E-waste recycling: an overview of hydrometallurgical processes used for metal recovery*

Nallely G. Picazo-Rodríguez[1], Gabriela Baltierra-Costeira[1], Ma de Jesús Soria-Aguilar[2], Zeferino Gamiño Arroyo[3], Norman Toro[4], Manuel Saldana[4,5], Jesús R. de la Garza de Luna[1] and Francisco Raúl Carrillo-Pedroza[2]

[1]*Instituto Tecnológico Superior de Monclova, Tecnológico Nacional de México, Monclova, México*
[2]*Facultad de Metalurgia, Universidad Autónoma de Coahuila, Monclova, México*
[3]*Departamento de Ingeniería Química, División de Ciencias Naturales y Exactas, Universidad de Guanajuato, Guanajuato, México*
[4]*Faculty of Engineering and Architecture, Universidad Arturo Prat, Iquique, Chile*
[5]*Departamento de Ingeniería Química y Procesos de Minerales, Universidad de Antofagasta, Antofagasta, Chile*

Abstract

Exponential population growth resulted in exponential demands for metals, especially for production of electronic devices, which are mainly sent to landfills at the end of their functional life. This practice poses a significant environmental hazard due to the presence of metals within these discarded materials, termed electronic waste or e-waste, which necessitate appropriate management strategies to avert adverse effects on both the ecosystem and human health. E-waste contains valuable metals often in concentrations rendering their recovery economically viable. Furthermore, the escalating demand for metals, driven by technological progress, has made the recycling of e-waste a crucial element of sustainable resource management. This work provides an overview of hydrometallurgical processing techniques for the recovery of valuable metals from the waste from electrical and electronic equipment, where hydrometallurgy plays a determinant role in the recovery of valuable metals such as copper, gold, and silver. These methodologies employ aqueous chemistry to facilitate the metal extraction, presenting a cost-effective and environmentally sustainable alternative when compared to production of metals by conventional mining practices. However, the economic viability of these alternative processes may fluctuate based on the specific type and concentration of metals present within the waste.

Keywords: hydrometallurgy; e-waste management; valuable metals; extraction; environmental sustainability.

REVIEW PAPER

UDC: 669.054.8:628.5

Hem. Ind. **79(4)** 191-207 (2025)

Available on-line at the Journal web address: http://www.ache.org.rs/HI/

1. INTRODUCTION

Waste from electrical and electronic equipment (WEEE), arising from both private homes and professional uses, may contain heavy metals such as Be, Cr, Cd, Ar, Se, Sb, Hg, Pb, as well as Au, Ag and Cu [1,2]. Improvements in the processing power of computers have shortened their average life. Every year, the amount of WEEE increases three times faster than that of the other forms of municipal waste [3].

As reported in literature [4], the copper content in electronic waste (e-waste) can be around 20 % while in primary metallic resources it ranges from 0.5 to 1 %. It should be thus profitable to develop feasible and environmentally friendly

Corresponding authors:
N. G. Picazo-Rodríguez, Instituto Tecnológico Superior de Monclova, Tecnológico Nacional de México, Monclova, México;
E-mail: nallely.pr@monclova.tecnm.mx; https://orcid.org/0000-0002-5780-2747
G. Baltierra-Costeira, Instituto Tecnológico Superior de Monclova, Tecnológico Nacional de México, Monclova, México;
E-mail: gabriela.bc@monclova.tecnm.mx; https://orcid.org/0000-0001-6269-1183
F. R. Carrillo-Pedroza, Facultad de Metalurgia, Universidad Autónoma de Coahuila, Monclova, México; https://orcid.org/0000-0002-0413-0676
E-mail: raul.carrillo@uadec.edu.mx
Co-authors: M. de J. Soria-Aguilar https://orcid.org/0000-0003-3910-7772, Z. Gamiño Arroyo https://orcid.org/0000-0002-6228-8586, N. Toro https://orcid.org/0000-0001-6269-1183, M. Saldana https://orcid.org/0000-0001-9265-1529, J. R. de la Garza de Luna https://orcid.org/0000-0002-6522-9514

Paper received: 18 November 2024; Paper accepted: 28 November 2025; Paper published: 16 December 2025.
https://doi.org/10.2298/HEMIND241118015D

*This manuscript is an expanded and peer-reviewed version of the preprint previously published as: Picazo-Rodríguez NG; Baltierra-Costeira G; Soria-Aguilar MJ, Gamiño-Arroyo Z, Toro, N, de la Garza de Luna JR, Carrillo-Pedroza FR, E-waste Recycling: An Overview of Hydrometallurgical Processes Used to Metals Recovery. *Preprints* 2023, 2023110933. https://doi.org/10.20944/preprints202311.0933.v1 methods to recover copper from such waste. Treatment of e-waste has consequently gained relevance in recent years, especially in developed countries. In addition, these wastes will become an important source of metals, especially when the primary sources are running out [5].

E-waste has increased significantly in all regions of the world because the use of electronic devices and equipment occurs massively in different sectors of human life (industrial, services, economic) [6]. According to literature [7], consumption of electrical and electronic devices is strongly linked to the development and economy of countries and in 2019 53.6 Mt of e-waste was generated globally (7.3 kg *per* capita) and it is expected that by 2030 74.7 Mt of this waste will be produced, almost double what was generated in 2019. It was also stated that computers, TV devices, and mobile phones constitute most of the e-waste and that in some advanced countries this waste makes up more than 80 % of municipal waste [8].

Nowadays, industrial waste is generally incinerated, which is detrimental to the environment due to the large number of metals it contains [9]. As reported in literature [5] incineration and thermal treatment of e-waste have raised concerns because of emissions of organic pollutants, which are toxic and can cause serious problems. However, recovery of metals from these wastes could be more economical than extraction them from their primary sources [10].

For example, as reported by Cui and Zhang [4], printed circuit boards (PCB) are the components of electronic scrap that contain the highest number of valuable metals in significant concentrations such as ~3300 ppm Ag, 80 ppm Au and 26.8 % Cu. Au and Ag are contained in native or alloy forms, mainly coated on the pins and holes of electronic components and the board, or within microprocessors [11]. Hsu *et al.* [12], mention in their research that PCBs represent 3 % of the total mass of e-waste worldwide appearing in the form of a copper-coated fiberglass and resin laminate.

To achieve optimal extraction of gold and silver, it is necessary to eliminate the common metals mentioned above and thus avoid the extra consumption of reagents that would be required by their presence. For example, the extraction of copper from computer PCBs has been investigated using inorganic acid leaching. These reagents dissolve other metallic elements such as iron, nickel, lead, and zinc, thereby removing a substantial portion of the base-metal matrix. As a result, the relative concentrations of gold and silver in the remaining solid residue increase, rising from 131.29 to 345.9 g t^{-1} for Au and from 310 to 864.8 g t^{-1} for Ag, respectively [13].

The technologies for metal recovery from electronic waste encompass pre-treatment operations (classification, dismantling, shredding, and physical separation), as well as hydrometallurgical routes based on acid or alkaline-oxidant and complexing systems, whose efficiency and selectivity have been extensively documented [14-22]. Emerging processes such as electrochemically assisted leaching, ionic-liquid extraction, and kinetic modelling for multicomponent systems have further optimized the dissolution and recovery of critical metals under controlled conditions [23-26]. In parallel, advances in catalytic pyrolysis, carbothermic treatments, and selective smelting contribute to the valorization of refractory metallic fractions [18,19,27,28]. Biohydrometallurgy, driven by microorganisms and microbial consortia capable of oxidizing or reducing metallic phases, has gained recognition as a sustainable alternative for complex WEEE matrices [29,30], while integrated physicochemical-biotechnological approaches increasingly support circular recovery schemes with reduced environmental impact. This paper presents a review of the main hydrometallurgical processes used in the recovery of metals from WEEE.

2. HYDROMETALLURGICAL PROCESSES: EXTRACTION AND RECOVERY FROM E-WASTE

Hydrometallurgical processes involve chemical reactions carried out in aqueous or organic solutions. The main steps are leaching, concentration/purification of metals and recovery, offering advantages such as the ability to control the level of impurities, low investment cost, lower environmental impact, and high metal recovery potentials [9,31].

If the hydrometallurgical route is to be followed for copper recovery sulfuric acid is used for leaching [32] as it provides copper extraction in high quantities, in addition to other heavy metals [33]. Park *et al.* [34], determined that the efficiency of the sulfuric acid leaching process increased with increasing agitation speed, temperature, oxygen flow and initial Cu^{2+} content so that the following conditions were proposed as optimal: sulfuric acid concentration (1 mol dm^{-3}), temperature (90 °C), stirring speed (600 rpm), pulp density (1 %), initial copper concentration (10 g dm^{-3}) and oxygen flow rate (1 dm^3 min^{-1}). Dávila-Pulido *et al.* [35] carried out copper leaching in a 2 mol L^{-1} H_2SO_4-H_2O_2 0.2 mol L^{-1} system, which allowed complete dissolution of copper present in the electronic waste samples. The same leaching system was recirculated in another study for up to 5 cycles, resulting in reduction of acid consumption by 60 % [36]. Other acid leaching media include ferric chloride with hydrochloric acid system, which was used to extract copper and antimony from PCBs followed by recovery them by electrodeposition, managing to obtain 96 % copper and 81 % antimony [37].

A study of the effectiveness of a new leaching system consisting of ionic hydrogen sulphate liquids to dissolve copper from PCBs showed that copper could be leached in large quantities, but with the presence of an oxidant such as H_2O_2 [38,39]. In other works where ionic liquids of hydrogen sulphate and hydrogen peroxide were used, it was found that the particle size had a great influence on the process [40].

Other researchers, such as Kavousi *et al.* [41], employed hydrogen peroxide in an HBF_4 leaching medium to simultaneously dissolve copper and the Sn-Pb solder phases, achieving a copper extraction efficiency of 99.99%. In another approach, hydrogen peroxide was combined with an environmentally benign lixiviant, sodium citrate, while ammonium phosphate was incorporated as a chemical inhibitor to suppress the co-dissolution of base metals, resulting in copper concentrations exceeding 30 g L^{-1} [42].

Other methods have been also used to leach copper such as application of electrogenerated chlorine in hydrochloric acid solution [43]. In specifically, in one experimental series generation of chlorine was carried out simultaneously with copper leaching, while in another two reactors were used, one for chlorine generation and the other for copper leaching. Better results were obtained in the latter case, achieving a recovery of copper of 71 % together with 98 % zinc, 96 % tin and 96 % lead using a 2 mol L^{-1} HCl solution at a current density of 714 A m^{-2}, 323 K and 400 rpm for 240 min.

After copper leaching from e-waste, the residue is further leached to recover the precious metals [1]. The most used chemical reagents during this leaching process are cyanide, halides, thiourea, thiosulfate, ethylenediaminetetraacetic acid (EDTA), oxalates, aqua regia, sodium hypochlorite, nitric acid, ferric chloride, and organic solvents [9].

According to Akcil *et al.* [5], cyanide leaching has been a successful technology worldwide for the recovery of precious metals (especially Au and Ag) from ores/concentrates/waste materials, because it is an effective, economical, and easy to implement leaching agent. However, its use requires treatment of the effluents generated during the recovery process. In response to the toxic nature and handling problems of cyanide, several non-cyanide leaching processes have been developed using non-toxic leaching agents such as thiourea, thiosulfate, aqua regia and iodine. Consequently, various recycling technologies have been established utilizing both cyanide or non-cyanide leaching methods to recover precious and valuable metals.

An example of a process for recovering precious metals from e-waste through the hydrometallurgical route was implemented by Mudila *et al.* [44] processed waste printed circuit boards from mobile phones by mechanically grinding and delaminating them to obtain powdered and liberated metallic fractions. The resulting material was then subjected to a two-stage leaching process: an initial nitric acid leaching step (3 M HNO_3, 30 °C) to dissolve base metals such as copper, followed by a second leach using a 3 M H_2SO_4 and 3 M NaBr system at 70 °C to solubilize the gold present in the residue. Recovery of gold from e-waste containing high copper content was carried out by applying chemical pretreatment first with inorganic acids (HCl, HNO_3 and H_2SO_4), organic substances (EDTA and citrate) and oxidants (air, ozone and hydrogen peroxide) resulting in more than 90 % of copper extracted when using peroxide and HCl or citrate [45]. In the second step, thiourea was used resulting in more than 90 % of the gold recovering after 1 h [45]. Table 1 shows a review of leaching processes of e-waste with the use of cyanide as well as other leaching agents considered as "green".

Table 1 shows hydrometallurgical processes carried out under alkaline and acid conditions. In the former case, leaching media such as cyanide, glycine, sodium, and ammonium thiosulfate are used. Glycine has been successfully employed for copper extraction under alkaline conditions; however, efficient leaching requires proper sample preparation. Since copper and other metals may remain trapped within solder joints and composite layers, Huan et al. [46] recommend a preliminary pretreatment step to expose the metallic fractions typically involving mechanical liberation and, when necessary, selective dissolution of solder using nitric acid prior to conducting glycine-based leaching [46]. On the other hand, in alkaline conditions glycinate ion ($H_2NCH_2COO^-$) is found in solutions, which can form complexes with cuprous (Cu^+) and cupric (Cu^{2+}) ions when in the presence of an oxidant such as ambient O_2 at room temperature. However, base metals such as Ni, Al, Sn, Zn, and Co are extracted simultaneously with their extraction favoured under alkaline conditions. In the case of gold and silver, their extraction does not exceed 2 %, as it requires a catalyst such as cyanide, which could be mixed with glycine in minimum permissible proportions for recovery. This step should occur recovering copper and other base metals since these metals interact with cyanide.

On the other hand, acid leaching in the presence of an oxidant such as H_2O_2 has been used for leaching copper, gold, and silver. Petter *et al.* [47] determined that nitric acid can dissolve up to 100 % of silver contained in PCB residues, while using aqua regia 882 g t^{-1} of gold and 417.9 kg t^{-1} of copper were achieved. However, in the case of silver, low recovery was obtained since it tends to form insoluble AgCl. Even though acid solutions offer good results in the extraction of metals such as copper, gold and silver, these leaching agents have some disadvantages such as high cost and high toxicity to the environment and health.

Table 1. Electronic waste leaching processes using cyanide and alternative leaching methods for PCBs treatment

Leaching medium	Preparation of sample	Conditions of leaching	Metal recovery (%)	Ref.
Glycine	Pulverized feed	0.5 M glycine pH 10, t = 72 h, particle size= <2 mm	• Au = 2 • Ag = 2; Pb = 16 • Cu = 96.5; Al = 12.6 • Ni = 9.3; Zn = 92.5 • Co = 3.1	[46]
Sodium ammonium thiosulfate	Particle size less than 1 mm obtained in a blade mill	8 M HNO_3, 0.1 M $Na_2S_2O_3$ and 0.1 M $(NH_4)_2S_2O_3$, pH 9.5 to 11 solid/liquid ratio = 1:20	• HNO_3- Ag = 100 • $Na_2S_2O_3$ and $(NH_4)_2S_2O_3$- Au = 15	[47]
Sodium ammonium thiosulfate and cyanide based pickling solution	Intact PCBs were used	0.12 M $Na_2S_2O_3$, 0.12 M $(NH_4)_2S_2O_3$ t = 4 and 24 h, T = 30 °C, pH 10	• Cyanide base pickling solution - Au = 88 • $(NH_4)_2S_2O_3$- Au = 75	[48]
Sodium thiosulfate	Crushed and toasted material at 800 °C	4 M HNO_3, 0.7 M $Na_2S_2O_3$ pH 10.5, shake for 6 h, T = 25 °C	• Au = 81 • Ag = 88 • Cu = 32	[49]
Thiosemicarbazide	Intact PCBs were used	2 M NaOH, 0.5 M CH_5N_3S, pH 11.5, T = 55 °C, stirring rate 1000 rpm, t = 220 min	• Au = 95.8 • Ag = 60 • Cu = 77.7	[50]
Sodium thiosulfate	Intact PCBs were used	2 M NaOH, 0.5 M $Na_2S_2O_3$, pH 12, T = 50 °C, stirring rate 900 rpm, t = 180 min	• Cu = 99.82	[51]
Sulfuric acid and hydrogen peroxide	PCBs milled	2 M H_2SO_4, 0.2 M H_2O_2, t = 150 min, stirring rate 200 rpm, T = 25 °C	• Cu = 100	[35]
Cyanide solution for cha-racterization and sodium ammonium thiosulfate	Intact PCBs were used	0.1 M $(NH_4)_2S_2O_3$, 0.2 M NH_4OH, 0.1 M H_2O_2	• Commercial cyanide: 86.23 g ton^{-1} Au • $(NH_4)_2S_2O_3$: Au = 11 %	[52]
Thiourea	PCBs <106 mm	0.1 M H_2SO_4 , 0.25 M CH_4N_2S	• Au = 17.3; Ag = 49.5	[53]
Thiourea	SH SIZE	24 g L^{-1} CH_4N_2S, 0.6 % Fe^{3+} T = ambient, t = 2 h	• Au = 90 • Ag = 50	[54]
Iodine-iodide	PCBs incinerated at 800 °C	Iodine-iodid mass ratio = 1:6, stirring speed 500 rpm, T = 40 °C, t = 24 h	• Au = 99 • Ag = 1 • Pd = 1	[55]
Iodine-iodide	Particle size less than 0.75 mm	8 mmol L^{-1} I_2, 70 mmol L^{-1} KI 30 mmol L^{-1} H_2O_2	• Au = 31.5	[56]

Batnasan *et al.* [55], used 1 mol L^{-1} thiourea and 0.25 mol L^{-1} H_2SO_4 at an acidic pH, achieving 17.3 % and 49.5 % Au and Ag dissolution, respectively. These authors found that a high redox potential and acidity of the solution increase leaching of Au and Pd, while decrease Ag leaching. Jing *et al.* [54], determined that a gold and silver leaching process by thiourea can be optimized by decreasing the particle size, due to the increased specific surface area. Extraction of 90 % gold and 50 % silver from PCB samples was achieved using the following conditions: 24 g L^{-1} solution of thiourea and Fe^{3+} at room temperature and 100 mesh particle size. Still, the authors mention that the thiourea process is expensive compared to conventional processes such as cyanidation. On the other hand, the iodine-iodide system at acidic pH has been used for the recovery of precious metals; it is worth mentioning that this system is selective towards gold [55].

In one study, the use of sodium and ammonium thiosulfate did not result in positive results reaching a maximum gold extraction of 15 %, and it was concluded that more than one leaching agent is needed to extract all the metals from PCBs [47]. Still, in another treatment process of intact PCBs also by using sodium and ammonium thiosulfate 70 and 75 % of gold was extracted, respectively, which was attributed to the size of the PCB samples since, according to this research, the use of intact PCB samples inhibits dissolution of base metals, whose release is favoured by grinding and once in solution they compete for the leaching reagent with gold [48].

On the other hand, Gámez *et al.* [52], found that dissolving copper with nitric acid before carrying out leaching with thiosulfate improved the recovery of gold and silver, reaching extraction efficiencies of 81 and 88 % respectively. The addition of H_2O_2 to the thiosulfate system a slight increase in the extraction of gold and silver. When base metals are completely separated, gold recovery is greatly improved, which can be also achieved by cyanide. According to Birich *et al.* [56], thiosulfate and thiourea are less sensitive to metallic impurities than other leaching agents; however, when these impurities are removed from PCBs, gold recovery improves. Based on the above, it could be concluded that while leaching PCB samples at acidic pH yields good results, it also presents the drawback of high reagent costs and toxicity. Conversely, glycine is an alternative that offers advantages such as low cost and environmental friendliness Additionally, it can be used in two stages: first, to eliminate base metals and second, to add a small amount of cyanide as a catalyst to extract metals such as gold and silver.

Recovery of metals from the solutions generated from leaching processes can be carried out by different methods, such as solvent extraction, ion exchange, adsorption, precipitation and cementation. Choice of the method depends on properties of the e-waste and the solution originating from leaching [4,18]. Examples of some metal recovery processes from e-waste leach solutions are shown in Table 2.

Table 2. Alternative metal recovery processes from e-waste leach solutions

Treated sample	Recovery method	Conditions	Recovery, %	Ref.
Thiosulfate leach solution	Solvent extraction (SX) and electrowinning (EW)	LIX984 N with kerosene for copper	SX - Cu=92 EW - Cu=99 EW - Au=87	[57]
3 M nitric acid solution used for Cu and 3 mol L^{-1} H_2SO_4 and Sodium Bromide solution used for Au.	Solvent extraction	ACORGA M5640 dissolved in kerosene and Tertiary amide extractant 0.1 mol L^{-1} dissolved in toluene.	Cu = 99 Au = 99.9	[58]
Solution containing Cu^{2+}, Zn^{2+}, Ni^{2+}, Pb^{2+} and Al^{3+} ions	Multi-element ion exchange	Three resins were used: Amberlite IRA 743, Lewatit TP 208 and Lewatit TP 260 at a dose of 90-100 g L^{-1}	Cu = 90	[59]
Mixture of chlorate and chitosan in HCl	Adsorption	Chitosan granules cross-linked with glutaraldehyde (GCC) were used as adsorbent at a dose of 1 g L^{-1}.	Au = 100	[60]
Leaching solution with hydrophilic quaternary salts from a CPU	Precipitation	Tetrabutylammonium based salts were added	Au = 91.4	[61]
16 % HCl leach solution	Cementation	Iron powder of commercial grade was used for precipitating Cu, at a stoichiometric ratio of 1:1	Cu = 85	[62]

Murali *et al.* [57] used the extractant LIX984 N with kerosene and found that pH and temperature are two parameters that significantly influence solvent extraction of copper. An increase in pH can enhance formation of complexes with the extractant, so that carrying out the process at pH below 2 was recommend, to avoid the risk of coprecipitation of other metals. Regarding the temperature, room temperature was recommended, since a decrease in copper extraction from 94 to 87 % was noted as temperature was increased from 30 to 45 °C. Similarly, extraction of copper and gold with the ACORGA M560 reagent in kerosene was found to be the best at pH in the range 1 to 2.5 [58], and by using the extractant in a ratio of 1:1, pH 2 and 4 mol L^{-1} H_2SO_4 as the extraction agent, 99.9 % of copper was recovered. As for gold, the use of a secondary amide enabled 99 % recovery.

Nekouei *et al.* [59], proposed sorption as another option for the recovery of metal ions from leaching solutions, being efficient and easy to operate. In this process a porous resin is commonly used as an ion exchanger. Cementation was proposed as an efficient method for copper recovery, reaching 90 % cemented with iron, while also recovering Al (5.8 %), Co (0.8 %) and Ni (1.5 %) [62]. Then, other authors have proposed a precipitation method as an effective and economical option for the recovery of metals, providing separation by stages [62].

According to Hsu *et al.* [12], successive electrowinning of multiple metals, particularly with Cu and Ni, and Cu and Au, in sulfuric acid and aqua regia baths, presents a promising option for combining individual electrowinning steps; this process takes advantage of the differences in electrode potentials of different metals.

The mentioned recovery techniques are effective; however, each has its advantages and limitations. In the case of the solvent extraction technique, a disadvantage is the need for the use of a wide variety of additives, while in cementation these are the high consumption of reagents and occurrence of coprecipitation of base metals. During the ionic exchange the need for regeneration of the adsorbents presents a drawback while although electrowinning provides metals of high purity, but at high energy consumption.

3. PATENTS AND INDUSTRIAL PROCESSES

Urban mining has recently gained significant relevance because it offers commercial, economic, social, and environmental opportunities. For this reason, many developed countries already have e-waste management technologies, know-how and systems in place [63]. Nevertheless, some developed countries export this waste to developing countries [64]. Arya and Kumar [63] highlight that India still lacks adequate waste management services, consisting mainly of collection, which hampers the implementation of industrial processes for waste treatment as accurate estimation of electronic waste generation is essential. In contrast, they note that the electronic waste management model in China is regarded as one of the preferred methodologies, involving collection, recycling, and value recovery [63].

As mentioned above, millions of tons of e-waste are generated annually, making recycling crucial for environmental protection. Current industrial processes for treating these materials include dismantling and granulation to particles in the range 0.17 mm to 5 cm, used for plastics and non-ferrous materials recovery. Additionally, industrial scale circuit board recycling machines utilize drum-type screwdrivers to separate metals such as copper from other components [65]. Table 3 presents focused on e-waste recycling.

Table 3. Examples of recovery of metals and other valuable materials from electronic waste

Overview	Items recovered	Types of e-waste	Recovery method	Ref.
It investigates the potentials and barriers for tantalum recovery from WEEE, highlighting the low current recycling rate of less than 1 % for tantalum. The study reveals challenges in accurately separating tantalum from PCBs, leading to the loss of other valuable metals like silver.	Tantalum, particularly from tantalum capacitors. Other significant materials that can be recovered include silver, manganese, silicon, aluminium, copper, iron, and nickel, with silver being noted for its surprisingly high content. The recovery processes for tantalum and silver are highlighted as essential due to their market value and scarcity.	Mobile phones, smartphones, tablets, notebooks, desktop personal computers (PCs), hard disk drives (HDDs), flat screen monitors, and servers, devices selected based on their expected high tantalum capacitor content and significant share of new electric and electronic products put on the market (POM).	Identification, liberation, separation, and concentration of tantalum capacitors from printed circuit boards. Manual removal of visually identifiable components is the primary method. Mechanical processing techniques include crushing and sieving. Acid leaching is also employed to separate tantalum from other materials.	[66]
It discusses the development of an eco-friendly and cost-effective process for recovering precious metals from electronic board waste, particularly focusing on a non-profit organization in Quebec, Canada.	The primary items recovered from electronic boards include precious metals such as gold, silver and palladium.	It discusses various types of e-waste, particularly focusing on electronic boards from telecommunications devices, computers, mobile phones, and smartphones.	The recovery methods for precious metals from electronic boards include bio metallurgy, pyrometallurgy, and hydrometallurgy, each with distinct advantages and limitations.	[67]
It focuses on the environmental and technological assessment of e-waste recycling, specifically targeting the extraction and concentration of metallic CU from PCBs. Results indicate that concentrated products contain approximately 78 % Cu.	Copper, which constitutes approximately 10 to 20 % of the PCB mass. Other metals that can be recovered include iron, zinc, nickel, silver, gold, and manganese, as indicated in the analysis of the concentrated class.	PCBs can contain approximately 28 metals, including copper, gold, and palladium, along with 23 polymers and ceramic materials. Other components in e-waste may include toxic elements such as lead, cadmium, mercury, arsenic, and chromium.	Dismantling, comminating, particle size classification, magnetic separation, and electrostatic separation. Initially, the pre-treatment aims to release metals, primarily copper, which is crucial for subsequent metallurgical processes.	[68]
It discusses the recovery of rare-earth elements from phosphor powder in spent fluorescent lamps as a critical step towards a bio-based economy. It emphasizes the importance of urban mining and bio-based technologies in achieving sustainable development goals.	Rare-earth elements such as europium, yttrium, and terbium from phosphor powder in spent fluorescent lamps. Other metals that can be recovered from E-waste include copper, nickel, iron, aluminium, and zinc, which also have known economic value.	E-waste encompasses a variety of discarded electrical and electronic devices, including but not limited to fluorescent lamps, high-intensity discharge lamps, and LED lamps. The composition of E-waste typically includes materials such as glass, metals, plastics, and toxic compounds.	Biohydrometallurgical processes (bioleaching and biosorption). Bioleaching utilizes microorganisms to secrete acids that enhance metal solubilization, while biosorption employs biosorbents to selectively remove metals through various mechanisms.	[69]

Overview	Items recovered	Types of e-waste	Recovery method	Ref.
It presents a systematic selective disassembly approach for WEEE, focusing on maximizing disassembly profit while adhering to environmental regulations. A case study on Changhong liquid crystal display televisions demonstrates the effectiveness of the approach.	Components such as metal fixing plates, metal washers, top metal supports, toughened glass seats, steel plates, rubber gaskets, control buttons, power switches, loudspeakers, control receiver boards, power supply boards, main boards, metal boards, surface frames, LCD screens, and cover plates.	E-waste can be categorized into five end-of-life types: reuse; repair; remanufacture; recycling; and disposal.	The recovery method discussed in the research paper focuses on a systematic selective disassembly approach for WEEE, particularly targeting components with recycling potential.	[70]
It examines the impact of eco-design measures on the recycling of plastics from WEEE in the EU. It identifies that while some measures, like improved disassembly, are beneficial, others, such as polymer marking, are underutilized and ineffective.	The contexts do not provide specific information regarding the items or types of metals recovered from e-waste recycling.	Encompasses a variety of discarded electrical and electronic devices, including but not limited to computers, televisions, mobile phones, and household appliances such as vacuum cleaners and coffee machines.	Manual dismantling and automated separation techniques. Froth flotation is a complex separation process that utilizes the hydrophobic properties of polymers. Electrical conductivity properties are leveraged to separate clean and dry plastics. The sink-float method is commonly used for sorting polymers due to its low cost.	[71]
It focuses on substance flow analysis (SFA) to quantify and characterize the flows of precious metals (silver, gold, palladium) during the preprocessing of WEEE. It highlights that despite high recovery rates for mass-relevant elements, only a quarter of gold and palladium is recoverable post-processing.	Precious metals such as silver, gold, and palladium. The recovery rates for these precious metals are notably low, with only 11.5 % of silver, 25.6 % of gold, and 25.6% of palladium reaching output fractions from which they may potentially be recovered. In addition to precious metals, mass-relevant materials such as copper and iron are also recovered, with recovery rates of 60 % for copper and 95.6 % for iron.	WEEE, which can be categorized into several groups. Common categories include IT and telecommunications equipment, consumer electronics, and large household appliances. Specific examples of electronic waste are mobile phones, computers, televisions, and kitchen appliances.	The recovery method for precious metals from WEEE involves a preprocessing phase that concentrates valuable materials into specific output streams. State-of-the-art metallurgical processes are employed to recover precious metals during the copper recovery process, which is designed to also capture these metals.	[72]
It discusses the significant growth of the electrical and electronic equipment (EEE) market in the Gulf Cooperation Council (GCC) region, driven by the oil and gas sector, leading to increased electronic waste (e-waste) due to shorter product lifespans. It proposes industrial remanufacturing as a viable strategy for e-waste management.	The focus is primarily on the recovery of reusable components from end-of-life electronic devices, rather than metals.	E-waste primarily includes discarded industrial EEE that has reached its end-of-life stage, such as computers, printers, televisions, and mobile phones, or industrial equipment like programmable logic controllers (PLCs), drives, and controllers also contribute to e-waste generation.	The recovery methods for end-of-life electronic products include five primary strategies: repair, refurbishment, remanufacturing, cannibalization and recycling.	[73]
It addresses the economic impact of recycling car electronics, particularly in light of increasing waste from end-of-life vehicles (ELVs) due to new European environmenttal policies. The findings confirm profitability across all analysed scenarios, emphasizing the importance of effective waste management in the automotive sector.	It discusses the recovery of metals from electronic components in ELVs, particularly focusing on gold recovery, which plays a decisive role in the economic impact of car electronics recycling processes. Its indicates that the metals extracted during the recycling process are assumed to be 95 % pure.	E-waste includes various types of WEEE of vehicle industry, with waste printed circuit boards (WPCBs) being a significant component.	Hydrometallurgy. This method involves extracting desired metals from metal-rich leached liquor through various techniques such as electrorefining, precipitation, cementation, absorption, ion exchange, or solvent extraction. The focus is primarily on recovering valuable metals like gold and silver.	[74]

Overview	Items recovered	Types of e-waste	Recovery method	Ref.
It reviews and summarizes advanced technologies for the recycling of waste electrical and electronic components (WECs), highlighting the need for a comprehensive approach to address the economic and environmental challenges associated with WEC recycling. It discusses various physical recovery methods, leaching systems, and their advantages and disadvantages, emphasizing the importance of efficiency and environmental safety.	Copper was recovered with rates of 98.21 and 99.16 %, with a purity of 92.75 % from various waste materials. Gold recovery rates were reported, although they were still quite low. Silver was recovered with a rate of 93 % from leach liquor using cementation with copper and zinc. A selective recovery of 99.94 % of silver was achieved using KCl from nitric acid leaching solution.	E-waste primarily includes WPCB and waste electronic components (WECs). E-waste encompasses various devices such as computers, mobile phones, digital cameras, and other electronic equipment that have reached the end of their life cycle. Specific components within e-waste include central processing units (CPUs), random access memory (RAM), tantalum capacitors (TCs), and aluminium electrolytic capacitors (AECs).	Disassembly, physical separation, and various metallurgical processes. Disassembly is the initial step, followed by classification of components for reuse or recycling. Physical methods such as crushing, sieving, and magnetic separation are employed to separate metals from non-metals. Pyrometallurgical processes, including smelting and refining, are widely used for metal recovery, while hydrometallurgical methods involve chemical leaching and bioleaching for selective recovery of metals from leachates.	[75]

Recycling e-waste is a critical environmental and economic challenge due to the rapid growth of discarded electronic devices. The papers provided in Table 3 explore various aspects of e-waste recycling, including methodologies, environmental impacts, and the role of remanufacturing in promoting a circular economy.

Recycling processes often include novel mechanical and physical processing, pyrometallurgical and hydrometallurgical methods, and biohydrometallurgical innovations. E-waste recycling often begins with mechanical processes such as dismantling, grinding, and separation based on different density and magnetic properties, processes that are crucial for preparing materials for further metallurgical recovery and enhancing the efficiency of subsequent extraction methods [68]. Then, pyrometallurgical or hydrometallurgical methods may be used offering advantages and weaknesses as discussed in the previous section [75]. And finally, emerging biohydrometallurgical techniques utilize activity of microorganisms to recover metals, presenting a more sustainable alternative to traditional methods [69]. These processes are gaining attention for their potential to reduce environmental impacts and improve resource recovery from complex e-waste streams.

In the estimation of environmental and economic impacts, life cycle analysis (LCA) is used to evaluate the environmental performance of e-waste recycling processes, highlighting the significant impacts of crushing and screening activities. LCA helps identifying opportunities for reducing carbon emissions and improving sustainability of recycling operations [64]. Efficient recycling can reduce the need for virgin material extraction, contributing to economic sustainability and resource conservation [75].

Remanufacturing extends the life of electronic products by restoring them to a near-original state, which reduces waste and conserves resources. Additionally, as a cost-effective strategy it supports the circular economy by promoting the reuse of materials and minimizing the environmental impact of new production [73]. Recycling of e-waste is a multifaceted challenge that requires a combination of mechanical, chemical, and biological processes to maximize the resource recovery and minimize environmental impacts. Advancements in biohydrometallurgical methods and integration of remanufacturing into the circular economy offer promising pathways for sustainable e-waste management.

On the other hand, extraction of metals from electronic waste can be dangerous [76] and industrial operations require the use of personal protective equipment as well as dust collector systems to minimize the presence of dust in air, since e-waste recycling may expose workers to toxic metals. In a study carried out by Gravel *et al.* [77], six electronic and commercial recycling facilities were investigated in which metal exposure was measured, and the presence of metals such as lead, beryllium, mercury, arsenic, barium, cadmium and chromium was found in the blood of the workers, as well as in the dust present in the air. It is worth mentioning that in this place the dust control was inadequate and personal protective equipment was not used.

Many business models for treating e-waste involve industries operating as isolated systems disconnected from other production chains. Marconi *et al.* [78] argue that this isolation leads to the loss of consistent residual economic value and they propose implementing an industrial symbiosis system as a solution. Zeng *et al.* [79] describes an eco-industrial park as the practical application of supply chain management at the industrial park level. Park *et al.* [80] reviewed the first phase of South Korea's National Ecological Program, which aimed to develop an industrial park, with achieving industrial symbiosis. The main focus was to bring together interested parties from companies, governments and research centres to facilitate industrial symbiosis projects. These efforts yielded significant environmental benefits, including reduction in greenhouse gases that achieved 51 % of the program's target.

Recycling industries are looking for alternatives to reduce the environmental impact and establish a successful business model, including several companies dedicated to the field of e-waste recovery by different methods. Today the academic and industrial sectors have combined theoretical and practical knowledge to provide practical solutions for society, resulting in scientific publications and registered patents, allowing in the long-term circular waste management [81]. Table 4 shows some of the recent patents that have been implemented in e-waste treatments.

Table 4. Recent patents related e-waste recycling

Patent number	Patent title	Invention	State	Country	Date	Ref.
MX 391678 B	Gold and copper recovery method from PCBs with an ionic solution	Ionic solution with low environmental and energy impact, made with leaching organic salts	Granted	Mexico	April 2022	[82]
MX/a/2018/006178	Process for the recovery of non-ferrous metals obtained from electronic scrap through physical-mechanical refining	Mechanical physical refining of a production line using mechanical and wind equipment	Applied	Mexico	Novembe r 2019	[83]
CN113732005A	Cleaning treatment method to efficiently recycle useful substances in electronic waste	Cleaning treatment to efficiently recycle useful substances, does not generate secondary pollution	Granted	China	December 2021	[84]
CN106520152A	Recovery processing of electronic waste by pyrolysis	Metal recovery system and an organic matter reaction system, by high efficiency pyrolysis method and notable energy savings	Granted	China	March 2017	[85]
US202217583385A	Simplified method of recovering gold from e-waste	2-step method, the first one uses a combination of acid weak with oxidant and the second solvents, water and wetting agent/surfactant	Granted	USA	July 2022	[86]
CN110639438A	Preparation for hollow polyaniline microspheres, method for recovering precious metals in electronic waste and method of recycling the recovery product	polyaniline hollow microspheres can efficiently recover materials	Granted	Canada	January 2022	[87]
US11608544B2	Recovery process from electronic waste	Use of biohydrometallurgical techniques; microorganisms	Granted	USA	March 2023	[88]
US11608544B2	Recovery process from e- waste	Use of biohydrometallurgical techniques; microorganisms	Granted	USA	March 2023	[89]
WO2023087114A1	A process to recover a metallic fraction of electronic waste and produce value-added products	Al, Zn, Ni, Cu, Au, Ag, Pt and Pd recovery, pyrolysis oil and added value to produce a conditioned material	Granted	Canada	May-23	[90]
CN110983031A	Comprehensive method of separation and recovery of electronic waste	Two leaching are carried out and subsequent solid- liquid separation and a second leaching, screening, screening, recovery of noble and basic metals	Granted	China	April 2020	[91]

In the invention of Alarcón *et al.* [82] an ionic solution is described comprising inorganic salts to recover gold and copper from e-waste PCBs with low environmental and energy impact. This method produces an Au/Cu precipitate obtained and offers an innovative alternative to traditional recovery processes, generating fewer toxic residues.

Berrueta *et al.* [83], focused on obtaining non-ferrous metals from electronic scrap by a four-stage physical-mechanical refining process. They formed a production line which uses different mechanical and wind equipment and includes: (1) reduction, pre-cleaning and cleaning of light contaminants, (2) elimination of heavier materials such as ferrous and other contaminants, (3) drying and a size homogenization, and (4) final cleaning and classification.

A clean treatment method is patented [84] aiming to efficiently recycle beneficial substances in WEEE, with saving resources at the same time without generating secondary pollution. A completely new treatment technology and a completely new processing device are described, which can almost completely recycle all useful substances in e-waste except filters, without producing secondary pollution. It not only solves the environmental pollution caused by traditional e-waste processing technology but also recycles various resources into electrons as much as possible.

Minjie *et al.* [85] developed a pyrolysis-based system for treating WEEE, which includes material treatment, metal recovery, and organic matter reactions. The process uses grinding and classifying equipment, acid leaching and electrolytic tanks, and an electronic waste pyrolysis reactor, with heating and separation systems. This integrated approach aims to recover metals, process non-metallic components, and maximize resource utilization from e-waste. This integrated approach aims to recover metals, process non-metallic parts, and maximize resource utilization from e-waste.

The invention of Lynn *et al.* [86] describes a two-step method for recovering gold from e-waste. In the first step a solution containing a weak acid in combination with an oxidant is used followed by the second step in which the delaminated gold from chip debris is isolated and purified by using solvents, water, and a wetting agent/surfactant shown to be effective without the need for leaching or the use of harsh or expensive chemicals.

Bin *et al.* [87] developed a method for preparing hollow polyaniline microspheres for efficient recovery of precious metals from e-waste without additional energy use. The polyaniline/precious metal nanocomposites obtained during the recovery process can be used as new electroactive materials to prepare electronic devices, promoting sustainable recycling.

Reece *et al.* [88] introduced bio-metallurgical techniques for recovering precious metals from WEEE. The process begins with removing at least a portion of non-target materials from e-waste or grinding it to the desired particle size. The preprocessed e-waste is then treated with a leach solution to dissolve at least a portion of the target metal. Next, microorganisms are added to adsorb the dissolved metal ions, resulting in metal-laden microorganisms. These microorganisms are subsequently separated from the solution, and the target metal(s) are recovered from the microorganisms.

Marlin *et al.* [89] developed a method for obtaining metals from group 8 to 14, raw copper, from WEEE. The process involves melting a mixed feed comprising WEEE in a smelting reactor to form separate metallic and slag phases. In the next step, the slag is removed, and the remaining first metallic phase is refined with an oxygen-containing gas, producing a second copper-enriched slag phase. This slag can be separated and the refining step repeated, if needed. The first refined metal phase is collected from the smelter reactor, and additional e-waste can be added to the copper-enriched slag to continue the recovery process.

The invention Mohamed *et al.* [90] includes recovering organic and metallic fractions of e-waste by conditioning the e-waste followed by pyrolysis resulting in gaseous and solid phases, wherein the latter comprises an organic and a metal fraction. The recovery further includes separating the metal fraction to recover at least one of the metals Al, Zn, Ni, Cu, Au, Ag, Pt and Pd. In the described process at least 95 wt.% of the e-waste can be recovered in the form of recovered metals, pyrolysis oil and value-added products.

Finally, the invention of Xiaohui *et al.* [91] provides an integrated method for separating and recovering materials from WEEE. The process involves mixing e-waste particles with acid liquor, low-temperature roasting, and performing sequential leaching and solid-liquid separations to obtain different components. If e-waste contains noble metals, HCl/Cl is used for the first leaching process. Depending on the presence of precious metals, specific leaching agents are used to recover noble and base metals. The remaining residues are screened to separate glass fibres and polymer roasting products. Thus, by this method precious metals, base metals, glass fibres, and polymer roasting products are separated, achieving comprehensive separation and recovery of e-waste.

4. FUTURE OF E-WASTE RECYCLING

The future of e-waste recycling is principally determined by technological advances, policy frameworks, and sustainable practices aimed at mitigating environmental impacts and maximizing resource recovery. With e-waste continuing to grow, fed by the demand for rapid technological change and consumerism, creative solutions are being developed worldwide to face the challenges that arise with e-waste management. These solutions encompass a variety of strategies, from improving recycling technologies to implementing comprehensive policy measures.

From the technological point of view, the future of e-waste management will likely focus on modular and upgradeable electronic devices, since they generate less waste, have a prolonged product life and are easier to repair and recycle [92]. Other recycling technologies, involving hydrometallurgical and biometallurgical processes, are also under scrutiny for applications in the recovery of valuable materials from e-waste. All these techniques are forecasted to be greener, more economically feasible, and to include several recycling technologies that ensure better performances [93,94]. In addition, AI and internet of things (IoT) technologies create new promising opportunities not only for automation in e-waste sorting and categorization but also for optimization of recycling processes and tracking/monitoring of e-waste flows along the value chain [92].

The implementation of extended producer responsibility (EPR) frameworks will be a fundamental aspect of future e-waste management from a regulatory and policy perspective. This includes designing devices for easy disassembly and recycling and creating efficient collection networks [92]. Then again, formal e-waste recycling, in line with circular economic principles, reduces much of the generated waste to a minimum while recovering resources maximally. Meanwhile, LCA tools increasingly have been applied for carrying out environmental performance evaluation of various approaches for dealing with e-waste management. This will result in significantly more environmentally friendly practices than those used today [95]. Public education and awareness play a crucial role in fostering sustainability. By increasing education on responsible consumption and proper recycling practices, a culture of sustainability can be cultivated. This involves promoting the longer use of devices and encouraging recycling [88]. In developing countries, integrating informal recycling sectors into structured management programs can improve the efficiency of e-waste recycling and reduce the environmental and health risks associated with informal practices [96].

The global electronics recycling market is expected to increase noticeably, reaching $65.8 billion by the year 2026. This, in turn, creates different opportunities for entrepreneurship and economic development regarding e-waste recycling industry [96]. However, despite all the advantages, WEEE management in developing countries seriously suffers because of poor infrastructure, lack of appropriate collection systems, and low level of awareness of the public. Solving these problems is very significant for effective recycling of WEEE [97]. Hydrometallurgical processes are an excellent option for recovering metals from e-waste, offering advantages such as higher selectivity and lower energy consumption compared to pyrometallurgical methods. However, they can also generate significant environmental impacts, mainly due to the production of liquid effluents containing dissolved metals, toxic compounds, and acidic residues. To prevent, reduce, or eliminate these impacts, specific measures should be implemented, including the use of less toxic leaching agents, the recirculation of solutions within closed-loop systems, the application of advanced wastewater treatment technologies, and the integration of tools like life cycle assessment and real-time monitoring. These strategies would help optimize the process and promote a safer and more sustainable approach to hydrometallurgy.

While the prospect for e-waste recycling is highly promising, several challenges continue to persist. Specifically, informal recycling activities, especially in developing countries, pose serious environmental and health hazards due to improper handling and disposal. Apart from this, the problem of e-waste materials' complexity and the demands on advanced recycling technologies have not yet been overcome. However, this can be elaborated by an integrated approach: one holistic method which embeds technological innovations, policy measures, and sustainable practices in the development of a more sustainable future for e-waste management.

CONCLUSIONS

From a circular economy and environmental sustainability perspective, the identification of alternative applications for waste materials has become a critical driver influencing social, economic, and ecological systems. The rapid growth of the global population and technological advancement have led to an exponential increase in the use of electronic devices, consequently generating large volumes of e-waste. This waste stream contains both hazardous substances and valuable metals such as copper, gold, and silver, whose recovery is essential for resource conservation and pollution prevention.

Various technologies have been developed to recover metals from e-waste, including pyrometallurgical, hydro-metallurgical, and bio-hydrometallurgical processes. Pyrometallurgical methods are effective in recovering metals rapidly and at high throughput but are energy-intensive and generate toxic emissions. Hydrometallurgical processes offer greater selectivity, operate at lower temperatures, and are more suitable for decentralized applications; however, they often involve corrosive leaching agents and produce liquid effluents that require advanced treatment. Bio-hydrometallurgical methods represent an environmentally friendly alternative using microbial activity to solubilize metals, yet they are limited by slower reaction kinetics and challenges in industrial scalability. Therefore, the selection of a recovery route must balance technical, environmental, and economic criteria.

In this work, an overview of leaching agents used in hydrometallurgical processes was presented, emphasizing the need to optimize these systems through the development of eco-friendly reagents and scalable designs. Future e-waste recycling strategies will depend on technological innovation, robust regulatory frameworks, and the integration of sustainable practices. Advances in artificial intelligence (AI) and the internet of things (IoT) hold promise for improving traceability and automation in e-waste processing. Likewise, policy mechanisms such as extended producer responsibility (EPR), supported by public awareness campaigns, will play a vital role in formalizing the recycling sector. Although the global market for e-waste recovery is projected to expand, significant barriers remain, particularly in developing regions where infrastructure is limited and informal practices persist. An integrated approach that combines technological, environmental, and policy-based solutions will be essential to advancing the efficiency and sustainability of e-waste recycling systems.

Declaration of interest statement: The authors declare they have no conflict of interest.

Acknowledgements: The authors appreciate the support provided by the UAdeC and the Tec NM. Manuel Saldana acknowledges the infrastructure and support from Doctorado en Ingeniería de Procesos de Minerales at the Universidad de Antofagasta.

REFERENCES

[1] Pinna EG, Sebastián Drajlin D, Toro N, Rodriguez MH. Kinetic modeling of the leaching of $LiCoO_2$ with phosphoric acid. *J Mater Res Technol.* 2020; 9(6): 14017-14028. https://doi.org/10.1016/J.JMRT.2020.09.109

[2] Toro Villarroel NR, Torres Albornoz DA. *La fuerza del litio*. Santiago de Chile: Memoria Creativa; 2023. https://doi.org/10.61303/978-956-416-471-7

[3] Chen J-J, Gamiño Arroyo Z, Recovery of copper from printed circuit and electronic waste. *Jóvenes Cienc.* 2017; 3(2); 2412-2416. https://www.jovenesenlaciencia.ugto.mx/index.php/jovenesenlaciencia/article/view/1997

[4] Cui J, Zhang L, Metallurgical recovery of metals from electronic waste. *J Hazard Mater.* 2008; 158(2-3): 228-256. https://doi.org/10.1016/j.jhazmat.2008.02.001

[5] Akcil A, Erust C, Sekhar C, Ozgun M, Sahin M, Tuncuk A, Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants. *Waste Manag.* 2015; 45: 258-271. https://doi.org/10.1016/j.wasman.2015.01.017

[6] Araiza JA, Escobar K, Nájara JA, Diagnóstico de generación y manejo de los residuos eléctricos y electrónicos en instituciones educativas: un caso de estudio. *Ing Rev Acad Fac Ing UADY.* 2016; 20: 115-126. https://www.revista.ingenieria.uady.mx/ojs/index.php/ingenieria/article/view/34 (in Spanish)

[7] Forti V, Balde CP, Kuehr R, Bel G, The global E-waste monitor 2020: Quantities, flows and the circular economy potential. Bonn, Geneva and Rotterdam: United Nations University/United Nations Institute for Training and Research, International Telecommunication Union, and International Solid Waste Association. https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf Accessed October 23, 2024.

[8] Dehchenari M, Hosseinpoor S, Aali R, Salighehdar N, Mehdipour M, Simple method for extracting gold from electrical and electronic wastes using hydrometallurgical process. *Environ Health Eng Manag J.* 2017; 4(1): 55-58. http://dx.doi.org/10.15171/EHEM.2017.08

[9] Krishnan S, Syahidah N, Kamyab H, Mat S, Fadhil M, Abd Z, Chaiprapat S, Kenzo I, Ichikawa Y, Nasrullah M, Chelliapan S, Othman N, Current technologies for recovery of metals from industrial wastes: An overview. *Environ Technol Innov.* 2021; 22: 101525. https://doi.org/10.1016/j.eti.2021.101525

[10] Yao Z, Xu Z, Shuai Q, Chen X, Jiang Z, Peng X, Li H, Solidification of municipal solid waste incineration fly ash through co-mechanical treatment with circulation fluidized bed combustion fly ash. *Materials*. 2020; 13(1): 141. https://doi.org/10.3390/ma13010141

[11] Li H, Oraby E, Eksteen J, Cyanide consumption minimisation and concomitant toxic effluent minimisation during precious metals extraction from waste printed circuit boards. *Waste Manag.* 2021; 125: 87-97. https://doi.org/10.1016/j.wasman.2021.02.033

[12] Hsu E, Barmak K, West A, Hyung A, Park A, Advancements in the Treatment and Processing of Electronic Waste with Sustainability: A Review of Metal Extraction and Recovery Technologies. *Green Chem.* 2019; 21: 919-936. https://doi.org/10.1039/C8GC03688H

[13] Pinillo GA. Lixiviación de cobre contenido en tarjetas de computador PCB para la extracción de metales preciosos. *Rev Ing Investig Desarr.* 2018; 18(2): 15-21. https://doi.org/10.19053/1900771X.v18.n2.2018.11873 (in Spanish)

[14] Barragan J, Alemán J, Peregrina A, Amaya M, Rivero E, Larios E. Leaching of Metals from e Waste: From Its Thermodynamic Analysis and Design to Its Implementation and Optimization. *ACS*. 2021; 6(18): 12063-12071. https://doi.org/10.1021/acsomega.1c00724
[15] Chatterjee S. Sustainable Electronic Waste Management and Recycling Process. *Am J Environ Eng.* 2012; 2(1): 23-33. http://dx.doi.org/10.5923/j.ajee.20120201.05
[16] Lee H, Molstad E, Brajendra M, Recovery of Gold and Silver from Secondary Sources of Electronic Waste Processing by Thiourea Leaching. *J Miner Metals Mater Soc.* 2018; 70: 1616-1621. https://doi.org/10.1007/s11837-018-2965-2
[17] Tuncuk A, Akcil A, Yazici E, Deveci H, Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. *Miner Eng.* 2012; 25(1): 28-37. https://doi.org/10.1016/j.mineng.2011.09.019
[18] Ashiq A, Kulkarni J, Vithanage M, *Hydrometallurgical recovery of metals from e-waste* in: Vara M, Vithanage M, eds. *Electronic Waste Management and Treatment Technology*, Elsevier Inc.; 2019: 225-246. https://doi.org/10.1016/B978-0-12-816190-6.00010-8
[19] Leiva-Guajardo SI, Toro N, Fuentealba E, Morel MJ, Soliz A, Portillo C, Galleguillos Madrid, FM, Contribution of Copper Slag to Water Treatment and Hydrogen Production by Photocatalytic Mechanisms in Aqueous Solutions: A Mini Review. *Materials* (Basel) 2024; 17(22): 5434. https://doi.org/10.3390/MA17225434
[20] Tamayo-Soriano DA, Soria-Aguilar M de J, Picazo-Rodríguez NG, Almaguer-Guzman I, Chaidez-Felix J, Carrillo-Pedroza FR, Acid Leaching of La and Ce from Ferrocarbonatite-Related REE Ores. *Minerals* 2024; 14(5): 504. https://doi.org/10.3390/MIN14050504
[21] Najera Ibarra JM, Soria-Aguilar M de J, Martínez-Luevanos A, Picazo-Rodriguez NG, Martínez-Luévanos A, Carrillo-Pedroza FR, Figueroa-López U, Valenzuela García JL, Zinc Extraction from Primary Lead Smelting Slags by Oxidant Alkaline Leaching. *Processes* 2024; 12(7): 1409. https://doi.org/10.3390/PR12071409
[22] González-Ibarra AA, Nava-Alonso F, Dávila-Pulido GI, Carrillo-Pedroza FR, Rodríguez-Flores AM, Dissolution behavior of elemental tellurium and tellurium dioxide in alkaline cyanide solutions. *Hydrometallurgy* 2021; 203: 105702. https://doi.org/10.1016/J.HYDROMET.2021.105702
[23] Garza-Román MR, Carrillo-Pedroza FR, Picazo-Rodríguez NG, Soria-Aguilar M de J, Almaguer-Guzmán I, Chaidez-Félix J. Effects of pretreatment and leaching medium on the extraction efficiency of Au and Ag from a chalcopyrite leaching by-product. DYNA 2021; 88(218): 119-26. https://doi.org/10.15446/dyna.v88n218.90284
[24] Ramos-Cano J, González-Zamarripa G, Carrillo-Pedroza FR, Soria-Aguilar MDJ, Hurtado-Macías A, Cano-Vielma A, Kinetics and statistical analysis of nickel leaching from spent catalyst in nitric acid solution. *Int J Miner Process.* 2016; 148: 41-47. https://doi.org/10.1016/J.MINPRO.2016.01.006
[25] Soria-Aguilar MDJ, Davila-Pulido GI, Carrillo-Pedroza FR, Gonzalez-Ibarra AA, Picazo-Rodriguez N, de Jesus Lopez-Saucedo F, Ramos-Cano J, Oxidative Leaching of Zinc and Alkalis from Iron Blast Furnace Sludge. *Metals.* 2019; 9(9): 1015. https://doi.org/10.3390/MET9091015
[26] Cháidez J, Parga J, Valenzuela J, Carrillo R, Almaguer I, Leaching Chalcopyrite Concentrate with Oxygen and Sulfuric Acid Using a Low-Pressure Reactor. *Metals.* 2019; 9(2): 189. https://doi.org/10.3390/MET9020189
[27] Hossain R, Sahajwalla V, Current recycling innovations to utilize e-waste in sustainable green metalmanufacturing. *Phil Trans R Soc A.* 2024; 382: 20230239. https://doi.org/10.1098/rsta.2023.0239
[28] Gulliani S, Volpe M, Messineo A, Volpe R. Recovery of metals and valuable chemicals from waste electric and electronic materials: a critical review of existing technologies. *RSC Sustainability 2023*; 1: 1085-1108. https://doi.org/10.1039/d3su00034f
[29] Magoda K, Mekuto, L. Biohydrometallurgical Recovery of Metals from Waste Electronic Equipment: Current Status and Proposed Process. *Recycling.* 2022; 7: 67. https://doi.org/10.3390/recycling7050067
[30] Nagarajan N, Panchatcharam P, A Comprehensive Review on Sustainable Metal Recovery from E-Waste Based on Physiochemical and Biotechnological Methods. *Eng Sci.* 2023; 22(844): 844. https://dx.doi.org/10.30919/es8d844
[31] Mura M, Castillo I, Torres D, Galleguillos Madrid FM, Gálvez E, Gallegos S, Castillo J, Varas M, Jamett, I, Toro N, Global Overview of the Lithium Market and Opportunities for Chile. *Resources.* 2025; 14(2): 33. https://doi.org/10.3390/RESOURCES14020033
[32] Rocchetti L, Vegliò F, Kopacek B, Beolchini F, Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. *Environ Sci Technol.* 2013; 47(3): 1581-1588. https://doi.org/10.1021/es302192t
[33] Hossain MS, Ahmad Yahaya AN, Suhaila Yacob L, Zulkhairi Abdul Rahim M, Mohamad Yusof NN, Bachmann RT, Selective recovery of Copper from waste mobile phone printed circuit boards using Sulphuric acid leaching. *Mater Today Proc.* 2018; 5(10): 21698-21702. https://doi.org/10.1016/j.matpr.2018.07.021
[34] Park Y, Eom Y, Yoo K, Jha MK, Leaching of copper from waste-printed circuit boards (Pcbs) in sulfate medium using cupric ion and oxygen. *Metals (Basel).* 2021; 11(9): 1369. https://doi.org/10.3390/met11091369
[35] Dávila-Pulido GI, Salinas-Rodríguez A, Carrillo-Pedroza FR, González-Ibarra AA, Méndez-Nonell J, Garza-García M, Leaching kinetics of electronic waste for the recovery of copper: Rate-controlling step and rate process in a multisize particle system. *Int J Chem Kinet.* 2021; 53(3): 379-389. https://doi.org/10.1002/kin.21450
[36] Rajahalme J, Perämäki S, Budhathoki R, Väisänen A, Effective Recovery Process of Copper from Waste Printed Circuit Boards Utilizing Recycling of Leachate. *JOM.* 2021; 73: 980-987. https://doi.org/10.1007/s11837-020-04510-z

[37] Barragan JA, Ponce De León C, Alemán Castro JR, Peregrina-Lucano A, Gómez-Zamudio F, Larios-Durán ER, Copper and Antimony Recovery from Electronic Waste by Hydrometallurgical and Electrochemical Techniques. *ACS Omega.* 2020; 5(21): 12355-12363. https://doi.org/10.1021/acsomega.0c01100

[38] Wstawski S, Emmons-Burzyńska M, Rzelewska-Piekut M, Skrzypczak A, Regel-Rosocka M, Studies on copper(II) leaching from e-waste with hydrogen sulfate ionic liquids: Effect of hydrogen peroxide. *Hydrometallurgy.* 2021; 205: 105730. https://doi.org/10.1016/j.hydromet.2021.105730

[39] Huang J, Chen M, Chen H, Chen S, Sun Q, Leaching behavior of copper from waste printed circuit boards with Brønsted acidic ionic liquid. *Waste Manag.* 2014; 34(2): 483-488. https://doi.org/10.1016/j.wasman.2013.10.027

[40] Zhang D-J, Dong L, Li Y-T, Wu Y, Ma Y-X, Yang B, Copper leaching from waste printed circuit boards using typical acidic ionic liquids recovery of e-wastes' surplus value. *Waste Manag.* 2018; 78: 191-197. https://doi.org/10.1016/j.wasman.2018.05.036

[41] Kavousi M, Sattari A, Alamdari EK, Firozi S, Selective separation of copper over solder alloy from waste printed circuit boards leach solution. *Waste Manag.* 2017; 60: 636-642. https://doi.org/10.1016/j.wasman.2016.07.042

[42] Segura-Bailón B, Lapidus GT, Selective recovery of copper contained in waste PCBs from cellphones with impurity inhibition in the citrate-phosphate system. *Hydrometallurgy.* 2021; 203: 105699. https://doi.org/10.1016/j.hydromet.2021.105699

[43] Kim EY, Kim MS, Lee JC, Jeong J, Pandey BD, Leaching kinetics of copper from waste printed circuit boards by electro-generated chlorine in HCl solution. *Hydrometallurgy.* 2011; 107(3-4): 124-132. https://doi.org/10.1016/j.hydromet.2011.02.009

[44] Mudila R, Singh KK, Morrison C, Love J, Recycling copper and gold from e-waste by a two-stage leaching and solvent extraction process. *Sep Purif Technol.* 2021; 263: 118400. https://doi.org/10.1016/j.seppur.2021.118400

[45] Torres R, Lapidus G, Copper leaching from electronic waste for the improvement of gold recycling. *Waste Manag.* 2016; 57: 131-139. https://doi.org/10.1016/j.wasman.2016.03.010

[46] Huan L, Oraby E, Eksteen J, Extraction of copper and the co-leaching behaviour of other metals from waste printed circuit boards using alkaline glycine solutions. *Resour Conserv Recycl.* 2020; 154: 104624. https://doi.org/10.1016/j.resconrec.2019.104624

[47] Petter P, Veit H, Bernardes A, Evaluation of gold and silver leaching from printed circuit board of cellphones. *Waste Manag.* 2014; 34(2): 475-482. https://doi.org/10.1016/j.wasman.2013.10.032

[48] Kasper A, Veit H, Gold recovery from printed circuit boards of mobile phones scraps using a leaching solution alternative to cyanide. *Braz J Chem Eng.* 2018; 35(3): 931-942. https://doi.org/10.1590/0104-6632.20180353s20170291

[49] Gámez S, Garcés K, De la Torre E, Guevara A, Precious metals recovery from waste printed circuit boards using thiosulfate leaching and ion exchange resin. *Hydrometallurgy* 2019; 186: 1-11. https://doi.org/10.1016/j.hydromet.2019.03.004

[50] Cerecedo-Sáenz E, Cárdenas-Reyes EA, Rojas-Calva AH, Reyes-Valderrama MI, Rodríguez-Lugo V, Toro N, Gálvez E, Acevedo-Sandoval OA, Hernández-Ávila J, Salinas-Rodríguez E, Use of the O_2-Thiosemicarbazide System, for the Leaching of: Gold and Copper from WEEE & Silver Contained in Mining Wastes. *Materials* 2021; 14(23): 7329. https://doi.org/10.3390/MA14237329

[51] Salinas-Rodríguez E, Hernández-ávila J, Cerecedo-Sáenz E, Arenas-Flores A, Veloz-Rodríguez MA, Toro N, del P. Gutiérrez-Amador M, Acevedo-Sandoval OA, Leaching of Copper Contained in Waste Printed Circuit Boards, Using the Thiosulfate-Oxygen System: A Kinetic Approach. *Materials* 2022; 15(7): 2354. https://doi.org/10.3390/MA15072354

[52] Halmenshlager P, Veit H, Bernardes A, Leaching of gold and silver from printed circuit board of mobile phones. *Rev Esc Minas.* 2015; 68(1): 61-68. https://doi.org/10.1590/0370-44672015680152

[53] Batnasan A, Haga K, Shibayama A, Recovery of Precious and Base Metals from Waste Printed Circuit Boards Using a Sequential Leaching Procedure. *JOM.* 2018; 70: 124-128. https://doi.org/10.1007/s11837-017-2694-y

[54] Jing L, Xiu X, Wen, L, Thiourea leaching gold and silver from the printed circuit boards of waste mobile phones. *Waste Manag.* 2012; 32(6): 1209-1212. https://doi.org/10.1016/j.wasman.2012.01.026

[55] Batnasan A, Haga K, Shibayama A, *Recovery of Valuable Metals from Waste Printed Circuit Boards by Using Iodine-Iodide Leaching and Precipitation i*n: Kim H, Wesstrom B, Alam S, Ouchi T, Azimi G, Neelameggham NR, Wang S, GuanedsX. *Rare Metal Technology 2018. TMS 2018. The Minerals, Metals & Materials Series.* Springer, Cham. 2018; 131-142. https://doi.org/10.1007/978-3-319-72350-1_12

[56] Birich A, Gao Z, Vrucak D, Friedrich B, Sensitivity of Gold Lixiviants for Metal Impurities in Leaching of RAM Printed Circuit Boards. *Metals (Basel)*. 2023; 13(5): 969. https://doi.org/10.3390/met13050969

[57] Murali A, Zhang Z, Shine A, Free M, Sarswat P, E-wastes derived sustainable Cu recovery using solvent extraction and electrowinning followed by thiosulfate-based gold and silver extraction. *J Hazard Mater Adv.* 2022; 8: 100196. https://doi.org/10.1016/j.hazadv.2022.100196

[58] Rao M, Singh K, Morrison C, Love J, Recycling copper and gold from e-waste by a two-stage leaching and solvent extraction process. *Sep Purif Technol.* 2021; 263: 118400. https://doi.org/10.1016/j.seppur.2021.118400

[59] Nekouei R, Pahlevani F, Assefi M, Maroufi S, Sahajwalla V. Selective isolation of heavy metals from spent electronic waste solution by macroporous ion-exchange resins. *J Hazard Mater.* 2019; 371: 389-396. https://doi.org/10.1016/j.jhazmat.2019.03.013

[60] Bui T, Jeon S, Lee Y, Facile recovery of gold from e-waste by integrating chlorate leaching and selective adsorption using chitosan-based bioadsorbent. *J Environ Chem Eng.* 2021; 9(1): 104661. https://doi.org/10.1016/j.jece.2020.104661

[61] Nogueira A, Carreira A, Vargas S, Passos H, Schaffer N, Simple gold recovery from e-waste leachate by selective precipitation using a quaternary ammonium salt. *Sep Purif Technol.* 2023; 316: 123797. https://doi.org/10.1016/j.seppur.2023.123797

[62] Mahapatra RP, Srikant SS, Rao RB, Recovery of basic valuable metals and alloys from E-waste using microwave heating followed by leaching and cementation process. *Sādhanā.* 2019; 44: 209. https://doi.org/10.1007/s12046-019-1193-y
[63] Arya S, Kumar S, E-waste in India at a glance: Current trends, regulations, challenges and management strategies. *J Clean Prod.* 2020; 271(): 122707. https://doi.org/10.1016/j.jclepro.2020.122707
[64] Ramesh M, Paramasivan M, Akshay P, Jarin T, A review on electric and electronic waste material management in 21st century. *Mater Today Proc.* 2023. https://doi.org/10.1016/j.matpr.2023.01.057
[65] Islam A, Ahmed T, Rabiul M, Rahman A, Sultana M, Abd A, Uddin M, Hwa S, Hasan M, Advances in sustainable approaches to recover metals from e-waste-A review. *J Clean Prod.* 2019; 244: 118815. https://doi.org/10.1016/j.jclepro.2019.118815
[66] Ueberschaar M, Dariusch Jalalpoor D, Korf N, Rotter VS, Potentials and Barriers for Tantalum Recovery from Waste Electric and Electronic Equipment. *J Ind Ecol.* 2017; 21(3): 700-714. https://doi.org/10.1111/JIEC.12577
[67] Blais C, Le Dinh AQ, Loranger É, Abdul-Nour G, Precious Metals Recovery Process from Electronic Boards: Case Study of a Non-Profit Organization (QC, Canada). *Sustainability.* 2024; 16(6): 2509. https://doi.org/10.3390/SU16062509
[68] Dias J, Pereira Silva AG, França de Holanda JN, Martins Delatorre F, Oliveira da Conceição A, Mendonça de Miranda G, Futuro A, Cardinal Pinho S. Environmental and Technological Assessment of Operations for Extraction and Concentration of Metals in Electronic Waste. *Sustainability.* 2023; 15(17): 13175. https://doi.org/10.3390/SU151713175
[69] Giese EC, E-waste mining and the transition toward a bio-based economy: The case of lamp phosphor powder. *MRS Energy Sustain.* 2022; 9(2): 494-500. https://doi.org/10.1557/s43581-022-00026-y
[70] Jin G, Li W, Wang S, Gao S. A systematic selective disassembly approach for Waste Electrical and Electronic Equipment with case study on liquid crystal display televisions. *Proc Inst Mech Eng B*. 2017; 231(13): 2261-2278. https://doi.org/10.1177/0954405415575476
[71] Fenwick C, Mayers K, Lee J, Murphy R, Recycling plastics from e-waste: Implications for effective eco-design. *J Ind Ecol.* 2023; 27(5): 1370-1388. https://doi.org/10.1111/JIEC.13409
[72] Chancerel P, Meskers CEM, Hagelüken C, Rotter VS, Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment. *J Ind Ecol.* 2009; 13(5): 791-810. https://doi.org/10.1111/J.1530-9290.2009.00171.X
[73] Alkouh A, Keddar KA, Alatefi S, Remanufacturing of Industrial Electronics: A Case Study from the GCC Region. *Electronics.* 2023; 12(9): 1960. https://doi.org/10.3390/ELECTRONICS12091960
[74] Cozza G, D'Adamo I, Rosa P, Circular manufacturing ecosystems: Automotive printed circuit boards recycling as an enabler of the economic development. *Prod. Manuf. Res.* 2023; 11(1): 2182837. https://doi.org/10.1080/21693277.2023.2182837
[75] Wu C, Awasthi AK, Qin W, Liu W, Yang C, Recycling value materials from waste PCBs focus on electronic components: Technologies, obstruction and prospects. *J Environ Chem Eng.* 2022; 10(5): 108516. https://doi.org/10.1016/j.jece.2022.108516
[76] Brindhadevi K, Barceló D, Lan C, Rene E, E-waste management, treatment options and the impact of heavy metal extraction from e-waste on human health: Scenario in Vietnam and other countries. *Environ Res.* 2023; 217: 114926. https://doi.org/10.1016/j.envres.2022.114926
[77] Gravel S, Roberge B, Calosso M, Gagné S, Lavoie J, Labrèche F, Occupational health and safety, metal exposures and multi-exposures health risk in Canadian electronic waste recycling facilities. *Waste Manag.* 2023; 165: 140-149. https://doi.org/10.1016/j.wasman.2023.04.026
[78] Marconi M, Gregori F, Germani M, Papetti A, Favi C, An approach to favor industrial symbiosis: The case of waste electrical and electronic equipment. *Procedia Manuf.* 2018; 21: 502-509. https://doi.org/10.1016/j.promfg.2018.02.150
[79] Zeng H, Chen X, Xiao X, Zhou Z, Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. *J Clean Prod.* 2017; 155: 54-65. https://doi.org/10.1016/j.jclepro.2016.10.093
[80] Park JM, Park JY, Park HS, A review of the National Eco-Industrial Park Development Program in Korea: Progress and achievements in the first phase, 2005-2010. *J Clean Prod.* 2016; 114: 33-44. https://doi.org/10.1016/j.jclepro.2015.08.115
[81] Ye Q, Umer Q, Zhou R, Asmi A, Asmi F, How publications and patents are contributing to the development of municipal solid waste management: Viewing the UN Sustainable Development Goals as ground zero. *J Environ Manag.* 2023; 325: 116496. https://doi.org/10.1016/j.jenvman.2022.116496
[82] Alarcón A. Method for recovering gold and silver from printed circuit boards using an ionic solution. MX 391678 B, 2022. https://patents.google.com/patent/MX391678B/en
[83] Berrueta F. Non-ferrous metals obtained from electronic scrap through physical-mechanical refining. MX/a/2018/006178, 2019. https://patents.google.com/patent/MX2018006178A/en
[84] Zhang Y. Cleaning treatment method to efficiently recycle useful substances of electronic garbage. CN113732005A, 2021. https://patents.google.com/patent/CN113732005A/en
[85] Minjie S. System and method for electronic waste pyrolysis recovery processing. CN106520152A, 2017. https://patents.google.com/patent/CN106520152A/en
[86] Lynn W. Simplified method of gold recovery from electronic waste. US20220235433A1, 2022. https://patents.google.com/patent/US20220235433A1/en
[87] Bin Z. Preparation for hollow polyaniline microspheres, method for recovering precious metals in electronic waste and method of recycling the recovery product. CN110639438A, 2022. https://patents.google.com/patent/CN110639438A/en

[88] Reece W. Process for recovering metal from electronic waste. US11608544B2, 2023. https://patents.google.com/patent/US11608544B2/en

[89] Marlin F. Method for the recovery of metals from electronic waste. CA3189365A1, 2022. https://patents.google.com/patent/CA3189365A1/en

[90] Mohamed K. A process to recover a metallic fraction of electronic waste and produce value-added products. WO2023087114A1, 2023. https://patents.google.com/patent/WO2023087114A1/en

[91] Xiaohui L. Comprehensive method of separation and recovery of electronic waste. CN110983031A, 2020. https://patents.google.com/patent/CN110983031A/en

[92] Kumar Sahoo P, Environmental Aspects of E-waste Management. In *Futuristic Trends in Chemical Material Sciences & Nano Technology*. 2024; 3: 306-318. https://doi.org/10.58532/V3BDCS1CH21

[93] Mishra K, Siwal SS, Thakur VK, E-waste recycling and utilization: A review of current technologies and future perspectives. *Curr. Opin. Green Sustain Chem.* 2024; 47: 100900. https://doi.org/10.1016/J.COGSC.2024.100900

[94] Alam T, Golmohammadzadeh R, Faraji F, Shahabuddin M. E-Waste Recycling Technologies: An Overview, Challenges and Future Perspectives. In: *Paradigm Shift in E-waste Management*, Editor1 A.; Editor2 B., Eds.; CRC Press: Boca Raton, FL, USA; 2022: 143-176. https://doi.org/10.1201/9781003095972-10

[95] He Y, Kiehbadroudinezhad M, Hosseinzadeh-Bandbafha H, Kumar Gupta V, Peng W, Lam SS, Tabatabaei M, Aghbashlo M, Driving sustainable circular economy in electronics: A comprehensive review on environmental life cycle assessment of e-waste recycling. *Environ Pollut.* 2024; 342: 123081. https://doi.org/10.1016/J.ENVPOL.2023.123081

[96] Seif R, Salem FZ, Allam NK. E-waste recycled materials as efficient catalysts for renewable energy technologies and better environmental sustainability. *Environ Dev Sustain.* 2023; 26: 5473-5508. https://doi.org/10.1007/S10668-023-02925-7

[97] Senthilnathan J, Philip L. Persistent Toxic Substances Released from Uncontrolled E-waste Recycling and Action for the Future. In: Jawaid, M, Khan, A, eds. *Conversion of Electronic Waste in to Sustainable Products. Sustainable Materials and Technology.* Singapore: Springer; 2023: 103-126. https://doi.org/10.1007/978-981-19-6541-8_4

Reciklaža elektronskog otpada: pregled hidrometalurških procesa koji se koriste za ekstrakciju metala

Nallely G. Picazo-Rodríguez[1], Gabriela Baltierra-Costeira[1], Ma de Jesús Soria-Aguilar[2], Zeferino Gamiño Arroyo[3], Norman Toro[4], Manuel Saldana[4,5], Jesús R. de la Garza de Luna[1] and Francisco Raúl Carrillo-Pedroza[2]

[1] *Instituto Tecnológico Superior de Monclova, Tecnológico Nacional de México, Monclova, México*
[2]*Facultad de Metalurgia, Universidad Autónoma de Coahuila, Monclova, México*
[3]*Departamento de Ingeniería Química, División de Ciencias Naturales y Exactas, Universidad de Guanajuato, Guanajuato, México*
[4]*Faculty of Engineering and Architecture, Universidad Arturo Prat, Iquique, Chile*
[5]*Departamento de Ingeniería Química y Procesos de Minerales, Universidad de Antofagasta, Antofagasta, Chile*

(Pregledni rad)

Izvod

Eksponencijalni rast stanovništva doveo je do eksponencijalne potražnje za metalima, posebno za proizvodnju elektronskih uređaja, koji se na kraju svog funkcionalnog veka najčešće odlažu na deponije. Ova praksa predstavlja značajnu opasnost po životnu sredinu zbog prisustva metala u ovim odbačenim materijalima, nazvanim elektronski otpad ili e-otpad. To zahteva odgovarajuće strategije upravljanja e-otpadom, kako bi se sprečili negativni efekti na ekosistem i na ljudsko zdravlje. E-otpad sadrži vredne metale, često u koncentracijama koje čine njihovu reciklažu ekonomski isplativom. Štaviše, rastuća potražnja za metalima, vođena tehnološkim napretkom, učinila je reciklažu e-otpada ključnim elementom održivog upravljanja resursima. Ovaj rad pruža pregled hidrometalurških tehnika obrade za reciklažu vrednih metala iz otpada od električne i elektronske opreme, pre svega metala kao što su bakar, zlato i srebro. Ove metodologije koriste vodene rastvore kako bi olakšala ekstrakcija metala, predstavljajući isplativu i ekološki održivu alternativu proizvodnji metala konvencionalnim rudarenjem. Međutim, ekonomska isplativost ovih alternativnih procesa može varirati zavisno od vrste i koncentracije metala prisutnih u otpadu.

Ključne reči: hidrometalurgija; upravljanje elektronskim otpadom; vredni metali; ekstrakcija; ekološka održivost