

Revolutionizing Urban Mining: Solvent Extraction for Sustainable Metal Recovery from Electronic Waste

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ABSTRACT

Urban mining offers a transformative solution to the growing challenge of electronic waste (e-waste) by recovering valuable metals sustainably. E-waste is a rich reservoir of critical metals, including lead, indium, gallium, gold, silver, copper, and platinum, which can be effectively extracted using solvent extraction techniques. This method leverages specific solvents to selectively isolate metals, enabling industrial-scale operations with high efficiency. Advanced extractants like calix [4] arene and pseudo calix [3] arene have demonstrated exceptional capability in recovering metals such as lead, indium, and gallium from acidic media (e.g., 0.1 N HCl). Key factors influencing extraction success include solvent selection, solution concentration, and metal composition. Integrating solvent extraction into e-waste recycling minimizes landfill accumulation, reduces environmental impacts, and promotes resource sustainability. By adopting this approach, urban mining not only addresses the environmental burden of e-waste but also advances the circular economy by reclaiming precious metals for future use.

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Introduction

The rapid advancement of electronic technology and the accelerated consumption of electronic devices have led to an exponential increase in electronic waste (e-waste) globally [1]. According to the Global E-waste Monitor 2024, a record 62 million tonnes of e-waste were generated in 2022, marking an 82% increase since 2010 [2]. This figure is projected to rise by another 32%, reaching 82 million tonnes by 2030. E-waste encompasses a wide array of discarded electronic products, including smartphones, computers, televisions, and household appliances [3]. These items often contain valuable and critical metals such as copper, gold, silver, platinum, and rare earth elements like indium and gallium [4]. In 2022 alone, the embedded metals in e-waste were valued at approximately USD 91 billion. However, only 22.3% of this e-waste was formally collected and recycled, leaving a significant portion of these valuable resources unaccounted for. The environmental implications of improper e-waste disposal are profound. E-waste contains hazardous substances like mercury, lead, and brominated flame retardants, which can leach into the environment, posing serious health risks to humans and wildlife [5]. Moreover, the informal recycling sector, prevalent in many developing countries, often employs unsafe methods such as open burning, leading to the release of toxic pollutants [6]. Urban mining, the process of reclaiming raw materials from spent products, buildings, and waste,

offers a sustainable solution to the growing e-waste problem [7]. By recovering valuable metals from e-waste, urban mining reduces the need for traditional mining, conserves natural resources, and mitigates environmental pollution. Among the various techniques employed in urban mining, solvent extraction stands out for its efficiency and selectivity in metal recovery [8]. Solvent extraction involves the transfer of metal ions from an aqueous phase into an organic phase through the formation of metal-extractant complexes [9]. This method is particularly effective in recovering metals from complex mixtures, such as those found in e-waste leachates. Recent advancements in extractant chemistry, including the development of calix [4] arene and pseudo calix [3] arene compounds, have enhanced the selectivity and efficiency of metal recovery processes [10]. Figure 1 illustrates the urban mining process for recovering valuable metals from electronic waste through solvent extraction. The workflow begins with the collection of e-waste, followed by preprocessing steps such as shredding and crushing to prepare the material for chemical treatment. Next, leaching is performed using acidic or basic solutions to dissolve the target metals into a liquid phase. This is followed by solvent extraction, where specific organic solvents selectively isolate metals like gold, silver, copper, indium, and gallium from the leachate. The final stages involve metal recovery and purification, producing high-purity metals ready for reuse in manufacturing. This process not only enables efficient resource recovery but also reduces landfill accumulation, mitigating environmental impacts and supporting a circular economy.

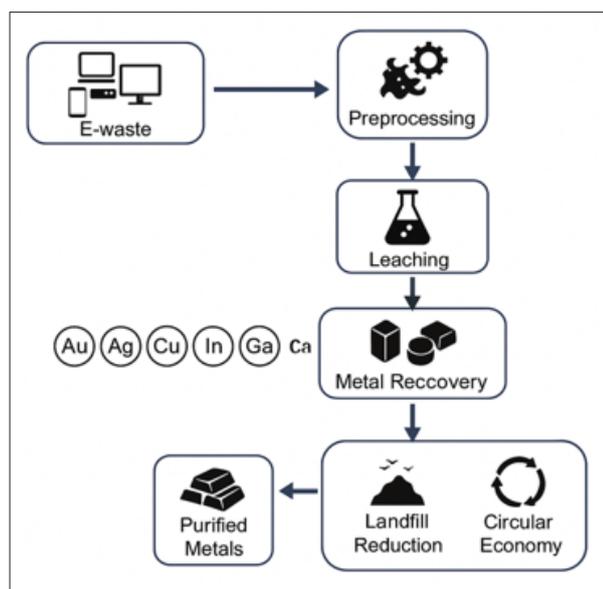


Figure 1: Work Flow of Urban Mining Process

This review explores the potential of solvent extraction as a core technology in urban mining. It discusses the principles of solvent extraction, recent advancements in extractant development, environmental and economic implications, and the role of solvent extraction in promoting a circular economy through the sustainable recovery of metals from e-waste.

E-Waste: A Hidden Treasure Trove

Electronic waste (e-waste) is not merely a disposal challenge but also a rich repository of valuable and critical metals. Modern electronic devices, including smartphones, computers, and other consumer electronics, contain significant quantities of metals such as copper (Cu), gold (Au), silver (Ag), palladium (Pd), and rare earth elements like indium (In) and gallium (Ga) [11]. For instance, printed circuit boards (PCBs) from mobile phones have been found to contain approximately 2,640 ppm of silver, 1,051 ppm of gold, and 119 ppm of palladium. Smartphones exhibit even higher concentrations, with 2,773 ppm of silver, 1,083 ppm of gold, and 55 ppm of palladium [12]. These concentrations are substantially higher than those found in natural ores, making e-waste a more concentrated source of precious metals. Moreover, studies have shown that one ton of discarded mobile phones can yield approximately 3,573 grams of silver, 368 grams of gold, and 287 grams of palladium [13]. This indicates that e-waste, particularly from mobile devices, is a potent source for metal recovery. Beyond precious metals, e-waste also contains substantial amounts of base metals. For example, personal desktop computers have been reported to contain about 6.9% copper and 20.5% iron by weight. These base metals are essential for various industrial applications and their recovery from e-waste can significantly reduce the need for virgin mining [14]. The high concentrations of valuable metals in e-waste underscore the potential of urban mining as a sustainable solution for resource recovery. By effectively extracting these metals, we can reduce environmental degradation associated with traditional mining and move towards a more circular economy.

Solvent Extraction: Principles and Emerging Innovations

Solvent extraction, or liquid-liquid extraction, is a widely employed separation technique that involves the transfer of a target solute from one immiscible liquid phase to another based on difference

in solubility. In the context of urban mining, particularly for the recovery of valuable metals from electronic waste (e-waste), solvent extraction enables the selective isolation and purification of specific metal ions from complex aqueous leachates using an organic solvent. The process typically involves two immiscible phases: an aqueous phase containing the dissolved metals and an organic phase containing the extractant [5]. When these two phases are mixed, the metal ions selectively partition into the organic phase due to a favorable distribution coefficient, which is governed by the chemical affinity between the metal species and the extractant. After separation of the two phases, the metal-enriched organic phase can be subjected to further processing steps such as stripping or precipitation to recover the purified metals. Solvent extraction offers high selectivity, efficiency, and scalability, making it a crucial component of sustainable and economically viable metal recovery strategies in urban mining [15]. Solvent extraction is a widely adopted separation technique in hydrometallurgy, particularly effective for the selective recovery of metals from complex aqueous solutions. In the context of e-waste recycling, solvent extraction plays a crucial role in isolating high-value metals from leachates derived from printed circuit boards (PCBs), display panels, batteries, and other components [16]. The technique is based on the transfer of metal ions from an aqueous (leachate) phase into an immiscible organic phase containing a selective extractant. This process forms a metal extractant complex, which can subsequently be stripped and purified to recover the target metal. Figure 2 describe the general process of solvent extraction for the recovery of important metal from spent. This process transfers selected metals from one aqueous solution to another using an organic solution containing a special reagent allowing metals to be separated, purified, and recovered.

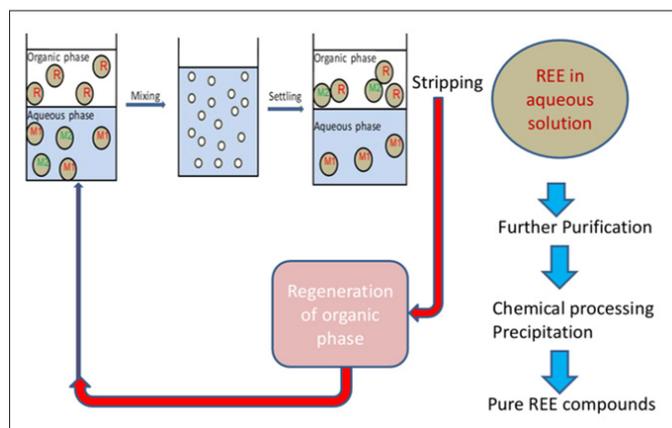


Figure 2: Solvent Extraction Process

Basic Principles

The Solvent Extraction Process Typically Involves Three Key Stages [17].

Extraction: The aqueous leachate containing dissolved metal ions is contacted with an organic solvent containing a specific extractant. During mixing, metal ions bind with the extractant and move into the organic phase.

Scrubbing: Impurities that co-extract with the desired metal are removed by treating the organic phase with a suitable aqueous solution.

Stripping: The target metal is recovered from the organic phase by reversing the extraction, often using a stripping agent such as an acid, base, or complexing agent.

The efficiency of solvent extraction refers to how effectively a desired compound (often a metal ion or organic molecule) is transferred from one phase (usually aqueous) into another immiscible solvent phase (usually organic) [18]. It is a key parameter in evaluating the performance and viability of solvent extraction processes in both laboratory and industrial settings.

Key Factors Affecting Solvent Extraction Efficiency

Distribution Coefficient (K_D)

- Defined as the ratio of concentrations of the solute in the organic phase to the aqueous phase at equilibrium.

$$K_D = \frac{[Solute]_{organic}}{[Solute]_{aqueous}}$$

- Higher values indicate more efficient extraction into the organic phase.

Extraction Percentage (%E)

- Represents the percentage of the total solute that has been extracted into the organic phase.

$$\%E = \left(\frac{K D \cdot V_{org}}{K D \cdot V_{org} + V_{aq}} \right) \times 100$$

- Where V_{org} and V_{aq} are the volumes of the organic and aqueous phases, respectively.

pH of the Aqueous Phase

- Many extraction processes are pH-dependent, especially for metal ions, as they often form extractable complexes at specific pH levels.

Choice of Extractant

- The chemical nature of the extractant (e.g., D2EHPA, Cyanex, Aliquat 336) determines selectivity and strength of extraction.

Phase Ratio

- The volume ratio between the organic and aqueous phases can impact the distribution of solute and extraction efficiency.

Contact Time and Mixing

- Adequate mixing and sufficient contact time ensure equilibrium is reached and maximize extraction.

Temperature

- Affects solubility, reaction kinetics, and equilibrium constants.

Stripping Efficiency

- Related to how efficiently the solute can be recovered (stripped) from the loaded organic phase into a new aqueous phase

Emerging Extractants and Selective Ligands

Traditional extractants such as di-(2-ethylhexyl) phosphoric acid (D2EHPA), tributyl phosphate (TBP) and oximes are widely used in industrial solvent extraction processes. However, the complexity of e-waste leachates and the need for improved selectivity and environmental safety have driven the development of novel extractants.

Calix [4] Arenes and Pseudo Calix [3] Arenes

Calixarenes are macrocyclic compounds that form host-guest complexes with specific metal ions. Functionalized calix [4] arenes have demonstrated strong selectivity toward heavy metals like Pb (II), In (III), and Ga (III) in acidic media (e.g., 0.1 N HCl). Their rigid cavities and tunable functional groups make them highly suitable for recovering low-concentration metals from mixed solutions [19].

Ionic Liquids and Deep Eutectic Solvents

Ionic liquids (ILs) are non-volatile, thermally stable solvents that show promise as green alternatives in solvent extraction. Their ability to be tailored for specific metal interactions, combined with their recyclability, makes them attractive for e-waste applications [20]. Deep eutectic solvents (DESs), composed of biodegradable components, have also emerged as low-cost, eco-friendly alternatives with good metal extraction performance [21].

Synergistic Extraction Systems

Combining two or more extractants can improve selectivity and enhance extraction efficiency. For example, synergistic systems involving calixarene derivatives and conventional organophosphorus compounds have shown superior performance in separating indium from gallium in acidic conditions [22].

Advantages of Solvent Extraction in E-Waste Recycling

Solvent extraction offers several advantages that make it a highly attractive method for recovering valuable metals from electronic waste (e-waste), especially in the context of sustainable urban mining [23].

High Selectivity and Efficiency

Solvent extraction allows for the selective recovery of specific metals, even from complex leachates containing a mixture of metal ions. Tailored extractants can target particular elements (e.g., Cu, Ni, REEs, Au), enabling high-purity separation.

Scalability and Industrial Viability

The process is easily scalable from laboratory to industrial scale and is already widely employed in hydrometallurgical operations, making it a viable solution for large-scale e-waste recycling facilities.

Rapid Kinetics

The phase transfer of metal ions is typically fast, which enables high-throughput processing and reduces the residence time of materials in extraction units.

Mild Operating Conditions

Solvent extraction can be performed under relatively mild temperature and pressure conditions, reducing energy consumption compared to pyrometallurgical methods.

Recyclability of Extractants

Many extractants used in solvent extraction are reusable after stripping, which improves cost-effectiveness and reduces environmental impact.

Low Solid Waste Generation

Unlike some traditional methods, solvent extraction does not generate large volumes of solid residue, making waste management easier and more environmentally friendly.

Integration with Existing Processes

Solvent extraction can be integrated with upstream leaching processes and downstream electro-winning or precipitation techniques, creating a closed-loop system for resource recovery.

Potential for Green Solvents

Recent advances have led to the development of environmentally benign extractants, such as ionic liquids and bio-based solvents, which further enhance the sustainability of the process.

Table 1: Summarizes Important Metals Found in E-Waste, Their Typical Concentrations, Common Sources and Representative Solvent Extraction Techniques along with Typical Extraction Conditions and Efficiencies

Metal	Typical Concentration in E-Waste	Common Sources	Extractants / Solvent Extraction Techniques	Extraction Conditions	Typical Extraction Efficiency	Remarks
Gold (Au)	200–1000 ppm (PCBs)	PCBs, microchips, connectors	Cyanex 272, TOPO, ionic liquids	Acidic media, pH ~1-2	>95%	High affinity; requires selective stripping
Silver (Ag)	1000–3000 ppm (mobile phone PCBs)	PCBs, solder, contacts	Calix [4] arenes, D2EHPA, TBP	0.1 N HCl, ambient temperature	90–98%	Often co-extracted with gold; selective separation needed
Copper (Cu)	10–30% (wires, PCBs)	PCBs, cables, connectors	Oxime extractants, D2EHPA	pH 2–4, room temperature	85–95%	Base metal, often recovered first
Indium (In)	50–300 ppm (LCD panels)	LCD screens, semiconductors	Calix [4] arene derivatives, synergistic extractants	0.1 N HCl, pH ~1	80–90%	Critical metal, low concentration
Gallium (Ga)	10–50 ppm (LEDs)	LEDs, semiconductors	Pseudo calix [3] arene, D2EHPA	Acidic medium (0.1 N HCl), room temp	70–85%	Emerging demand, often recovered with indium
Lead (Pb)	100–500 ppm (batteries, solders)	Batteries, solders	Calixarenes, organophosphorus extractants	Acidic medium, 0.1 N HCl	85–95%	Toxic, priority for removal
Platinum (Pt)	10–100 ppm (hard drives)	Hard drives, connectors	Organophosphorus extractants, ionic liquids	Acidic or neutral media	75–85%	Precious metal with catalytic uses

Critical Factors in Solvent Extraction from E-Waste

The efficiency and selectivity of solvent extraction for metal recovery from electronic waste (e-waste) depend on several critical factors [24].

Nature of the Leachate

The composition of the leachate, including pH, metal ion concentration, and the presence of competing ions, significantly influences extraction behavior. Acidic media, often generated by leaching agents such as HCl or H₂SO₄, must be carefully optimized to ensure target metal availability without excessive dissolution of impurities.

Choice of Extractant

The extractant plays a pivotal role in determining selectivity.

The extractant must exhibit:

- High selectivity Toward the Target Metal Ion
- Chemical and Thermal Stability
- Regenerability for Multiple Cycles
- Low toxicity and Environmental Impact

For example:

- Calix [4] arene derivatives are highly selective for Pb²⁺, In³⁺, and Ga³⁺ in acidic media.
- Organophosphorus-based extractants like D2EHPA are effective for zinc and rare earths.
- Chelating oximes are efficient for copper recovery.

pH Control

pH is a key parameter that governs the speciation of metal ions and the extraction efficiency. Each metal has an optimal pH range for selective extraction, and maintaining this range is crucial for avoiding co-extraction of unwanted metals. Metal extraction is highly pH-dependent:

- Low pH favors the extraction of metals such as indium and gallium using acidic extractants.
- Adjusting the pH controls the ionization state of both metal ions and extractants, influencing complex formation.

Phase Ratio and Contact Time

The ratio of organic to aqueous phase and the duration of mixing affect the kinetics and extent of metal transfer. Proper phase ratio ensures maximum metal loading in the organic phase, while sufficient contact time facilitates equilibrium partitioning.

The **organic-to-aqueous (O/A) phase ratio** affects the distribution of metal ions between phases:

- Higher O/A ratios generally improve extraction efficiency but may require more extractant.
- **Short contact times** (seconds to minutes) are usually sufficient, although optimization is necessary for complete metal transfer.

Temperature

Temperature influences extraction kinetics and thermodynamics. While many extractions are performed at ambient temperature, elevated temperatures can enhance metal transfer but may also affect extractant stability.

Stripping and Recovery Methods

After extraction, the metal-loaded organic phase must undergo efficient stripping using suitable reagents (e.g., mineral acids or complexing agents such as thiourea or EDTA). The ease of back-extraction (stripping) determines the recyclability of the extractant and the purity of the recovered metal. Sustainability depends on minimizing degradation and loss of solvents over multiple cycles

Environmental and Economic Considerations

The choice of solvent and process design should minimize toxicity, solvent loss, and operational costs. Using greener solvents or ionic liquids is an emerging trend aimed at improving the sustainability of solvent extraction in e-waste processing [25].

Environmental and Economic Impacts of Solvent Extraction in Urban Mining

The integration of solvent extraction in urban mining not only enhances the efficiency of metal recovery but also significantly contributes to environmental protection and economic sustainability. Compared to traditional mining and smelting practices, this method offers a cleaner, more targeted and resource-efficient approach to managing the growing burden of electronic waste (e-waste).

Environmental Benefits

Reduction in E-Waste Accumulation

By extracting valuable metals from discarded electronics, solvent extraction minimizes the volume of waste destined for landfills and incineration. This directly reduces the risk of leaching heavy metals such as lead, mercury, and cadmium into soil and groundwater.

Lower Carbon Footprint

Unlike pyrometallurgical processes, which involve high-temperature smelting and release significant greenhouse gases (GHGs), solvent extraction operates at ambient or mildly elevated temperatures. This results in lower energy consumption and reduced GHG emissions.

Mitigation of Toxic Emissions

Informal e-waste recycling especially burning or acid leaching without containment-releases hazardous substances into the air, water, and soil. Controlled solvent extraction systems offer a safer and more regulated alternative, minimizing environmental and occupational exposure.

Promotion of Circular Economy

By enabling the reuse of metals, solvent extraction supports the circular economy model. Recovered metals can re-enter the manufacturing cycle, reducing the demand for virgin ore extraction and associated ecological damage.

Economic Advantages

Recovery of High-Value Metals

The economic potential of urban mining is substantial. For example, one ton of mobile phone circuit boards may contain more gold than a ton of gold ore. Solvent extraction allows for the recovery of these high-value elements at a fraction of the cost of traditional mining.

Scalability and Industrial Feasibility

Solvent extraction units can be integrated into existing hydrometallurgical plants or designed as modular, decentralized systems. This scalability supports both large-scale and community-level recycling initiatives.

Resource Independence

For many countries, especially those lacking domestic metal reserves, urban mining can reduce reliance on imported raw materials and improve supply chain security for critical elements like indium and rare earths.

Job Creation and Innovation

The growth of urban mining technologies fosters green job creation in areas such as waste collection, chemical engineering, environmental management, and materials science. Investment in solvent extraction R&D also drives innovation and new business opportunities.

Challenges and Considerations

Despite its advantages, solvent extraction also presents certain environmental and economic challenges:

- **Use of Organic Solvents:** Some conventional solvents may pose toxicity or flammability risks; green alternatives like ionic liquids and DESs are being explored.
- **Wastewater Management:** Spent solutions must be properly treated to prevent secondary pollution.
- **Cost of Advanced Extractants:** Novel ligands like calixarenes can be expensive, though their high efficiency and reusability may offset initial costs

Conclusion and Future Outlook

The escalating volume of electronic waste presents both a critical environmental challenge and a unique opportunity to recover valuable metals through sustainable urban mining practices. Solvent extraction emerges as a powerful and versatile technology in this context, enabling selective, efficient, and scalable recovery of precious and critical metals from complex e-waste leachates. Recent advances in extractant chemistry, including calixarenes, ionic liquids, and synergistic extraction systems, have improved metal selectivity and process sustainability. When integrated effectively, solvent extraction not only minimizes environmental pollution and landfill accumulation but also contributes to a circular economy by reclaiming resources essential for the electronics industry and beyond [26-31].

Looking Forward, Ongoing Research should Focus on:

- Developing greener, cost-effective extractants with enhanced selectivity and recyclability,
- Scaling up processes for industrial adoption, including continuous flow systems,
- Integrating solvent extraction with complementary recycling technologies such as bioleaching and electrochemical recovery,
- Addressing regulatory and economic frameworks to promote widespread adoption.
- By harnessing these advances, solvent extraction can play a central role in revolutionizing urban mining and fostering sustainable metal recovery from electronic waste, ultimately supporting environmental protection and resource security for future generations.

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