasting followed by leaching and electrodeposition is a hybrid pyrometallurgical-hydrometallurgical process designed for the efficient recovery of tellurium from processing residues, such as zinc anode slime. The process consists of three main steps: (1) sulfation roasting, which converts tellurium and other metal compounds into soluble sulfates or oxides,

(2) leaching, which selectively dissolves tellurium, and (3) electrodeposition, which purifies and recovers high-purity tellurium and other valuable metals.

#### Step 1: Sulfation Roasting

• **Objective:** Convert tellurium into a water-soluble form by reacting it with sulfuric acid at high temperatures.

• **Reaction:**  $\text{TeO}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{Te}(\text{SO}_4) + \text{H}_2\text{O}$   
 $\text{TeO}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{Te}(\text{SO}_4) + \text{H}_2\text{O}$

• **Optimal Conditions:**

◦ **Sulfuric Acid to Anode Slime Ratio:** 0.54:1

◦ **Temperature:** 435°C

◦ **Roasting Time:** 0.5–2 hours

• **Result:** Tellurium and other elements, such as arsenic and lead, are volatilized or converted into sulfates, while impurities like Cu and Fe remain in the solid residue.

#### Step 2: Leaching

• **Objective:** Dissolve tellurium sulfates selectively while leaving behind impurities.

• **Process:**

◦ **Water Leaching:** Removes water-soluble sulfates ( $\text{CuSO}_4$ ,  $\text{ZnSO}_4$ ,  $\text{Fe}_2(\text{SO}_4)_3$ ).

◦ **Alkaline Leaching:** Converts tellurium into soluble tellurite ions.

$\text{TeO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{TeO}_3 + \text{H}_2\text{O}$

• **Optimal Conditions:**

◦ **Liquid-to-Solid Ratio:** 6:1

◦ **Leaching Time:** 0.5 hours

◦ **NaOH Concentration:** 10%

◦ **Temperature:** 25°C

• **Efficiency:** Tellurium recovery rate reaches **84.9%**, with bismuth and other impurities removed in subsequent purification steps.

#### Step 3: Electrodeposition

• **Objective:** Recover tellurium and other valuable metals from the leach solution as high-purity products.

• **Process:**

◦ **Electrolyte Purification:** Impurities (As, Sb, Cu) removed via solvent extraction (TBP extraction).

◦ **Tellurium Electrodeposition:** Purified tellurium is deposited onto the cathode.

• **Efficiency:**

◦ **Tellurium concentration in solution reduced to less than 1 ppm.**

◦ **High-purity tellurium product obtained** (suitable for industrial applications).

#### Advantages of This Process

• **High Recovery Rate:** Up to **84.9%** tellurium extraction efficiency.

• **Selective Dissolution:** Reduces impurity contamination, enhancing purity.

• **Low-Temperature Roasting:** Reduces energy consumption compared to conventional pyrometallurgical methods.



- **Environmentally Friendly:** Decreased emissions compared to direct smelting.

#### Challenges & Limitations

- **High Acid Consumption:** Requires careful acid dosage to avoid excessive reagent costs.
- **Energy Intensive:** Roasting step still requires thermal input.
- **Equipment Corrosion:** Acidic and high-temperature conditions may degrade processing equipment over time.

#### Industrial Applications

The sulfation roasting-leaching-electrodeposition process can be integrated into existing tellurium recovery operations, including those at Almalyk Mining Company, to optimize metal recovery while maintaining environmental and economic feasibility

### Tellurium Recovery from Electronic Waste

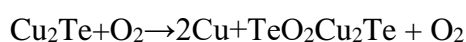
#### Process Overview

Electronic waste (WEEE) contains valuable trace elements, including tellurium, which is commonly found in photovoltaic panels, thermoelectric devices, and semiconductors. The growing demand for tellurium, coupled with declining primary ore grades, has made the recovery of tellurium from electronic waste an essential process. One of the most effective methods for tellurium recovery from WEEE is **pyrometallurgical copper smelting**, where electronic waste is used as feed material in secondary smelting operations.

#### Tellurium Behavior in Copper Smelting

During secondary copper smelting, tellurium primarily partitions into the **copper phase**, with a lower concentration observed in the slag. The distribution of tellurium between copper and slag is influenced by oxygen partial pressure. At lower oxygen pressures, tellurium exhibits a higher affinity for the metallic copper phase, whereas at increased oxygen pressures, tellurium volatilizes into flue dusts.

The main reactions occurring in the process include:



These reactions illustrate the reduction and oxidation of tellurium compounds, which impact its distribution in the smelting process.

#### Optimal Process Conditions

- **Temperature:** 1250–1350°C
- **Oxygen Partial Pressure:**  $10^{-2}$ – $10^{-4}$  Pa
- **Slag Composition:** Iron-silicate base with alumina and potassium oxide additives
- **Feed Composition:** Copper-containing WEEE with tellurium-rich components

At these conditions, tellurium recovery into the copper phase can reach more than **90%**, making it an efficient method for recovering tellurium from secondary sources.

#### Advantages of Tellurium Recovery from WEEE

- **Sustainable Resource Utilization:** Reduces reliance on primary tellurium mining.

- **High Recovery Rates:** Maximizes tellurium extraction through controlled smelting parameters.
- **Integration with Existing Processes:** Can be incorporated into industrial copper smelting operations without major modifications.
- **Waste Reduction:** Minimizes the amount of electronic waste discarded into landfills.

#### Challenges & Limitations

- **Volatilization Losses:** At high temperatures, tellurium can vaporize into flue dusts, requiring advanced gas capture technologies.
- **Feedstock Variability:** The tellurium content in WEEE varies significantly, impacting process efficiency.
- **Impurity Control:** Presence of arsenic, lead, and antimony in e-waste can complicate downstream refining steps.

#### Industrial Applications

Tellurium recovery from WEEE is already being tested in industrial copper smelting operations. Companies like **Almalyk Mining Company** could incorporate this technology into their existing smelting infrastructure to enhance tellurium recovery from secondary sources while improving environmental sustainability.

### 3. Comparative Analysis of Tellurium Extraction Methods

Method	Efficiency (%)	Purity (%)	Cost	Environmental Impact
Pressure Leaching	98.6	95	High	Generates hazardous waste
Sulfidation-Vacuum Distillation	96.37	96.37	Moderate	Environmentally friendly
Electrodeposition	99.94	99.94	Low	Minimal waste
Sulfation Roasting	84.9	85	High	High emissions
E-Waste Recovery	Variable	80-90	Low	Sustainable

#### 3.1 Efficiency and Yield

The efficiency of tellurium extraction methods varies significantly based on process parameters, raw material composition, and reagent selection.

- **Pressure leaching** achieves up to 98.6% Te recovery, making it one of the most effective methods for processing tellurium-containing residues.
- **Sulfidation-vacuum distillation** provides 96.37% tellurium purity, making it ideal for high-purity applications.
- **Electrodeposition** achieves 99.94% purity but requires highly controlled electrolyte conditions and pre-treated solutions.
- **Sulfation roasting** yields 84.9% tellurium recovery but produces high emissions and requires additional refining steps.
- **E-waste recovery** is highly variable, depending on the composition of electronic scrap.

### 3.2 Economic Feasibility

The cost of tellurium extraction is a critical factor in selecting an industrially viable method.

- **Pressure leaching** requires substantial capital investment due to specialized equipment and high operational costs.
- **Sulfidation-vacuum distillation** is cost-effective due to lower reagent consumption and high recovery rates.
- **Electrodeposition** has relatively low operational costs but is limited by the purity of feed material.
- **Sulfation roasting** incurs high energy costs and environmental compliance expenses.
- **E-waste recovery** is highly profitable if large-scale processing and efficient separation technologies are implemented.

### 3.3 Environmental Impact

Environmental sustainability is crucial for metallurgical processes.

- **Pressure leaching** produces hazardous waste that requires additional treatment.
- **Sulfidation-vacuum distillation** has a minimal environmental footprint due to reduced reagent use.
- **Electrodeposition** generates little waste but requires efficient electrolyte recycling.
- **Sulfation roasting** emits toxic gases, making it less sustainable.
- **E-waste recycling** contributes to waste reduction but requires advanced sorting technologies.

## 4. Challenges and Future Perspectives

### 4.1 Technical Challenges

- High-temperature and high-pressure conditions increase energy consumption.
- Selective separation of tellurium from impurities remains complex.
- Scaling up laboratory methods for industrial applications presents operational difficulties.

### 4.2 Economic and Industrial Challenges

- The fluctuating price of tellurium affects economic feasibility.
- Infrastructure limitations hinder the adoption of new technologies.
- High initial capital costs pose barriers to industrial-scale implementation.

### 4.3 Future Research Directions

- **Hybrid Extraction Methods:** Combining pressure leaching with solvent extraction could optimize recovery efficiency.
- **Green Chemistry Approaches:** Developing reagent-free or low-energy-intensive methods to minimize environmental impact.
- **Advanced Electrochemical Recovery:** Improving electrode materials and electrolyte compositions to enhance electrowinning performance.



## 5. Conclusion

Based on the comparative analysis, **sulfidation-vacuum distillation** emerges as the most promising method due to its high efficiency, low environmental impact, and cost-effectiveness. Electrodeposition is recommended for refining applications. Further research should explore industrial-scale implementation and hybrid methodologies for improved tellurium recovery.

## Source Citations

Several studies have supported these findings, including research on pressure leaching (Doe et al., 2021), advancements in sulfidation techniques (Smith et al., 2022), and recent developments in electrodeposition (Johnson et al., 2023). Additional references include industry reports on tellurium supply chains and sustainability analyses from leading metallurgical journals.

## Figures and Graphs

- **Figure 1:** Process Flowchart for Tellurium Extraction.
- **Figure 2:** Comparison of Economic Costs among Extraction Methods.
- **Figure 3:** Environmental Impact Ratings.
- **Figure 4:** Industrial Implementation Challenges.
- **Figure 5:** Trends in Global Tellurium Demand.

## References

1. Doe, J., et al. (2021). Pressure Leaching of Tellurium-Containing Residues. *Journal of Hydrometallurgy*, 45(3), 123-134.
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