

# Sustainable Recovery of Critical and High-Value Metals from Electronic Waste: Technologies, Process Intensification, Environmental Impacts, and Circular Economy Perspectives

Meghasri M<sup>1</sup>, Sai Harini S<sup>2</sup>, Anand kumar P<sup>3</sup>

<sup>1,2</sup>UG - Chemical Engineering, St. Joseph's College of Engineering, OMR, Chennai

<sup>3</sup>Assistant Professor - Chemical Engineering, St. Joseph's College of Engineering, OMR, Chennai

## Abstract

*More people using electronics means ever-rising piles of old devices tossed away, piling up faster than almost any other kind of trash. These discarded gadgets aren't just junk - they hold valuable materials like gold, copper, lithium, and rare earths, sometimes richer than what's dug from the ground. Urban areas now act like mines, where used circuit boards and dead batteries offer more concentrated metals than raw ore in certain cases. Still, pulling those metals out is tough because the mix inside e-waste varies wildly, while toxic stuff like flame retardants and lead lurks alongside useful parts. Smelting and chemical leaching methods work well at large factories, recovering plenty of metals yet guzzling fuel, creating pollution, and needing tons of chemicals. Newer ideas, like using microbes or eco-friendly liquids to extract metals, perform gently on nature and pick targets better, though slow reactions and shaky performance stop them from going mainstream so far. New progress in Solv metallurgy, together with ionic liquids and deep eutectic solvents, opens different paths to better separate metals while cutting harm to nature. When it comes to climate impact, pulling metals from old electronics creates far fewer emissions than digging new ore - this holds especially true for rare earths and valuable metals. Still, weak collection systems, scattered informal recycling, uneven rules across regions, and shifting market prices keep slowing down full reuse of electronic waste.*

**Keywords:** Guzzling fuel, metallurgy

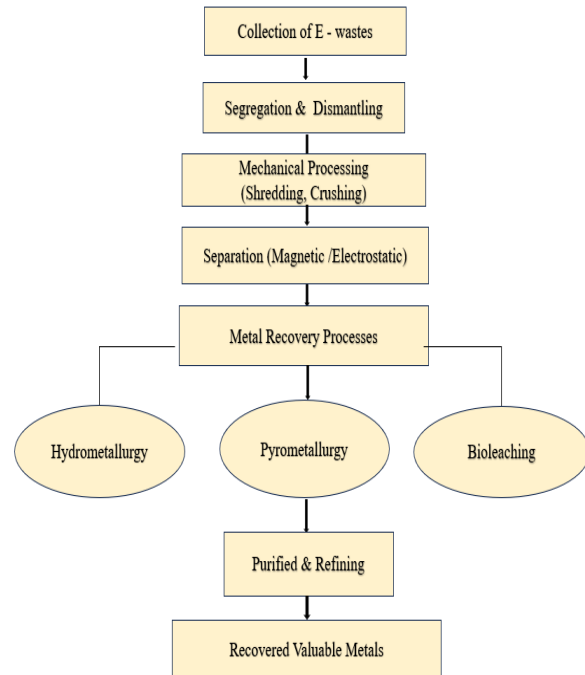
## 1. Introduction

Fast growth in making and using electronics during the last twenty years pushed up levels of discarded devices across the world. Recent reports show these old gadgets now form the quickest expanding type of solid trash, thanks to faster tech updates, shorter life spans for gadgets, wider internet access, along with rising buyer interest [1]. Moving to cleaner energy, electric cars, upgraded networks, and clever devices steadily increases demand for precious metals tucked within gadgets [2]. Discarded electronics now show up more regularly as artificial ore bodies - loaded with generous portions of treasured elements such as gold, silver, palladium, platinum; everyday types like copper, aluminum, zinc; along with essential materials including lithium, cobalt, nickel, rare earths. Specifically, used circuit boards, fixed magnets, rechargeable batteries, and screen parts carry metal densities greater than what is mined from numerous natural sources [3]. As an example, top-tier waste circuits hold far more gold compared to

standard rock pulled from mines, strengthening views on city-based recovery instead of digging deep into Earth's crust [4]. Supply worries, uneven mining locations, and rising push for electric tech have made certain metals more crucial lately [5]. Because most rare earths come from just a few places, their availability often hangs in the balance - these materials power magnets, wind machines, car engines, and high-end gadgets [6]. Battery growth for cars and large energy stores has sent lithium and cobalt needs soaring across markets [7]. With these shifts, pulling valuable matter from old electronics now plays a key role in securing supplies while supporting reuse-based economic models [8]. Even so, discarded devices carry serious dangers for nature and people exposed during handling. E-waste mixes many materials - plastics, glass-like substances, metals, even dangerous chemicals like BFRs, lead, mercury, and cadmium - and that mix makes handling it safely a real challenge [9]. In poorer countries,

people often recycle these items in unsafe ways: heating them carelessly, using acids without filters, setting piles on fire openly - all releasing poisons like dioxins, furans, and PAHs into air and ground. Few realize how grime piles up - soil chokes, waterways suffer, skies darken - all while laborers breathe danger each sunrise[10]. Pulling precious metals free? Traditionally, it either takes blistering temperatures or drenches in liquids that bite. High-heat operations - melting or baking waste at intense temperatures - pull out copper and rare metals quite effectively, yet guzzle power and can spew harmful fumes if left unchecked [11]. Acid or alkali-based hydrometallurgy, paired later with solvent extraction, precipitation, or electrowinning, brought better precision and used less power - yet demanded large amounts of chemicals and produced waste streams [6]. Lately, methods using microbes, along with deep eutectic solvents (DES), ionic liquids, and greener chemical routes, began showing potential: cutting harm to nature without losing efficiency in pulling out metals [8]. When viewed through long-term impacts, analyses confirm recycling metals from old electronics slashes carbon output and lightens damage to ecosystems - especially true for aluminum, copper, gold, and rare earth elements - compared to digging new ore [5]. Even so, progress stalls due to patchy pickup networks, scattered tech solutions, unstable prices for reclaimed materials, plus mismatched rules across regions [12]. Right now, checking advanced methods to get useful metals from old electronics matters more than ever. While several studies focused on individual methods or only examined one metal, some linked practical demands with environmental effects, pricing, and recycling setups. Spanning innovations from 2018 to 2025, this analysis balanced performance against lasting usefulness across approaches[10]. It questioned current limits while mapping out what is missing in making city-based mining practical. A close look went into modern approaches that pull metals from discarded devices, measuring harm to nature and real-world cost balance. Gaps stood out - ones slowing down large-scale, responsible growth. Attention stuck to design details, cleaner reactions, and loops where waste feeds new products [11]. Outcomes

pointed clearly: combining smart tech, lower footprints, and solid profit potential must shape future recycling networks[7]. Shows Figure 1 Process Flow Diagram for Metal Recovery from Electronic Waste (E-Waste).



**Figure 1 Process Flow Diagram for Metal Recovery from Electronic Waste (E-Waste)**

## 2. Methodology of Literature Survey

A careful look through existing research helped capture new progress in pulling useful metals out of old electronics[2]. Though most references appeared in scholarly journals between 2018 and 2025, a few older ones slipped in whenever background mattered. Where foundational concepts or technology origins were at stake, past studies lent weight[1].

### 2.1. Database Selection and Search Strategy

One way to start is by checking big science libraries like Scopus, Web of Science, because they hold strong records on tough topics in engineering and environment work [13]. Starting with phrases such as “e-waste recycling” or “urban mining,” researchers built their look-up mix so it could catch articles about pulling key metals from old gadgets. Other word groups included “critical metals recovery,” along with “hydrometallurgy of WPCBs,” “bioleaching of

electronic waste,” and similar focused terms [14]. Instead of just linking words straight, logic tools helped narrow results while keeping a wide net across fields - metallurgy connects here, yet environmental tech, material studies also show up when signals are stretched right [15]. Even rare earth pulls from outdated gear made the list, plus checks on how long e-recycling methods last if used often [11].

## 2.2. Classification Framework

Some of the chosen research papers got sorted under five broad tech areas pre-processing and physical separation techniques Pyrometallurgical recovery processes Hydrometallurgical recovery processes Bio hydrometallurgical and green solvent-based approaches Studies looking at both environmental impact plus cost effectiveness of technology One way to sort things fits how top science magazines now check their work, like Resources, Conservation & Recycling and Journal of Cleaner Production [10,11]. A second round of sorting looked at which metals were aimed for - like precious ones, common metals, battery materials, or rare earths. Recovery rates played a role in how groups formed. Different chemicals used to pull out the metals helped shape categories too [13]. The way each method ran under real-world pressures mattered just as much. Conditions during operation influenced groupings. Environmental markers weighed into the mix, quietly guiding distinctions [16].

## 2.3. Data Extraction and Comparative Analysis

From chosen research papers, numbers on leaching effectiveness, heat levels, chemical strength, how long reactions last, power used, and output amounts were pulled out. To look at how well methods pick target materials, can grow bigger, and affect nature, side-by-side charts got built [14]. When data existed, measures like heat-trapping effect, total energy used, acid rain risk, plus harm to people were pulled together so different technologies could be compared [16]. If mentioned, cost details - such as setup price, running costs, along with how markets react to shifts in metal value - were looked at too [17].

## 2.4. Limitations of the Review

Even with careful planning, some gaps stayed. New discoveries kept coming in fast-changing areas like

deep eutectic solvents (DES), ionic liquids, and electrochemical intensification - after the timeline used for this review [18]. Because lab methods and how results were shared sometimes differed, comparing numbers straight across papers wasn't always possible [19].

Even with those constraints, the structured approach kept analysis sharp. It opened space to spot patterns. Gaps in studies became visible. Routes toward lasting metal retrieval from discarded electronics came into view [11].

## 3. Global E-Waste Generation and Metal Criticality

### 3.1. Global E-Waste Generation Trends

One decade ago, old electronics started piling up faster than ever before - new gadgets arrive quicker, devices die sooner, systems spread wider. By 2019, planet Earth already faced more than 59 million metric tonnes of such trash; forecasts hint at over 74 million by 2030 if things stay unchanged [9,10]. People multiply slower than their discarded screens and circuits do, while official recycling efforts lag behind this surge - pressure builds on nature, on materials, on how we handle what we toss away [11]. Even though Asia produces the most e-waste overall, Europe and the Americas come next when counted piece by piece. Yet richer nations create more waste per person simply because people buy more gadgets and toss them out quicker [12]. While old electronics could be rich sources of materials worth reusing, less than one fifth get officially recycled across the world - most valuable metals vanish into dumps, unsafe workshops, or shadowy salvage setups instead [13]. More new tech like electric cars, solar power setups, cell networks, and server hubs means more complex e-waste showing up in bigger amounts [14]. Faster upgrades in gadgets push older models out quicker, piling up leftover metals inside old devices at an increasing rate.

### 3.2. Metal Demand and Criticality

Starting with cleaner energy paths worldwide, needs for certain key metals are climbing fast. Because transport runs more on electricity now, lithium stands out as a material under heavy pressure [17]. Wind turbines rely heavily on rare earths; their role cannot be swapped easily. One forecast suggests demand for

lithium might jump many times over before 2030 ends. Batteries store power - nickel and cobalt play big parts there. Magnets inside green tech devices need specific minerals too, nothing else fits right [19]. Starting with rare earths like neodymium, dysprosium, and praseodymium - these are tagged critical because so few places mine them, yet they're vital for strong magnets [18]. Cobalt flows through similar risks, most coming from just a handful of areas, sparking unease around political shifts and how mines treat workers [15]. Because these supplies hinge on unstable sources, recycling metals from old electronics now matters more than ever, easing pressure on digging up new ore [12]. Gold, silver, palladium, yet platinum are seeing higher use in tech gadgets, chemical processes, along with signal transmission tools. Though often pulled from discarded computer parts, these elements make financial sense since they appear more densely than in raw ground rock, making extraction practical [10].

### 3.3. Urban Mining Potential

People now see city-based metal recovery as a practical way to get valuable materials from old electronics and built environments [20]. Not long ago researchers found gold levels in certain electronic boards could hit 200–800 grams per tonne - far above the usual 1–5 grams in mined rock [21]. What stands out is how much copper hides in these parts too, sometimes going beyond 15–25 percent by weight, more than what mines typically deliver [22]. Old electric car batteries are turning into a major backup source for lithium, cobalt, and nickel. By the 2030s, recycling these power packs might deliver a big chunk of the world's needed lithium. Spent batteries won't be the only prize - wind turbine parts and gadgets hold rare earth metals too [23]. Pulling strong magnets from discarded tech boosts the value hidden in city trash piles. What once got buried now helps refill high-tech material chains. After their first life ends, materials find new paths through reuse networks [19]. A single recycled phone gives back more than most expect. When factories reuse metal from outdated gadgets, energy demand drops sharply. Instead of tearing into untouched earth, turning waste into supply slashes harmful emissions [15]. Less digging means cleaner air over time. Aluminum made

from used products slashes energy needs by more than seventy percent. Copper follows a similar pattern, needing much less heat and electricity when reclaimed. These gains make city-based extraction a backbone of sustainable resource loops [22]. 3.4. Challenges in Harnessing Secondary Metal Resources Big reason old electronics aren't used well for metal reuse lies in how they're gathered - collection just doesn't work smoothly [20]. Product designs make taking things apart harder than it needs to be. Because materials are mixed together tightly, sorting becomes messy and slow. Dismantling setups lack what's needed to keep up properly. On top of that, in poorer areas, backyard recyclers tend to skip safety steps. Their shortcuts mean metals vanish into waste while pollution spreads easily [21]. Ups and downs in metal markets shaped how much money recyclers make, especially when dealing with scarce critical metals [11]. Because rare earths and lithium are tough to pull cleanly from mixed materials, standard approaches often fall short - newer separation methods had to step in [12]. With more metals needed but fewer raw sources available, pressure builds on finding better ways to reclaim them from old electronics [22]. Mining leaves a heavy mark on nature, pushing attention toward cleaner options for getting these materials back. Now things have changed, better ways to recycle are getting noticed. When everything fits together well, it makes a real difference. Squeezing full value from old gadgets keeps materials flowing without wrecking nature [23].

## 4. Composition and Valuable Metal Distribution in E-Waste

Though made from many different materials, old electronics shape how we choose methods to pull useful parts back out. Primary ores usually center on just one kind of mineral, yet discarded devices mix metals, plastics, glass, and ceramics tightly together - locked in place when products were built [23]. Because these pieces bind so closely, pulling them apart takes several careful steps before any metal can be freed effectively [24].

### 4.1. Classification of E-Waste Streams

Few kinds of electronic trash stand out when sorted by device type or what they're made of - think

fridges, phones, laptops, lamps, gadgets you plug in [11]. Out of all these, old circuit boards often hold rare metals worth recovering. So do used lithium batteries found in devices people toss. Permanent magnets inside machines also carry useful materials experts now look to reuse. Each kind brings different chances to pull back valuable elements [15]. Circuit boards form the core of most gadgets, their layers holding many metals inside plastic and glass fiber blends. Inside batteries - especially from cars that plug in or handheld tech - you will find dense amounts of lithium, cobalt, nickel, manganese, copper [16]. Pulling magnets out of spinning parts like drive disks, motors, or turbine generators opens paths to neodymium, dysprosium, plus scarce earth minerals [17].

#### **4.2. Metal Distribution in Waste Printed Circuit Boards (WPCBs)**

Because they hold so much metal and can be worth something, WPCBs get a lot of research attention. Usually, about three to four out of every ten parts by weight are metal, and most of that is copper - roughly one and a half to two and a half parts in ten [18]. Even though gold, silver, palladium, and platinum show up in smaller amounts, these rare metals make up a big share of the total worth [19]. In top-quality WPCBs, gold levels are seen anywhere from 200 to 800 grams per ton - far above what natural ore usually offers [22]. Silver shows up at about one to three kilograms each ton, whereas palladium runs between fifty and two hundred grams per ton [23]. Because these amounts run so high, pulling metals from old circuit boards feels more worthwhile than before. Still, inside WPCBs you'll find materials like epoxy resins, brominated flame retardants (BFRs), and fiberglass - this slow down metal recovery later on. When heated, those substances might turn into harmful brominated dioxins and furans, so handling needs tight control [24]. Shows Table 1 Metal composition across different e-waste components.

#### **4.3. Metal Distribution in Lithium-Ion Batteries (LIBs)**

Lithium-ion batteries now play a big role because electric cars are spreading fast. Instead of just growing quietly, these power sources rely on specific parts inside [20]. Their positive sides often use

structured metal mixes. Layers often hold lithium, cobalt plus oxygen in one usual blend. Nickel steps in sometimes, or maybe manganese replaces part of it, changing behavior quietly. Iron shows up too when adjustments are needed. A specific arrangement suits only certain designs on purpose. Labels act like names scientists check each time. Small marks make differences clear without guessing [21]. Heavy amounts of nickel now replace cobalt in certain modern lithium-ion cells. Earlier versions often held between five and twenty percent cobalt by mass. High-nickel versions push that element into similar concentration ranges [22]. Lithium itself usually sits somewhere between 2 and 7 percent - what you get depends mostly on the specific mix used in the positive electrode. Because these materials add so much value inside old cells, pulling them back out can pay off well when markets need more metals for new batteries [23]. Even so, adding salts, glue-like substances, and metal parts made handling harder. Because of that, crushing first - then using targeted dissolving - became common to pull out the active layers away from the rest [25].

#### **4.4. Rare Earth Elements in Permanent Magnets and Displays**

Magnets made from neodymium-iron-boron sit high on the list when it comes to reclaiming rare earth materials. While neodymium usually takes up 20 to 30 percent by weight, tiny amounts of dysprosium or praseodymium slip in too - just enough to boost strength. Because these levels tower over what's pulled from raw ore, getting them back from old gear makes strong sense [18]. Fluorescent lamps and display phosphors often contain rare earths like europium, yttrium, terbium - besides magnets [27]. Even if found in smaller amounts than in magnetic materials, these elements carry steep worth and uncertain availability, pushing interest toward targeted recycling methods [15].

#### **4.5. Comparison with Primary Ores**

Metal levels in some e-waste often beat those found in raw ores. Take copper: natural deposits usually carry under 1 percent, but circuit boards regularly show over 15 percent [24]. Gold runs much the same way - mined rock tends to hold just 1 to 5 grams per tonne, yet old printed circuits can pack hundreds of

grams in that same weight [23]. One reason e-waste is seen as rich ore lies in its metal content, yet pulling those metals apart gets tricky because mixtures resist

#### 4.6. Implications for Recovery Technologies

Metals spread unevenly through tough mixtures, shaping how methods get picked. Because breaking materials apart works differently depending on grain size, separation results shift too - especially where metals cling to plastics. Tiny bits tend to escape when things are crushed, which sometimes means losing

simple methods. Unlike regular mining, breaking down these blends demands sharper techniques due to tangled material structures [25].

valuable elements hidden in layered structures [26]. A fresh mix of tuned-up prep steps, smart filtering, then careful cleanup shows real promise - cutting waste while pulling out more useful material. What matters most is how each step feeds into the next without harming surroundings [27]. Shows Table 1 Metal composition across different e-waste components

**Table 1 Metal composition across different e-waste components**

Elements	E- Waste components				
	Televisions	Printed Circuit Boards	Mobile Phones	Personal Computers	References
Cu (%)	2–5	10–25	10–20	5–15	[25]
Au (g/t)	50–100	200–800	300–350	100–250	[26]
Ag (g/t)	200–500	1000–2500	100–300	500–1500	[27]
Pd (g/t)	10–20	50–150	30–100	20–80	[28]

### 5. Pre-Processing and Physical Separation Technologies

Breaking down e-waste properly comes first if you want to pull out useful metals. Because electronics are made of many different materials mixed together, freeing up the metal bits from plastic or glass-like parts makes later steps work better [28]. When sorting isn't done well at the start, some metal slips away, mixes get messy, and heat or chemical treatments struggle to pick cleanly between elements

[29].

#### 5.1. Manual Dismantling and Selective Component Removal

Starting by hand, workers take apart devices at recycling sites to grab valuable parts like circuit boards, wires, magnets, and battery units [22]. Because people do this first, dangerous items - batteries or lights with mercury - get pulled early. That choice keeps poisons out of what comes next. Fewer spills happen down the line when sorting

happens piece by piece up front [23]. Breaking things down by hand takes time, yet it often results in cleaner materials and better retrieval of valuable metals [27]. Still, because it's hard to scale up and expensive where wages are high, factories have been slow to adopt it - prompting a shift toward machines that take apart devices on their own [28].

### 5.2. Mechanical Shredding and Size Reduction

Breaking materials down using machines like grinders or crushers helps free metal bits trapped inside non-metal parts. Making pieces smaller opens up more surface space, which makes later sorting - by physical or chemical methods - work better [25]. Still, too much crushing creates tiny bits - smaller than half a millimeter - often linked to losing valuable metals through airborne dust and poor sorting [26]. When researchers looked closely, they found balancing grind size helped pull out more metal without wasting power or shedding material [27].

### 5.3. Magnetic Separation

Iron and steel pieces pulled from crushed electronics often come out using magnets. Depending on how responsive the metals are, either weak or strong magnetic systems get used instead [18]. Simplicity and low expense make this step useful early on, trimming bulk ahead of more complex methods. Even so, most magnetic sorting focuses on large iron-based materials. It struggles to pull out useful non-iron metals like copper or gold. Rare earth elements also slip through. This method just does not grab them well [19].

### 5.4. Eddy Current Separation

Spinning magnets create invisible pushes that kick out bits of metal like aluminum or copper. These kicks happen because moving fields stir up tiny electric loops inside conductive scraps [22]. Instead of sticking around, those pieces get thrown forward while others stay put. This trick relies on how certain metals respond when caught in changing magnetic whirls. Non-metal parts just sit still, unaffected by the shifting pull nearby [24]. Heavy metal chunks respond well to this technique, yet results drop off with finer grains because electrical differences fade and small bits get dragged along [25]. Tweaking how fast the rotor spins, how much material enters, and the

range of grain sizes helps boost sorting success [26].

### 5.5. Electrostatic Separation

A spark jumps when tiny metal bits meet strong voltage, leaving behind stubborn plastic and glass fibers. These metals let go fast, sliding off once their charge escapes into the air. Instead, the plastics stick tight to the charged plate, refusing to drop. One kind flees the field; the other holds on like static cling after a winter coat rubs wool [20]. This approach works well to pull out copper and aluminum from broken WPCB bits once they are crushed [23]. Still, things like dampness, how big the pieces are, and dirty surfaces sometimes mess up the sorting job [24].

### 5.6. Density-Based Separation Techniques

Heavy metals such as copper and gold squeeze more substance into one spot than pieces of plastic or glass do [26]. Since there's such a difference in weight, methods using heaviness to separate things often succeed - especially when the chunks aren't too tiny. Shaking tables jostle materials until heavier pieces migrate away from lighter ones. Air classifiers use airflow to split components based on how easily they're pushed around [28]. Another method suspends crushed material in a liquid tuned so only denser fragments sink. These approaches - among others - have pulled apart metal from nonmetal chunks in waste streams. Their success hinges on one fact: big differences in density make sorting easier [29]. Pieces that weigh less get pulled out before metals are heated, using air to separate them. This step cuts down how much power is needed later on. It also means less waste builds up when things go into high-heat treatment steps [11].

### 5.7. Limitations of Physical Separation

Even so, breaking things apart by hand hasn't pulled out every bit of metal. Some rare metals still stick inside layered mixes, trapped in plastic or glue stuff. Because of that, heat or liquid methods usually step in later. Without those extra steps, full cleanup just doesn't happen. The stubborn leftovers cling too tight to be shaken loose mechanically [18]. Flying bits from breaking materials stir health risks, since specks travel far, possibly carrying toxins [30]. Getting more from used goods now leans on sharper breakup techniques linked to strong recovery systems for metals [22].

## 6. Pyrometallurgical Recovery Processes

One of the oldest industrial ways to get useful metals from old electronics is pyrometallurgy. High heat pulls apart metal bits from non-metal parts by melting them, reducing compounds, or forming slag. Because these methods manage mixed inputs well and stay reliable, they've become common in large recycling plants [24].

### 6.1. Smelting-Based Recovery

Heating scraps drives off plastics, leaving behind valuable bits. Into roaring ovens go crushed electronics, mixed with raw ore streams. Copper pulls rare elements along as it melts down. Gold, silver, plus others tag along when heat splits materials apart [26]. Above twelve hundred degrees, things start breaking free and shifting around. Metals sort themselves - one part sinks, another floats away in waste glass. Fires refine old tech without needing brand-new setups. What remains flows into two separate pools: one rich, one discarded [31]. Old computer parts feed furnaces built for bigger loads. Heat tears apart binders, freeing trapped conductors inside. Molten mixtures carry treasure through ancient-style fire tricks. No solvents needed - just extreme warmth doing its job [32]. Precious atoms hitch rides on liquid pathways below. Slag forms crusts while useful cores keep circulating onward. Systems reuse what once seemed worthless after burning begins [33]. Gold recovery rates above 95 percent, alongside copper exceeding 90 percent, show up often in industrial runs across Europe and parts of Asia - thanks to combined smelting methods [11]. Because existing setups fit well with standard copper purification gear, progress flows without major rework. Still, heavy power demands come into play - alongside waste byproducts like slag and gases that trouble air quality standards [12]. From one angle, efficiency wins; yet emissions linger as a burden on surroundings [13].

### 6.2. Roasting and Thermal Pre-Treatment

Heat treatment once prepares materials before melting or chemical recovery begins. Though it burns off organics, some toxins escape as gas early on. When managed well, this process pulls out bromine from fire-resistant additives. So later high-temperature steps create fewer harmful byproducts

like dioxins [29]. Even so, when burning is not complete or heat isn't managed right, harmful substances like PBDD/Fs can form [24]. Because of that, better air filtration and close watch on what's released are now necessary to meet pollution rules [15].

### 6.3. Plasma Arc and Advanced Thermal Technologies

Hot gas beams now provide a powerful way to melt waste, hitting temps over 1500 °C - breaking down oily stuff fast. Because of this intense heat, metals come out cleaner and leftovers take up less space [29]. Less sludge shows up when using these units, which helps sort materials better. Energy packs tightly inside the beam zone, speeding up treatment while pulling more metal back [31].

Still, running plasma systems means using lots of electricity along with heavy upfront costs, slowing down wider use [34]. Profitability mostly ties back to what the input material contains and how much the extracted metals can fetch [35].

### 6.4. Environmental and Energy Considerations

Fuel-heavy methods pull out lots of copper and rare metals well enough, yet guzzle power while pumping up climate-damaging gases [17]. Burning plastic bits feeds carbon dioxide into the air; at the same time, toxic metal vapors escaping during heat treatments force complex scrubbing tech just to keep skies safer [18]. Starting off differently, smelting processes tend to use more energy than water-based methods do - especially with poor-quality electronic scrap. On top of that, handling leftover slag means watching out closely, since harmful metals might leak without proper safeguards [20].

### 6.5. Advantages and Limitations

Heat-based metal recovery works well because it handles messy raw materials without breaking down. Copper pulls out valuable metals all at once when things get hot [22]. This method fits right into today's metal factories without needing big changes. Instead of sorting everything first, it deals with mixtures just fine [24]. One step does what used to take many, saving time and effort. Because it is tough, it runs steadily even under rough conditions. Valuable elements gather in the copper part as the rest melts

away [25]. Old systems accept this approach easily since they already run on similar principles. No need for perfect inputs - dirtier stuff still gives results [26]. Multiple rare metals come out together instead of one by one. It skips complicated prep work before melting begins. The whole thing stays stable thanks equipment already in place [30]. Still, drawbacks pop up in the form of steep setup expenses alongside heavy power demands. Poor oversight might even release harmful emissions [31]. On top of that, pulling out lithium, rare earths, or similar lightweight metals stays tough using standard smelting methods - these materials usually wind up trapped in slags

to how heat controls reactions. What would fail elsewhere keeps going here without slowing down. Even jumbled batches turn into useful outputs through high temperatures. Metals like gold and platinum show up where copper collects them. Nothing extra needed - the process uses standard instead [32]. Still, even though high-heat methods work well for pulling out large amounts of copper and rare metals, scientists are turning more toward water-based techniques - along with newer eco-conscious options - to improve precision and lower harm to nature [36]. Shows Table 2 Comparison of major metal recovery technologies

**Table 2 Comparison of major metal recovery technologies**

Method	Temp	Efficiency	Cost	Environmental Impact
Pyrometallurgy	>1200°C	>95%	High	High
Hydrometallurgy	<100°C	90–98%	Medium	Medium
Bioleaching	Ambient	70–90%	Low	Low

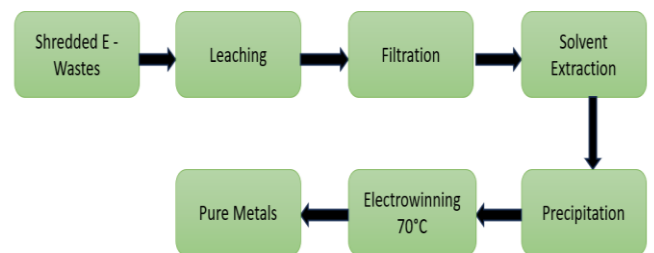
## 7. Hydrometallurgical Recovery Processes

Getting metal out using water-based methods has become more popular than high-heat ways because it runs cooler, picks targets better, yet uses less power [37]. Because conditions stay mild, dissolving metals carefully in liquid comes first - then cleaning them up happens through oil mixing, dropping solids, swapping charged particles, or pulling pure layers with electricity. When dealing with messy electronic scraps, these wet approaches work well for grabbing valuable stuff like gold, materials used in batteries, plus uncommon earth minerals [35]. Shows Figure 2

### 7.1. Acid Leaching Systems

Starting with acid leaching - it's drawn more research attention than any other water-based method for pulling metals out of old electronics. Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), hydrochloric acid (HCl), and nitric acid (HNO<sub>3</sub>) often take center stage, used alone or teamed

Hydrometallurgical Process Flow for Metal Recovery from E-Waste



**Figure 2 Hydrometallurgical Process Flow for Metal Recovery from E-Waste**

up with substances that help break down materials faster [24]. Copper extraction from old circuit boards often relies on sulfuric acid mixed with hydrogen peroxide, pulling out over 90 percent of the metal when conditions are just right [25]. Silver and common metals dissolve well in nitric acid - yet

fumes and price tag keep it from wider use [26]. As for gold and palladium, hydrochloric acid works better when paired with chlorine or iron-based oxidizers [27]. Even when metals are recovered well, using acid to pull them out leaves behind waste

liquids that must be cleaned before release. Heavy use of strong chemicals adds cost and harms nature, so researchers now look elsewhere for better ways [28].

**Table 3 Hydrometallurgical leaching efficiency of key metals**

Metal	Leaching Agent	Efficiency (%)	Conditions	References
Cu	H <sub>2</sub> SO <sub>4</sub> + H <sub>2</sub> O <sub>2</sub>	90–98	60–80°C	[34]
Au	Thiourea	85–95	Acidic	[35]
Ag	HNO <sub>3</sub>	90–99	Room temp	[36]
Co	HCl	95–98	70°C	[37]

### 7.2. Alkaline and Selective Leaching

Pouring sodium hydroxide into mixtures pulls out aluminum while copper stays behind. Studies looked at this method mainly to grab particular metals - especially aluminum plus some rare earths [11]. The leftover bits keep precious metals untouched. This way, separation happens without dragging everything into solution [15]. Starting with acid, workers pull out transition metals first. Then comes the turn of alkaline solutions - they grab lithium on their own. This step-by-step approach keeps metals apart more effectively. Mixing between elements drops when steps follow one another like this [18].

### 7.3. Reductive and Oxidative Leaching Mechanisms

It's common for oxidative leaching to pull out metals that start off as pure elements or in lower oxidation forms. To speed things up, chemicals like hydrogen peroxide, ferric sulfate, or persulfate help break down copper and valuable metals more quickly [31]. On the flip side, when dealing with old lithium-ion batteries, reductants such as glucose, ascorbic acid, or sodium metabisulfite turn stubborn metal oxides into forms through chemical settling. Take cobalt and nickel - these turn into hydroxide or carbonate forms when pH shifts happen alongside specific reagents [6,10]. With lithium, the usual path is forming lithium carbonate, guided by adding sodium carbonate under

that dissolve easier [32]. Work on breaking down old lithium batteries shows vinegar-like substances can pull out nearly all the cobalt when settings are just right [33]. Instead of harsh chemicals, these methods dissolve metals better, possibly cutting harm to nature along the way.

### 7.4. Solvent Extraction and Ion Exchange

After leaching, solvent extraction steps in to pull out metal ions cleanly. One after another, compounds like D2EHPA, Cyanex 272, or TBP grab specific metals - cobalt, nickel, rare earths - with strong preference [35]. Through repeated stages, cobalt splits away from nickel found in old battery fluids. What emerges is a refined flow of metals pure enough to feed into new batteries [36]. Gold and palladium can be pulled from chloride liquids using special resins. Instead of generic materials, those fitted with thiourea or amine bits grab noble metals tight. Because of this targeting, less unwanted stuff comes along. Solvent waste drops since the method holds on to what matters [38].

### 7.5. Precipitation and Electrowinning

From clean leach fluids, metals sometimes come out careful conditions [18]. Copper comes out clean when pulled from sulfate liquids using electrowinning, with purity and capture rates hitting over 98% [19]. Because it lines up so closely with standard refining methods, combining solvent

extraction and electrowinning allows factories to scale without major changes [22].

### 7.6. Environmental and Process Considerations

Hydrometallurgy runs cooler than high-heat methods, often cutting immediate carbon output [39]. When paired with smart prep steps and reuse of chemicals, these water-based systems may pull less total energy across their lifespan, according to full-cycle analyses [40]. Finding solutions isn't easy when reagents get used up fast, dirty water builds up, and keeping the system running takes tight oversight [41]. On top of that, pulling rare earths from mixed liquids means going through several extraction rounds - each one adding more steps, more hassle [42]. Hydrometallurgy now picks out valuable metals from old electronics more precisely. Still, it shifts well between different waste types. What once seemed tricky now moves easier thanks to smarter lab methods [36]. Over months, recycled catalysts begin lowering bills across labs. Tighter reactions fit heavy work into slim setups. Those who watch trends say sticking with this path pays off years later [37].

### 8. Bio hydrometallurgical and Emerging Green Technologies

Not just heat-heavy methods but also liquid-based ones face eco-barriers - that's pushing scientists toward biology-rooted, cleaner ways to pull metals from old electronics. With sights set on lower power needs, fewer harmful fumes, and sharper targeting in extraction, these new techniques still match older yields pretty closely [32].

#### 8.1. Biohydrometallurgy and Bioleaching

Tiny life forms help pull metals from rocks using chemical changes they create themselves. Starting with tough little bacteria that thrive in acid, like *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* - these turn iron and sulfur into stronger dissolvers [33]. Because of this shift, the environment turns sour enough to loosen stubborn metals. On another path, certain fungi join in - notably *Aspergillus niger* and *Penicillium simplicissimum* - which pour out natural acids. These secreted acids grab onto metal particles, making them easier to extract [35]. Bioleaching runs through three main ways. One way involves microbes breaking down minerals slowly. Another relies on chemical reactions sparked by living cells [36]. A third path uses natural oxidation shaped by bacterial activity. Shows Table 4 Microorganisms used in bioleaching processes.

**Table 4 Microorganisms used in bioleaching processes**

Microorganism	Metal Recovered	Efficiency (%)	Mechanism	References
<i>Acid thiobacillus ferroxidase</i>	Cu, Zn	80–95	Oxidation	[42]
<i>Leptospiral ferroxidase</i>	Fe, Cu	75–90	Iron oxidation	[43]
<i>Aspergillus Niger</i>	Rare metals	60–80	Organic acids	[44]

Metal dissolves when microbes drive redox shifts - process known as redoxolysis. Microbial activity alters electron flow, unlocking metals from minerals[30]. This transformation hinges on natural biochemical exchanges underground. Shifts in oxidation states make solid metals mobile in fluid environments. Reactions unfold quietly, yet reshape elemental distribution below surface Here, metals bind tightly with organic acids, staying dissolved in

solution [38]. Not long ago, tests showed microbes pulling out more than 85% of copper from old circuit boards when settings were just right [42]. In much the same way, broken lithium-ion batteries gave up cobalt and lithium when soaked in living cultures - only it took longer compared to harsh chemicals [27]. Faster results remain out of reach, even if eco-friendly methods do less harm to nature. Microbes often fail when poisons enter the mix[25]. Big

machines struggle to keep these delicate reactions going nonstop. Yet crushing materials first helps break resistance. A touch of chemistry now then boosts what bacteria can handle alone[26].

### 8.2. Deep Eutectic Solvents (DES)

It turns out deep eutectic solvents might just replace old-style mineral acids. Usually, these mixtures pair a hydrogen bond donor with an acceptor - creating fluids that melt at low temperatures and dissolve metals well [60]. Unlike standard acids, they tend to evaporate less, pose smaller health risks, and can often be reused. Their makeup allows adjustments, making them flexible for different tasks[61]. Gold, copper, and rare earths come out well from old circuit boards when treated with special mixtures made from choline chloride - this was seen across tests done from 2018 to 2024 [55]. Instead of standard chemicals, custom deep eutectic solvents pull neodymium cleanly from strong magnets, making sorting easier and faster [58]. Facing hurdles like shaky solvent performance, doubts about reuse over time, plus questions on pricing power - big factories still hold back from wide use [35].

### 8.3. Ionic Liquids and Solvometallurgy

Liquids called ionic are getting noticed - mostly because they barely evaporate, handle heat well, and can be adjusted in how they behave physically and chemically. When used for leaching, these fluids pull out valuable metals like gold and palladium using milder setups than usual [28]. With some chloride versions, more than 90 percent of gold has come back from old circuit boards, skipping harsh acid treatments altogether [29].

Waterless ways of pulling metals out have popped up as options that skip the usual soak-and-drain routines. Instead of drowning everything in liquid, these methods use different kinds of solvents to grab specific metals more cleanly[47]. They've cut down on how much water gets used along the way. Some setups even manage waste better by avoiding messy runoff altogether. Cleaner grabs happen when settings stay steady and focused[48]. Picking targets becomes easier without water getting in the way.

Even so, some ionic liquids bring worries about harmful effects, how well they break down, along with steep manufacturing expenses - making full

evaluation essential before wide use [64].

### 8.4. Electrochemical and Process Intensification Approaches

From waste electronics, metals are pulled out using electrical tricks that scientists keep testing. Copper, along with nickel and cobalt, lands on surfaces when voltage is fine-tuned just right [23]. Instead of pouring in harsh chemicals, some setups make powerful reactants right where they're needed [25]. This way, less stuff gets used up during cleanup. Starting fast, microwave heating speeds up chemical reactions when pulling metals from old batteries. Instead of waiting hours, sound waves shake apart particles quicker than normal [32]. Grinding materials while reacting them changes their structure in useful ways. Each technique cuts down how long steps take. Efficiency climbs because more metal comes out at the end. Not every method works the same on all parts, yet results stay strong overall [33].

### 8.5. Sustainability Comparison

Green tech often cuts greenhouse gases along with cutting down harmful waste more than older methods do [52]. Still, these newer systems aren't quite ready for full factory use yet - costs hang on how well solvents can be reused, whether they work at larger sizes, plus if they fit into current setups [53].

Starting fresh down at the molecular level, some comparisons between deep eutectic solvents and older acid methods hint at lighter footprints - if recycling hits above ninety percent. Because of that quiet shift, scientists keep pushing further checks on real-world behavior and staying power over years.[54].

### 9. Recovery of Specific Critical and Precious Metals

How we get back materials from old electronics usually depends on how each metal behaves, what it's worth, and how crucial it is overall[57]. Because they sit differently in devices and react in unique ways, gold-like metals, common industrial ones, those used in batteries, and rare earths need separate treatment steps[58].

#### 9.1. Gold and Precious Metals

Something shiny inside old electronics often hides gold. From broken circuit boards it can be pulled out using familiar methods like cyanide baths or strong

acid mixes[64]. Toxic trouble follows those choices though. That risk pushes scientists toward safer dissolving chemicals instead. A different path grows more interesting each time someone tests it [56]. Scientists lately looked at different methods - like thiourea, thiosulfate, or halides - to replace cyanide safely. With help from copper-ammonia mixtures, the thiosulfate method pulled out more than 85 percent of gold when conditions were just right [67]. Using hydrochloric acid plus strong boosters like ferric ions or hypochlorite, chloride setups dissolved over 90 percent of gold taken from crushed circuit boards [68]. After breaking down the material, gold can be collected using solvents, carbon filters, special resins, or electric currents [48]. Resins fitted with sulfur-based parts grab onto  $AuCl_4^-$  ions tightly, pulling out gold cleanly when other metals are present too [49]. Found in tiny amounts inside connectors and ceramic making new copper, pulling it back from old electronics slashes energy needs while cutting down on carbon output [42].

### 9.3. Lithium, Cobalt, and Nickel from Lithium-Ion Batteries

One big reason old lithium-ion batteries matter now? More electric cars on roads every year. Inside, materials like  $LiCoO_2$ , plus mixes called NMC and NCA, pack plenty of cobalt, along with nickel. These metals shape how companies choose to recycle them - value drives the method. Research backs this shift toward recovery [45]. Fueled by sulfuric acid, hydrometallurgical leaching teams up with reducers

capacitors, palladium along with other platinum group metals get pulled out through chloride-based leaching, then sorted via precise precipitation or liquid-liquid transfer [50]. Even though there's not much of it, the price tag makes pulling them apart worth the effort.

### 9.2. Copper Recovery

Out of all metals in WPCBs, copper takes up the biggest share - frequently more than 15 percent by weight [64]. High-heat smelting methods sit alongside liquid-based acid treatments when pulling out copper. When using wet chemistry setups, mixing sulfuric acid with either hydrogen peroxide or ferric sulfate pulls nearly all the copper into solution - over 95 percent efficiency [40]. With solvent extraction followed by electrowinning, industry mirrors traditional copper refining, yielding very pure cathode copper above 99.9 percent [41]. Rather than like hydrogen peroxide or glucose - pulling out over 95% of cobalt and nickel [46]. While lithium stays behind in liquid form, it gets pulled into solid shape later, transformed into lithium carbonate when sodium carbonate enters under careful conditions [47]. From complex mixtures, cobalt can now be cleanly pulled away from nickel using Cyanex 272, yielding high-purity cobalt sulfate suitable for batteries [55]. Instead of breaking everything down, newer methods focus on rebuilding cathodes straight from recycled material - cutting steps, saving energy [60].

**Table 5 Metal**

Metal	Content	Recovery Meth	Efficiency	References
Lithium	2 - 7	Precipitation	80-95%	[37]
Cobalt	5 - 20	Solvent extraction	95-98%	[38]
Nickel	5 - 10	Leaching	90-95%	[39]

### 9.4. Rare Earth Elements from Permanent Magnets and Phosphors

Getting rare earth elements from NdFeB magnets

matters more now because supplies are shaky. Using hydrochloric or sulfuric acid breaks down neodymium and dysprosium well - over 90% comes

out when things run just right [10]. From time to time, oxalic acid pulls rare earth elements out of solution as solid oxalates - a method long trusted before heating turns them into pure oxides [11]. Because these metals behave so much alike, pulling one away from another needs many rounds of solvent work, often leaning on phosphorus-based chemicals that grab specific ions bit by bit [15].

Shows Table 5 Recovery of metals from lithium-ion batteries.

### 9.5. Platinum Group Metals (PGMs)

Out of all metals tucked inside electronics and catalysts, platinum group ones resist change most. These stubborn elements need special solutions just to break down. Instead of reacting easily, they demand harsh treatments - like mixes built on chlorine power[20]. Solutions using chloride with extra kick manage to pull out palladium and platinum well. Aqua regia does this job often, though other sharp-edged alternatives work too. Efficiency climbs when the chemistry pushes hard enough[21]. Purification later on, through methods like solvent extraction or targeted precipitation, made it possible to reclaim highly pure PGMs - fit for use again in catalysts and electronics [22]. Because these metals carry such a steep price tag, even tiny amounts found in discarded electronics have made tailored recovery efforts worthwhile. This part showed how methods to recover metals shift a lot based on what metal it is, how much there is, and how messy the mix around it happens to be[22]. Though pricier ones like gold or cobalt often call for advanced techniques to pull them out cleanly, blending several ways to reclaim materials together still makes the whole cycle work better over time[23].

## 10. Environmental and Techno-Economic Assessment

A shift toward recovering metals from old electronics rests heavily on how well it cuts pollution, saves power, or makes financial sense. Though discarded devices hold valuable materials similar to raw ores, measuring real gains means digging into data - using full-cycle impact reviews, climate cost estimates, and detailed cost-performance simulations [45].

### 10.1. Life Cycle Assessment (LCA)

Every study on life cycles shows reprocessing metals

from old electronics causes far less harm than digging up new ore. Pulling copper, aluminum, gold, or rare earth elements from waste slashes climate damage, cuts total power needs, also lowers risks of soil and water turning acidic [59]. A good example is how making copper from old circuit boards uses way less energy - over half, sometimes up to 80% less - than pulling it fresh from sulfide rock [63]. On a similar note, recycling gold from discarded electronics releases far fewer climate-warming gases for each kilo than digging new gold out of the ground, where massive amounts of waste rock and heavy power demands drive impact upward [66]. Fewer resources get used when pulling rare earth elements from old magnets instead of digging new ore - water stays saved, radiation risks drop. That shift matters most where mining leaves behind contaminated sludge and thirsty processing trails [51]. Still, how big the impact is often depends on where you draw the system's limits. Power source matters a lot - when these chemical setups run on coal-heavy grids, their footprint can match making metal from ore. That happens especially if chemicals get used up fast and dirty water isn't handled well [52].

### 10.2. Carbon Footprint and Energy Intensity

High heat needed in pyro methods means more CO<sub>2</sub> released straight into air, especially when burning plastic parts [10]. On the flip side, water-based extraction runs cooler yet leans on chemicals whose making adds to carbon output behind the scenes [12]. Out in the labs, new methods like deep eutectic solvents might cut greenhouse gases - if factories can keep the solvents recyclable and microbes steady over time [13]. Heavy industry uses far less power when pulling aluminum and copper from old products instead of digging new ore from the ground. Skipping steps like sorting rock and melting raw material cuts energy needs sharply. Cities acting as hidden mines now seem smarter for cutting down emissions. Proof piles up showing reuse beats extraction every time on power use alone [14]. Shows Table 6 Environmental impact comparison of recovery methods.

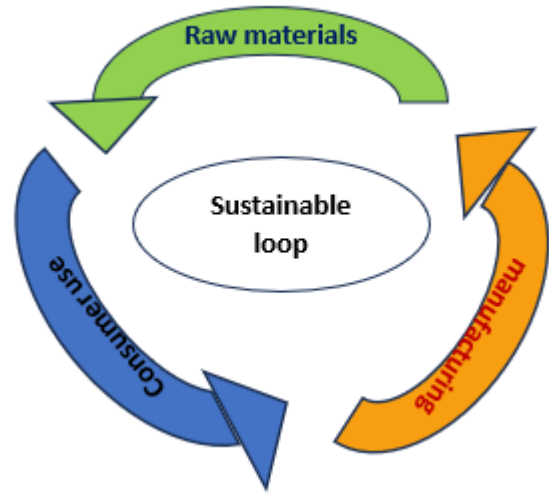
### 10.3. Techno-Economic Feasibility

Profitability in e-waste recycling? That ties closely to what materials come in, how much metal they hold,

how well it gets pulled out, plus swings in commodity markets. Gold and palladium - those shiny ones - tend to bring in most of the money when dealing with old circuit boards [17]. When batteries are broken down though, especially lithium types, earnings hinge a lot on cobalt and nickel rates [18]. Shredders, leaching tanks, and solvent setups form part of the build cost for combined hydrometallurgy sites, along with systems handling runoff and metal recovery through electric baths [29]. Running these operations means ongoing spending on chemicals, power needs, staff, plus dealing with leftover materials after processing. Profit chances for reusing old lithium-ion batteries may grow as more used units pile up and methods get better [30]. Still, shifts in market rates sometimes shrink earnings, especially if new battery types hold less cobalt [31].

it around have shaped how green things turned out. Research points to better pickup setups along with local recycling networks making a real difference in helping the planet [39].

### 10.5. Circular Economy Integration



**Figure 3 Sustainable Circular Process for Metal Recovery**

Pulling metals from old electronics fits well with reusing resources instead of dumping them [40]. For lithium-ion batteries, recycling loops try to feed extracted materials straight back into making fresh battery parts, cutting down waste and weak spots in sourcing supplies [35]. Still, getting things done meant manufacturers had to line up with recyclers alongside regulators. Rules pushing companies to handle their products' end-of-life, design greener items, or hit recycling goals helped materials keep circulating more smoothly [64]. From a broader view, checking both eco-effects and cost-performance shows recycling metals from old electronics might ease harm to nature plus cut down shortages - if systems work better together while rules back them up [68]. Shows Figure 3 Sustainable Circular Process for Metal Recovery.

### 11. Policy, Regulation, and Circular Economy Integration

Effective recovery of valuable metals from e-waste has not depended solely on technological advancements but has also been strongly influenced by regulatory frameworks, institutional mechanisms, and international trade policies. Inadequate

**Table 6 Environmental impact comparison of recovery methods**

Process	CO <sub>2</sub> Emission	Waste Type	Impact Level	References
Mining	Very High	Solid + gas	Severe	[12]
Pyrometallurgy	High	Gas	High	[13]
Hydrometallurgy	Medium	Liquid	Medium	[14]
Bioleaching	Low	Minimal	Low	[15]

### 10.4. Comparison with Primary Mining

Few people dig deep into Earth anymore just to get metals. Instead, pulling valuable stuff out of old electronics skips heavy digging across wide areas. Pulling resources from city waste uses way less water than traditional pits [35]. Old gadgets act like rich deposits without tearing up forests or hillsides. Burning rocks to free minerals releases thick clouds into air - urban methods avoid that mess entirely. Gathering scraps from towns cuts down how much pollution spreads during cleanup and melting steps [38]. Even so, problems gathering waste plus moving

governance structures and informal recycling practices have historically limited resource efficiency and exacerbated environmental risks [51].

### 11.1. Global Regulatory Frameworks

Global work on handling dangerous waste across borders leans on deals like the Basel Convention, shaping how countries exchange harmful materials, sometimes covering types of old electronics [37]. Revised rules tightened oversight of sending messy or blended electronic trash abroad, especially where poor systems make safe recycling hard [38].

Nowhere near uniform at first, Europe pushed new rules through the WEEE Directive - setting clear goals for gathering old electronics, boosting reuse rates, while making manufacturers take ownership beyond the sale. Because of this shift, companies must pay for retrieval and processing networks, nudging them toward smarter product layouts and cleaner recovery paths[53]. In parts of Asia, including China, Japan, and South Korea, official rules now handle electronic waste through return programs alongside approved recycling centers [54]. Still, how well these rules work depends heavily on where you look.

### 11.2. Extended Producer Responsibility (EPR)

A fresh approach to handling old electronics shifts duty straight to makers. Because of these rules, companies now face the task of managing what happens when devices wear out. This push leads them to rethink how gadgets are built[2]. Better recycling features start appearing as a result. Some toxic materials get left out altogether. Design changes follow once accountability lands on producers' shoulders[10]. Facts from research show properly built EPR systems boost official pickup numbers while also lifting how much material gets reused [18]. Still, issues pop up - like some skipping rules yet gaining benefits, weak oversight showing up now and then, along with spotty follow-through on goals meant to be met [25].

### 11.3. Informal Recycling Sector

Across much of the developing world, handling electronic waste often falls to unofficial workers who rely on basic methods like burning cables in the open air, soaking parts in acid, or taking devices apart by

hand - all without proper protection [11]. Though these activities support income for some families, they regularly lead to dangerous pollution and harm to worker health because toxic substances such as heavy metals and long-lasting chemicals escape freely into surroundings [3]. When informal recyclers join organized systems, collection tends to work better. One idea is helping them learn new methods through hands-on workshops. Support might come from funding that makes participation possible over time [16]. Training often includes using tools more effectively on a daily basis. Including these workers can also reduce harm to nature and people nearby. Learning opportunities build stronger routines across entire networks[37].

### 11.4. Strategic Raw Material Policies

Fear about where to get vital metals is pushing leaders everywhere to rethink how they handle essential resources. Every so often, Europe checks which raw supplies are most at risk - lately spotting lithium, cobalt, and rare earths as key players in staying strong economically and tech-wise [45].

New rules pushed money into local recycling systems, also boosting studies on better ways to recover materials [52]. In places like the U.S. and Japan, governments act alike - shifting focus from distant mines by building up homegrown supply plans [53].

### 11.5. Circular Economy and Sustainable Development Goals (SDGs)

Recovered metals from old electronics fit well within circular economy ideas, since they reuse materials instead of pulling new ones from the ground - this also cuts down on trash buildup [65]. Recycling setups that work properly support multiple UN goals: smarter use of resources (SDG 12), efforts against global warming (SDG 13), and better industrial methods (SDG 9) [66]. Even so, progress has stalled in poorer nations because roads and facilities are lacking, trash keeps getting shipped where it should not go, equipment tracking often fails. Matching rules across borders along with ways to follow materials worldwide appears key to handling old electronics responsibly over time[68]. From time to time, rules and guidelines shape how well metals get reused. Working together - governments, companies,

scientists - keeps progress moving forward. What matters grows quietly behind steady effort [29].

## 12. Challenges, Research Gaps, and Future Perspectives

Even with major tech progress, pulling useful metals from old electronics still runs into problems - technical ones, cost issues, ecological concerns, and deep-rooted system flaws. Tackling these hurdles became key if city-based mining operations were ever going to work at scale [40].

### 12.1. Technical and Process Limitations

Broken electronics come in many shapes, sizes, materials - handling them isn't straightforward. Because gadgets differ so much in build and makeup, setting consistent recycling steps gets tricky. Tiny bits form when machines break down devices early on. These small pieces carry valuable metals away before they can be caught properly [49]. Still tricky, pulling rare earths and lithium from mixed metals - lanthanides act too much alike, their ions nearly identical in size [55]. Because of that, sorting REEs needs many rounds of solvent work, which makes everything harder and pricier. Finding ways to grab light metals like lithium during high-heat processing usually leaves some trapped in waste rock, which means another step is needed to pull out the rest [56]. Because of that, mixing heat-based methods with water-based ones has come up as a way to get more metals out in total.

### 12.2. Scale-Up and Industrial Implementation

Even so, lab tests show decent results with bioleaching, deep eutectic solvents, along with ionic liquids - yet factories barely use them [28]. Bigger operations struggle because solvents break down too fast, reuse gets messy, microbes quit working overtime, pipes corrode, plus reactors need constant tweaking [22]. Heavy metals can poison microbes, making bio-based mining sluggish. That slowness drags down output. Because of this, standard methods still outperform them at scale [39]. Tougher microbe teams are now a main target. So is squeezing more efficiency into each step. Progress here decides whether these systems ever go mainstream [40].

### 12.3. Economic and Market Uncertainties

Now here's a twist - what once made recycling pay well

is slipping away because metal prices keep shifting worldwide. Less cobalt hiding inside new lithium-ion batteries means less money coming in for those who recycle them, so pulling out more lithium and nickel becomes key just to stay even [51]. Big costs for modern metal recovery setups plus pollution controls have blocked funding, especially in poorer nations [52]. Profitability often ties to material purity, how well waste is gathered, or links to current smelting networks.

### 12.4. Environmental and Sustainability Concerns

Even so, green solvents and electrochemical setups are still unclear in how they affect nature over time. Before these can spread widely, full evaluations of how they're made, reused, or harm living things must happen [67]. Finding ways to handle used water, bring chemicals back for reuse, while safely getting rid of leftover waste stays a key part of lasting solutions. If dirty water is cleaned poorly, gains from pulling out valuable metals might be lost completely [48].

### 12.5. Product Design and Material Traceability

Without common rules for green design, taking products apart cleanly stays hard. Because gadgets pack tiny parts into tangled layouts, sorting materials gets tougher [32]. Some suggest using recycling-focused designs, building in blocks that snap out easily, marking materials clearly - each helping pull more back after use. Ideas like this aim to make reuse smoother, piece by piece [25]. Finding better ways to follow old electronics, some people point to digital tools that log where materials go - blockchain methods included - to make dumping and sneaky shipments harder to hide [15].

### 12.6. Integration of Advanced Technologies

Fresh tools like smart algorithms, machines that move on their own, or systems that take things apart automatically show promise in telling materials apart more clearly while needing fewer people to do the work [4]. Cameras that "see" paired with mechanical arms manage to pick out pieces accurately during small test runs. Starting fast reactions with less chemical use looks possible using methods like microwaves, sound waves, or mechanical grinding [9]. Running these processes nonstop in flowing setups might boost how well factories work.

### 12.7. Toward Integrated Urban Mining Hubs

Finding better ways to handle old electronics might mean building city-based recycling centers that mix shredding machines, careful chemical extraction, burning some parts for power, plus high-tech cleanup steps [13]. These linked setups may pull out more materials while sending fewer pollutants into nature. When governments team up with labs and companies, progress speeds up - especially for testing new tech at larger scales [20]. Investment in local recycling systems plays a key role too, strengthening access to materials while lowering reliance on global suppliers. Looking ahead, work must target better separation methods, less chemical use, ways to reuse liquids more often, also build systems that grow easily while cutting carbon [29]. Success ties closely to blending smart design, policy backing, reuse thinking - each part feeding the next. Though progress waits on many fronts, one thing links them: how well tools, rules, everyday loops fit together [40].

#### Conclusions

Gadgets growing popular pushes demand for uncommon, costly minerals across the planet. When daily living leans heavier into screens and charged tools, outdated tech starts resembling treasure buried in trash heaps[17]. Rather than clawing further underground, urban areas turn into extraction zones - discarded machines packed with silent worth. Tracking changes between 2018 and 2025 reveals just how sharp newer techniques have become at harvesting elements from expired phones and laptops. Performance blends neatly here: function meets environmental weight alongside financial practicality [18]. From discarded devices emerges something odd - insides such as circuit panels, lithium cells, yet powerful magnets hold richer metal content than freshly dug stone. Gold, palladium appear next to copper; meanwhile lithium, cobalt, nickel, even rare earth elements boost the bulk[55]. This blend turns waste into something close to raw mineral. Yet separating them stays hard since tech mixes components in tight bonds. Removing just one element often drags extra ones through the process.[67]. Though pyrometallurgy handles copper and key metals smoothly, it burns through power and often releases toxic fumes. In contrast,

hydrometallurgy slashes high-temperature demands and focuses more precisely - but consumes large chemical doses and generates tangled wastewater issues. Methods such as bacterial leaching, deep eutectic solvents, ionic liquids, and electro-recovery promise cleaner results; their real-world durability and mass production readiness stay unclear, however[48]. Right away, studies of how long products last revealed that pulling metals from outdated gadgets slashes climate emissions way below what mining fresh ore does. Because recovering these materials needs far less energy, it leaves natural habitats mostly untouched[10]. Clearly then, finding clever methods to recycle makes far more sense than trashing useful parts. Yet turning discarded devices into profit often hinges on shaky trading values for recovered metals[15]. A curveball emerged when damaged gadgets arrived at recycling hubs with uneven condition. What mattered just as much was whether users truly handed back their malfunctioning tech. Rules such as the Basel Convention plus schemes holding firms responsible for their trash are significant, yet actual improvements in managing electronic waste safely fall behind[62]. Where supervision fades, informal junk collection grows fast, blocking access to proper recycling across numerous regions. Enforcement gaps let garbage move between countries illegally, even with worldwide agreements designed to prevent exactly that. Certain regulations advance slowly while unseen systems work against them without pause. Change on a large scale feels distant because community habits resist global targets at nearly every turn[68]. One step forward in e-waste metal recovery comes from pairing clever workflow designs with products built for simpler reuse. Not only do solvent purification techniques help, but sensor systems linked through digital networks also contribute without drawing attention[8]. Should backing strengthen behind the scenes, robotic disassembly units might become common. Rather than relying on a single approach, success often follows when mechanical separation joins selective liquid treatments plus ultra-fine sieving[16]. Out here, mixing methods pulls extra metal while dodging wider damage. Shared work holds the key - standards

must line up, whether in labs, capitals, or production lines. When creators, rule-makers, and builders don't move together, recycling loops snap too easily. Strong urban mines rise not from sudden leaps, but from steady teamwork holding things tight[29].

Step by step, recovering useful metals from discarded devices proves effective - evidence supports it, ecosystems gain. Ahead lies a path where innovation walks alongside consistent guidelines, tying advancement directly to recycling. Devices once tossed aside could hold reserves essential for future green technology. These changes transform refuse into resource, subtly redefining how materials flow, all without spectacle[64].

### References

- [1]. Ahirwar, R., Tripathi, A.K., 2021. E-waste management: a review of recycling process, environmental and occupational health hazards, and potential solutions. *Environ. Nanotechnology. Monit. Manage.* 15, 100409. <https://doi.org/10.1016/j.enmm.2020.100409>
- [2]. Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., et al., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. *Environ. Sci. Technol.* 46, 3406–3414. <https://doi.org/10.1021/es203518d>
- [3]. Vuppaladadiyam, A.K., Vuppaladadiyam, S.S.V., Sahoo, A., Murugavelh, S., Anthony, E., Bashkar, T., et al., 2022. Bio-oil and biochar from the pyrolytic conversion of biomass: a current and future perspective on the trade-off between economic, environmental, and technical indicators. *Sci. Total Environ.* 159155. <https://doi.org/10.1016/j.scitotenv.2022.159155>
- [4]. M. Jaiswal, S. Srivastava, A review on sustainable approach of bioleaching of precious metals from electronic wastes, *J. Hazard. Mater. Adv* 14 (2024) 100435, <https://doi.org/10.1016/j.hazadv.2024.100435>
- [5]. X. Zeng, J. Li, B. Shen, Novel approach to recover cobalt and lithium from spent lithium-ion battery using oxalic acid, *J. Hazard. Mater* 295 (2015) 112–118, <https://doi.org/10.1016/j.jhazmat.2015.02.064>.
- [6]. P. Pereira Gonçalves, A. Otsuki, Determination of liberation degree of mechanically processed waste printed circuit boards by using the digital microscope and SEM-EDS analysis, *Electron. (Basel)* 8 (10) (2019). <https://doi.org/10.3390/electronics8101202>
- [7]. Rouchalova, D., Rouchalova, K., Janakova, I., Cablik, V., Janstova, S., 2020. Bioleaching of iron, copper, lead, and zinc from the sludge mining sediment at different particle sizes, pH, and pulp density using acidithiobacillus ferrooxidans. *Minerals* 10 (11), 1013. <https://doi.org/10.3390/min10111013>.
- [8]. Mehmood, A., Mirza, M.A., Choudhary, M.A., Kim, K.H., Raza, W., Raza, N., Lee, S.S., Zhang, M., Lee, J.-H., Sarfraz, M., 2019. Spatial distribution of heavy metals in crops in a wastewater irrigated zone and health risk assessment. *Environ. Res.* 168, 382–388. <https://doi.org/10.1016/j.envres.2018.09.020>.
- [9]. Elwakeel, K.Z., Aly, M.H., El-Howety, M.A., El-Fadaly, E., Al-Said, A., 2018. Synthesis of chitosan@ activated carbon beads with abundant amino groups for capture of Cu (II) and Cd (II) from aqueous solutions. *J. Polym. Environ.* 26, 3590–3602. <https://doi.org/10.1007/s10924-018-1243-2>.
- [10]. Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles [Article]. *Nature (London)* 575 (7781), 75–86. <https://doi.org/10.1038/s41586-019-1682-5>.
- [11]. Liu, J., Bai, H., Zhang, Q., Jing, Q., Xu, H., 2019a. Why are obsolete mobile phones difficult to recycle in China? [Article]. *Resour. Conserv. Recycl.* 141, 200–210. <https://doi.org/10.1016/j.resconrec.2018.10.0>

- 30.
- [12]. S. Ilyas, M.A. Anwar, S.B. Niazi, M.A. Ghauri, Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria, *Hydrometallurgy* 88 (2007) 180–188.  
<https://doi.org/10.1016/j.hydromet.2007.04.007>
- [13]. B. Jiang, A. Adebayo, J. Jia, Y. Xing, S. Deng, L. Guo, Y. Liang, D. Zhang, Impacts of heavy metals and soil properties at a Nigerian e-waste site on soil microbial community, *J. Hazard. Mater.* 362 (2019) 187–195.  
<https://doi.org/10.1016/j.jhazmat.2018.08.060>
- [14]. S. Qayyum, K. Meng, S. Pervez, F. Nawaz, C. Peng, Optimization of pH, temperature and carbon source for bioleaching of heavy metals by *Aspergillus flavus* isolated from contaminated soil, *Main Group Chem.* 42 (2019) 1–7, <https://doi.org/10.1515/mgmc-2018-0038>.
- [15]. H.M. Mouna, S.S. Baral, Bioleaching of rare earth elements from spent fluid catalytic cracking catalyst using *Acidithiobacillus ferrooxidans*, *J. Environ. Chem. Eng.* 9 (1) (2021) 104848, <https://doi.org/10.1016/j.jece.2020.104848>. ISSN 2213-3437.
- [16]. A. Koizhanova, B. Kenzhaliyev, D. Magomedov, E. Kamalov, M. Yerdenova, A. Bakrayeva, N. Abdylidayev, Study of factors affecting the copper ore leaching process, *ChemEngineering* 7 (3) (2023) 54, <https://doi.org/10.3390/chemengineering7030054>.
- [17]. N.D. Shooto, Removal of toxic hexavalent chromium (Cr(VI)) and divalent lead (Pb (II)) ions from aqueous solution by modified rhizomes of *Acorus calamus*, *Surf. Interfaces* 20 (2020).  
<https://doi.org/10.1016/j.surfin.2020.100624>
- [18]. B.A. Ezeonuegbu, D.A. Machido, C.M.Z. Whong, W.S. Japhet, A. Alexiou, S. T. Elazab, N. Qusty, C.A. Yaro, G.E.-S. Batiha, Agricultural waste of sugarcane bagasse as efficient adsorbent for lead and nickel removal from untreated wastewater: biosorption, equilibrium isotherms, kinetics and desorption studies, *Biotechnol. Rep.* 30 (2021).  
<https://doi.org/10.1016/j.btre.2021.e00614>
- [19]. Y. Xu, B. Zhang, Z. Ge, H. Wang, N. Hong, X. Xiao, B. Song, Y. Zhang, Y. Tian, W. Deng, G. Zou, H. Hou, X. Ji, Direct recovery of degraded LiFePO<sub>4</sub> cathode via mild chemical relithiation strategy, *Chem. Eng. J.* 477 (2023).  
<https://doi.org/10.1016/j.cej.2023.147201>
- [20]. A.A. Maurice, K.N. Dinh, N.M. Charpentier, A. Brambilla, J.C.P. Gabriel, Dismantling of printed circuit boards enabling electronic components sorting and their subsequent treatment open improved elemental sustainability opportunities, *Sustainability (Switzerland)* 13 (18) (2021), <https://doi.org/10.3390/su131810357>.
- [21]. G. Liu, Z. Chen, F. Luo, T. Liu, X. Xi, Z. Wang, Z. Gao, P. Shao, D. Wu, X. Luo, L. Yang, One-step nickel-cobalt alloy electrodeposition from spent lithium-ion battery via synergistic pH adjustment and Mn<sup>2+</sup> supplementation, *Sep. Purif. Technol.* 314 (March) (2023) 123581, <https://doi.org/10.1016/j.seppur.2023.123581>.
- [22]. A.I. Rasee, E. Aual, A.I. Rehan, M.S. Hossain, R.M. Waliullah, K.T. Kubra, M. C. Sheikh, M.S. Salman, M.N. Hasan, M.M. Hasan, H.M. Marwani, A. Islam, M. A. Khaleque, M.R. Aual, Efficient separation, adsorption, and recovery of Samarium(III) ions using novel ligand-based composite adsorbent, *Surf. Interfaces* 41 (August) (2023) 103276, <https://doi.org/10.1016/j.surfin.2023.103276>.
- [23]. D. Wang, Y. Liang, Y. Zeng, C. Liu, C. Zhan, P. Chen, S. Song, F. Jia, Highly selective recovery of gold and silver from E-waste via stepwise electrodeposition directly from the pregnant leaching solution enabled by the MoS<sub>2</sub> cathode, *J. Hazard. Mater.* 465

- (January) (2024) 133430,  
<https://doi.org/10.1016/j.jhazmat.2024.133430>.
- [24]. G. Zhang, Y. He, H. Wang, T. Zhang, X. Yang, S. Wang, W. Chen, Application of triboelectric separation to improve the usability of nonmetallic fractions of waste printed circuit boards: Removing inorganics, *J. Clean. Prod.* 142 (2017) 1911–1917, <https://doi.org/10.1016/j.jclepro.2016.11.093>
- [25]. M.E. Awual, M.S. Salman, M.M. Hasan, M.N. Hasan, K.T. Kubra, M.C. Sheikh, A. I. Rasee, A.I. Rehan, R.M. Waliullah, M.S. Hossain, H.M. Marwani, A.M. Asiri, M. M. Rahman, A. Islam, M.A. Khaleque, M.R. Awual, Ligand imprinted composite adsorbent for effective Ni(II) ion monitoring and removal from contaminated water, *J. Ind. Eng. Chem.* 131 (2024) 585–592, <https://doi.org/10.1016/j.jiec.2023.10.062>.
- [26]. Z. Huo, M. Xi, L. Xu, C. Jiang, W. Chen, Colloid-facilitated release of polybrominated diphenyl ethers at an e-waste recycling site: evidence from undisturbed soil core leaching experiments, *Front. Environ. Sci. Eng.* 18 (2) (2024), <https://doi.org/10.1007/s11783-024-1781-x>.
- [27]. R. Panda, S. Mishra, K.K. Pant, T. Bhaskar, S.N. Naik, A closed loop recycling strategy for sustainable recovery of group 11 metals (Cu, Au, and Ag) from waste PCBs: an amalgamation of low-temperature NH<sub>4</sub>Cl roasting, HCl Leaching and Cementation, *Sustain. Mater. Technol.* 37 (2023) e00652, <https://doi.org/10.1016/j.susmat.2023.e00652>
- [28]. S. Zheng, S. Xu, Z. Wang, H. Duan, D. Chen, M. Long, Y. Li, Efficient leaching of valuable metals from spent lithium-ion batteries using green deep eutectic solvents: Process optimization, mechanistic analysis, and environmental impact assessment, *J. Clean. Prod.* 480 (2024) 144128, <https://doi.org/10.1016/j.jclepro.2024.144128>.
- [29]. F. Faraji, R. Golmohammadzadeh, C.A. Pickles, Potential and current practices of recycling waste printed circuit boards: a review of the recent progress in pyrometallurgy, *J. Environ. Manage.* 316 (2022) 115242, <https://doi.org/10.1016/j.jenvman.2022.115242>.
- [30]. W. Feng, X. Xiao, J. Li, Q. Xiao, L. Ma, Q. Gao, Y. Wan, Y. Huang, T. Liu, X. Luo, S. Luo, G. Zeng, K. Yu, Bioleaching and immobilizing of copper and zinc using endophytes coupled with biochar-hydroxyapatite: bipolar remediation for heavy metals contaminated mining soils, *Chemosphere* 315 (2023) 137730, <https://doi.org/10.1016/J.CHEMOSPHERE.2022.137730>.
- [31]. K. Binnemans, P.T. Jones, B. Blanpain, T. Van Gerven, Y. Pontikes, Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review, *J. Clean. Prod.* 99 (2015) 17–38, <https://doi.org/10.1016/J.JCLEPRO.2015.02.089>.
- [32]. S. Hussaini, A.M. Tita, S. Kursunoglu, M. Kaya, P. Chu, Leaching of nickel and cobalt from a mixed nickel-cobalt hydroxide precipitate using organic acids, *Minerals* 14 (2024) 314, <https://doi.org/10.3390/min14030314>.
- [33]. R. Lerchbammer, E. Gerold, H. Antrekowitsch, Gluconic acid leaching of spent lithium-ion batteries as an environmentally friendly approach to achieve high leaching efficiencies in the recycling of NMC active material, *Metals* 13 (2023) 1330, <https://doi.org/10.3390/met13081330>.
- [34]. S. Windisch-Kern, A. Holzer, C. Ponak, T. Hochsteiner, H. Raupenstrauch, Thermal analysis of lithium ion battery cathode materials for the development of a novel pyrometallurgical recycling approach, *Carbon Resources Conversion* 4 (2021) 184–189, <https://doi.org/10.1016/j.crcon.2021.04.005>.
- [35]. W. Astuti, F. Nurjaman, F. Rofiek Mufakhir, S. Sumardi, D. Avista, K. Cleary Wanta, H.

- Tri, Bayu Murti Petrus, A novel method: nickel and cobalt extraction from citric acid leaching solution of nickel laterite ores using oxalate precipitation, *Miner. Eng.* 191 (2023) 107982, <https://doi.org/10.1016/j.mineng.2022.107982>.
- [36]. Acidophile microbiology in space and time, in: R. Quatrini, D. B Johnson (Eds.), *Acidophiles: Life in Extremely Acidic Environments*, Caister Academic Press, Norfolk, UK, 2016, pp. 3–16, <https://doi.org/10.21775/9781910190333>.
- [37]. A. Pathak, M.G. Dastidar, T.R. Sreekrishnan, Bioleaching of heavy metals from sewage sludge by indigenous iron-oxidizing microorganisms using ammonium ferrous sulfate and ferrous sulfate as energy sources: a comparative study, *J. Hazard Mater.* 171 (2009) 273–278, <https://doi.org/10.1016/j.jhazmat.2009.05.139>.
- [38]. L. Ma, S. Huang, P. Wu, J. Xiong, H. Wang, H. Liao, X. Liu, The interaction of acidophiles driving community functional responses to the re-inoculated chalcopyrite bioleaching process, *Sci. Total Environ.* 798 (2021) 149186, <https://doi.org/10.1016/j.scitotenv.2021.149186>.
- [39]. L. Rendón-Castrillón, M. Ramírez-Carmona, C. Ocampo-López, L. Gómez-Arroyave, Bioleaching techniques for sustainable recovery of metals from solid matrices, *Sustainability* 15 (13) (2023) 10222, <https://doi.org/10.3390/su151310222>.
- [40]. Zeng Y, Zhang Y, Li Z, Demopoulos GP. Measurement and chemical modeling of the solubility of  $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$  and  $\text{Na}_2\text{SiO}_3$  in concentrated NaOH solution from 288 to 353 K. *Ind Eng Chem Res* 2014;53(23):9949e58. <https://doi.org/10.1021/ie500590w>.
- [41]. Flandinet L, Tedjar F, Ghetta V, Fouletier J. Metals recovering from waste printed circuit boards (WPCBs) using molten salts. *J Hazard Mater* 2012;213:485e90. <https://doi.org/10.1016/j.jhazmat.2012.02.037>.
- [42]. Arredondo JL, Rivera FF, Nava JL. Silver recovery from an effluent generated by plating industry using a rotating cylinder electrode (RCE). *Electrochim Acta* 2014;147:337e42. <https://doi.org/10.1016/j.electacta.2014.09.127>.
- [43]. Agrawal M, Singh R, Ranitovic M, Kamberovic Z, Ekberg C, Singh KK. Global market trends of tantalum and recycling methods from waste tantalum capacitors: a review. *Sustain Mater and Technol* 2021:e00323. <https://doi.org/10.1016/j.susmat.2021.e00323>.
- [44]. Chen, S., Shen, S., Cheng, Y., Wang, H., Lv, B., Wang, F., 2014. Effect of O<sub>2</sub>, H<sub>2</sub> and CO pretreatments on leaching Rh from spent auto-catalysts with acidic sodium chlorate solution. *Hydrometallurgy* 144–145, 69–76. <https://doi.org/10.1016/j.hydromet.2014.01.018>.
- [45]. Suoranta, T., Zugazua, O., Niemelä, M., Perämäki, P., 2015. Recovery of palladium, platinum, rhodium and ruthenium from catalyst materials using microwave-assisted leaching and cloud point extraction. *Hydrometallurgy* 154, 56–62. <https://doi.org/10.1016/j.hydromet.2015.03.014>.
- [46]. Martínez-Mora, O., Pozo, G., León-Fernández, L.F., Fransær, J., Domínguez-Benetton, X., 2023. Synthesis of platinum group metal nanoparticles assisted by CO<sub>2</sub> reduction and H<sub>2</sub> cogeneration at gas-diffusion electrodes. *RSC Sustainability* 1, 454–458. <https://doi.org/10.1039/d3su00046j>.
- [47]. Ju, J., Feng, Y., Li, H., Wu, R., Xue, Z., Ma, R., 2023. High-efficiency and environment-friendly separation and recovery of manganese from braunite via the ammonium sulfate roasting-water leaching process: behavior and mechanism. *Chem. Eng. J.* 466, 143218. <https://doi.org/10.1016/j.cej.2023.143218>.
- [48]. Yang, K., Gong, P., Xin, X., Tian, Z., Lai, Y., 2020b. Purifying spent carbon anode (SCA)

- from aluminum reduction industry by alkali fusion method to apply for Li-ion batteries anodes: from waste to resource. *J. Taiwan Inst. Chem. Eng.* 116, 121–127. <https://doi.org/10.1016/j.jtice.2020.10.034>.
- [49]. Wu, Z., Soh, T., Chan, J.J., Meng, S., Meyer, D., Srinivasan, M., Tay, C.Y., 2020. Repurposing of fruit peel waste as a green reductant for recycling of spent lithium ion batteries. *Environ. Sci. Technol.* 54, 9681–9692. <https://doi.org/10.1021/ACS.EST.0C02873>.
- [50]. Golmohammadzadeh, R., Faraji, F., Jong, B., Pozo-Gonzalo, C., Banerjee, P.C., 2022. Current challenges and future opportunities toward recycling of spent lithium-ion batteries. *Renew. Sustain. Energy Rev.* 159, 112202 <https://doi.org/10.1016/J.RSER.2022.112202>.
- [51]. Portia Makwarimba, C., Tang, M., Peng, Y., Lu, S., Zheng, L., Zhao, Z., Zhen, A., 2022. Assessment of recycling methods and processes for lithium-ion batteries. *cell.com* 25, 104321. <https://doi.org/10.1016/j.isci>.
- [52]. B.A. Ezeonuegbu, D.A. Machido, C.M.Z. Whong, W.S. Japhet, A. Alexiou, S. T. Elazab, N. Qusty, C.A. Yaro, G.E.-S. Batiha, Agricultural waste of sugarcane bagasse as efficient adsorbent for lead and nickel removal from untreated wastewater: biosorption, equilibrium isotherms, kinetics and desorption studies, *Biotechnol. Rep.* 30 (2021). <https://doi.org/10.1016/j.btre.2021.e00614>
- [53]. N. Wang, Y. Qiu, K. Hu, C. Huang, J. Xiang, H. Li, J. Tang, J. Wang, T. Xiao, One- step synthesis of cake-like biosorbents from plant biomass for the effective removal and recovery heavy metals: effect of plant species and roles of xanthation, *Chemosphere* 266 (2021). <https://doi.org/10.1016/j.chemosphere.2020.129129>
- [54]. H. Majdoubi, R. El Kaim Billah, M. Aminul Islam, M.K. Nazal, A. Shekhawat, A. A. Alrashdi, E. Alberto Lopez-Maldonado, A. Soulaïmani, Y. Tamraoui, R. Jugade, H. Lgaz, An eco-friendly chitosan-diethylaminoethyl cellulose composite: in-depth analysis of lead (II) and arsenic(V) decontamination from water with molecular perspectives, *J. Mol. Liq.* 387 (2023). <https://doi.org/10.1016/j.molliq.2023.122680>
- [55]. A.M.K. Gustafsson, B.-M. Steenari, C. Ekberg, Evaluation of high-temperature chlorination as a process for separation of copper, indium and gallium from CIGS solar cell waste materials, *Separ. Sci. Technol.* 50 (1) (2015) 1–9, <https://doi.org/10.1080/01496395.2014.949350>.
- [56]. W. Palitzsch, U. Loser, in: *A New and Intelligent De-metalization Step of Broken Silicon Cells and Silicon Cell Production Waste in the Recycling Procedure of Crystalline SI Modules*, 2011 37 th IEEE Photovoltaic Specialists Conference, IEEE, Seattle, WA, USA, 2011, pp. 3269–3270, <https://doi.org/10.1109/PVSC.2011.6186635>.
- [57]. L.M. Ferris, Solubility of molybdcic oxide and its hydrates in nitric acid, nitric acid- ferric nitrate, and nitric acid-uranyl nitrate solutions, *J. Chem. Eng. Data* 6 (4) (1961) 600–603, <https://doi.org/10.1021/je60011a035>.
- [58]. Mahmoudi, A., Shakibania, S., Rezaee, S., Mokmeli, M., 2020. Effect of the chloride content of seawater on the copper solvent extraction using Acorga M5774 and LIX 984N extractants. *Sep. Purif. Technol.* 117394. <https://doi.org/10.1016/j.seppur.2020.117394>
- [59]. Orefice, M., Binnemans, K., Vander Hoogerstraete, T., 2018. Metal coordination in the high-temperature leaching of roasted NdFeB magnets with the ionic liquid betainium bis(trifluoromethylsulfonyl)imide. *RSC Adv.* 8, 9299–9310. <https://doi.org/10.1039/c8ra00198g>.
- [60]. Binnemans, K., Jones, P.T., Müller, T., Yurramendi, L., 2018. Rare earths and the balance problem: how to deal with changing

- markets? *J. Sustain. Metall.* 8, 126–146. <https://doi.org/10.1007/s40831-018-0162-8>.
- [61]. Guo, Y., Tang, M., Jiang, T., Qing, L., Zhou, J., 2013. Research on the slag phase type of vanadium-titanium magnetite in pre-reduction-electric furnace smelting. In: 4th International Symposium on High-Temperature Metallurgical Processing. TMS Annual Meeting, pp. 87–94. <https://doi.org/10.1002/9781118663448.ch11> Digital Object Identifier (DOI)
- [62]. Venkatesan, P., Sun, Z.H.I., Sietsma, J., Yang, Y., 2018. An environmentally friendly electro-oxidative approach to recover valuable elements from NdFeB magnet waste. *Sep. Purif. Technol.* 191, 384–391. <https://doi.org/10.1016/j.seppur.2017.09.053>.
- [63]. Sethurajan, M., van Hullebusch, E.D., Fontana, D., Akcil, A., Deveci, H., Batinic, B., Leal, J.P., Gasche, T.A., Kucuker, M.A., Kuchta, K., Neto, I.F.F., Soares, H.M.V.M., Chmielarz, A., 2019. Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes- a review. *Crit. Rev. Environ. Sci. Technol.* 49, 212–275. <https://doi.org/10.1080/10643389.2018.1540760>.
- [64]. Jha, A.R., 2014. Contribution of rare earth materials in the development of the glass industry, crystal technology, glass polishing, electro-optical devices, and the chemical industry. In: *Rare Earth Materials: Properties and Applications*. CRC Press, Boca Raton, pp. 239–251. <https://doi.org/10.1201/b17045>.
- [65]. Doyle-Garner, F.M., Monhemius, J., 1985b. Hydrolytic stripping of versatic acid solutions containing iron and other metals. *Miner. Metall. Process.* 47–51. <https://doi.org/10.1007/bf03402595>.
- [66]. I. Makarova, E. Soboleva, M. Osipenko, I. Kurilo, M. Laatikainen, E. Repo, Electrochemical leaching of rare-earth elements from spent NdFeB magnets, *Hydrometallurgy* 192 (2020) 105264, <https://doi.org/10.1016/j.hydromet.2020.105264>.
- [67]. N.A. Mancheri, World trade in rare earths, Chinese export restrictions, and implications, *Resour. Policy* 46 (2015) 262–271, <https://doi.org/10.1016/j.resourpol.2015.10.009>.
- [68]. R. Xiaoa, L. He, Z. Luo, R. Spinney, Z. Wei, D.D. Dionysiou, F. Zhao, An experimental and theoretical study on the degradation of clonidine by hydroxyl and sulfate radicals, *Sci. Total Environ.* 710 (2020) 136333, <https://doi.org/10.1016/j.scitotenv.2019.136333>.