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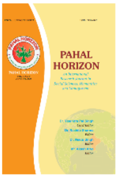

# Circular Economy Solution for Heavy Metal-Rich E-waste

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## ABSTRACT

The increasing generation of electronic waste (e-waste) has become a major environmental concern due to the presence of toxic heavy metals such as lead, cadmium, mercury, and chromium. Improper disposal of heavy-metal-rich e-waste results in severe ecological degradation and health risks. A circular economic approach provides a sustainable solution by promoting resource recovery, material reuse, and waste minimization. These abstract highlights circular economy strategies for managing heavy metal–laden e-waste, focusing on environmentally friendly recycling technologies and metal recovery processes. Emphasis is placed on closing material loops through advanced recovery methods, eco-design, and extended producer responsibility. Implementing circular economic principles can significantly reduce environmental pollution, conserve valuable resources, and support sustainable development in electronic waste management.

*Keywords*: E-waste, heavy metals, circular economy, environmental pollution.

## 1. INTRODUCTION

E-waste can be defined as unwanted, not working, or any equipment which has reached its useful life, also it should be operated on an electromagnetic field and electrical currents (UNEP 2007). It includes a wide range of electronic devices, varying from heavy domestic appliances to equipment used in the IT and telecom sectors. It also encompasses appliances from the medical, automobile, sports, and high-end toy sectors (Li et al. 2007; Chen et al. 2015). Different parts of electric and electronic equipment (EEE), like used batteries, electric wires, printed circuit boards (PCBs), plastic casings, cathode ray tubes

(CRTs), poly (p-phenylene terephthalamide, activated glass, and lead capacitors, are also categorized as e-waste (Lambert et al. 2015; Ilankoon et al. 2018; Mazrouaa et al. 2019). The basic design of EEE is very complex, as 69 elements from the periodic table can be found in EEE, including precious metals (like Pt, Au, Rh, Ag, Cu, Ir, Ru, and Os), Critical Raw Materials (CRM) (like In, Co, Bi, Pd, Sb, and Ge), and other noncritical metals, such as Fe and Al.

E-waste has emerged as one of the fastest-growing waste streams across the globe due to rapid technological advancement, AI applications, urbanization, industrial expansion, and increasing consumer demand for electronic items. While e-waste poses serious environmental and health risks because of the presence of hazardous substances and heavy metals, it also represents a valuable secondary resource containing economically important materials such as Cu, Au, Ag, and rare earth elements. This dual nature of e-waste presents both a challenge and an opportunity for sustainable resource management. The circular economy concept offers a promising framework to address this issue by shifting from the traditional linear "take–make–dispose" model toward systems that prioritize resource efficiency through recycling, reuse, remanufacturing, and sustainable product design. By extending product life cycles and recovering valuable materials, circular economy approaches aim to reduce environmental impacts while retaining economic value within the production system.

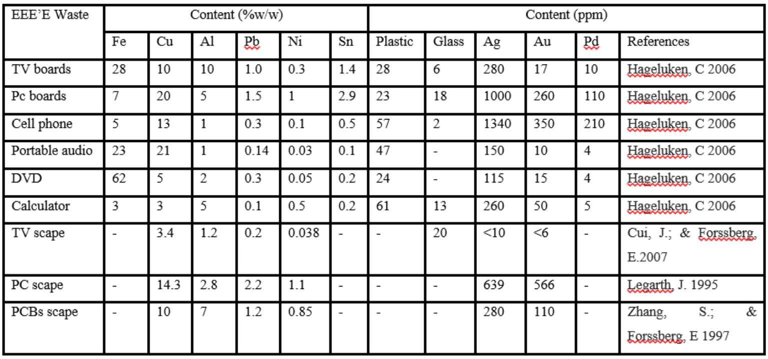
Figure 1. Circular diagram of e-waste sources and sinks (2019 data), the waste deposit picture was obtained from the public domain (Ghimire, H., & Ariya, P. A. 2020).

Global statistics highlight the urgency of adopting sustainable e-waste management strategies. According to recent reports, global e-waste generation reached approximately 53.6 million metric tons in 2019 and is projected to increase significantly in the coming decades, potentially exceeding 74 million metric tons by 2030. Despite the substantial material and economic value embedded in discarded electronic products, estimated at nearly USD 57 billion in recoverable raw materials, only a limited proportion of e-waste is formally collected and recycled. As a result, large quantities of valuable resources are lost, and improper disposal practices contribute to environmental contamination and human health risks. The management of e-waste is therefore a multidisciplinary issue encompassing environmental sustainability, economic development, and technological innovation, public health, and policy frameworks. Although challenges such as the heterogeneous composition of e-waste, high processing costs, toxic emissions during treatment, management of hazardous residues, and insufficient international cooperation remain significant barriers, the transition toward circular economy principles provides an opportunity to transform e-waste from an environmental burden into a resource-efficient and economically beneficial system.

## 2. HEAVY METALS IN E-WASTE

### 2.1 Composition of E-waste

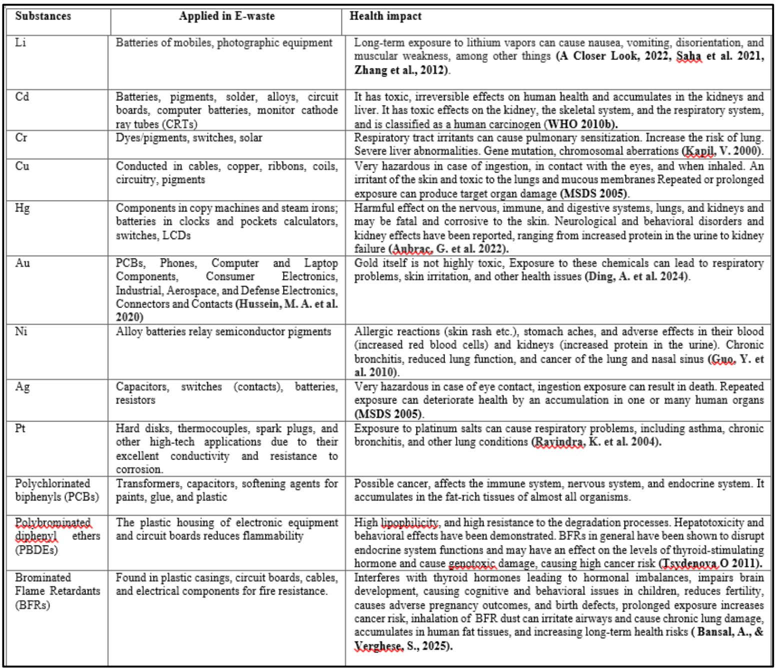
E-waste comprises a vast range of substances depending upon the age of e-waste, type, and categories of EEEs (Santhanam, N.; et al., 2014; Robinson, B.H., 2009). For example, a mobile phone can contain more than 40 reusable elements (Li, Y. et al. 2008, Blass, V.D. et al., 2006, Liu Q et al., 2009). Some materials found in e-waste are precious metals (Au, Ag, Pd, Pt), base metals (Cu, Al, Ni, Sn, Zn, Fe, etc.), metals of concern (Hg, Be, In, Pb, Cd, As, Sb, etc.), halogens (bromine, fluorine, chlorine), and combustibles (plastics, organic fluids, etc.) (Hageluken, C 2006, Ghimire, H., & Ariya, P. A. 2020)



| EEE’E Waste | Content (%w/w) | | | | | | Content (ppm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fe | Cu | Al | Pb | Ni | Sn | Plastic | Glass | Ag | Au | Pd | References |
| TV boards | 28 | 10 | 10 | 1.0 | 0.3 | 1.4 | 28 | 6 | 280 | 17 | 10 | Hageluken, C 2006 |
| Pc boards | 7 | 20 | 5 | 1.5 | 1 | 2.9 | 23 | 18 | 1000 | 260 | 110 | Hageluken, C 2006 |
| Cell phone | 5 | 13 | 1 | 0.3 | 0.1 | 0.5 | 57 | 2 | 1340 | 350 | 210 | Hageluken, C 2006 |
| Portable audio | 23 | 21 | 1 | 0.14 | 0.03 | 0.1 | 47 | - | 150 | 10 | 4 | Hageluken, C 2006 |
| DVD | 62 | 5 | 2 | 0.3 | 0.05 | 0.2 | 24 | - | 115 | 15 | 4 | Hageluken, C 2006 |
| Calculator | 3 | 3 | 5 | 0.1 | 0.5 | 0.2 | 61 | 13 | 260 | 50 | 5 | Hageluken, C 2006 |
| TV scape | - | 3.4 | 1.2 | 0.2 | 0.038 | - | - | 20 | <10 | <6 | - | Cui, J.; & Forssberg, E.2007 |
| PC scape | - | 14.3 | 2.8 | 2.2 | 1.1 | - | - | - | 639 | 566 | - | Legarth, J. 1995 |
| PCBs scape | - | 10 | 7 | 1.2 | 0.85 | - | - | - | 280 | 110 | - | Zhang, S.; & Forssberg, E 1997 |

Table 1. Literature reported information on material composition in different types of electrical and electronic equipment (EEE) and e-waste (Ghimire, H., & Ariya, P. A. 2020).
Note- “-“indicates data unavailable

## 2.2 Environmental and Health Impacts



| **Substances** | **Applied in E-waste** | **Health impact** |
|---|---|---|
| Li | Batteries of mobiles, photographic equipment | Long-term exposure to lithium vapors can cause nausea, vomiting, disorientation, and muscular weakness, among other things **(A Closer Look, 2022, Saha et al. 2021, Zhang et al., 2012)**. |
| Cd | Batteries, pigments, solder, alloys, circuit boards, computer batteries, monitor cathode ray tubes (CRTs) | It has toxic, irreversible effects on human health and accumulates in the kidneys and liver. It has toxic effects on the kidney, the skeletal system, and the respiratory system, and is classified as a human carcinogen (**WHO 2010b).** |
| Cr | Dyes/pigments, switches, solar | Respiratory tract irritants can cause pulmonary sensitization. Increase the risk of lung. Severe liver abnormalities. Gene mutation, chromosomal aberrations **(Kapil, V. 2000)**. |
| Cu | Conducted in cables, copper, ribbons, coils, circuitry, pigments | Very hazardous in case of ingestion, in contact with the eyes, and when inhaled. An irritant of the skin and toxic to the lungs and mucous membranes Repeated or prolonged exposure can produce target organ damage **(MSDS 2005)**. |
| Hg | Components in copy machines and steam irons; batteries in clocks and pockets calculators, switches, LCDs | Harmful effect on the nervous, immune, and digestive systems, lungs, and kidneys and may be fatal and corrosive to the skin. Neurological and behavioral disorders and kidney effects have been reported, ranging from increased protein in the urine to kidney failure **(Aubrac, G. et al. 2022).** |
| Au | PCBs, Phones, Computer and Laptop Components, Consumer Electronics, Industrial, Aerospace, and Defense Electronics, Connectors and Contacts **(Hussein, M. A. et al. 2020)** | Gold itself is not highly toxic, Exposure to these chemicals can lead to respiratory problems, skin irritation, and other health issues **(Ding, A. et al. 2024)**. |
| Ni | Alloy batteries relay semiconductor pigments | Allergic reactions (skin rash etc.), stomach aches, and adverse effects in their blood (increased red blood cells) and kidneys (increased protein in the urine). Chronic bronchitis, reduced lung function, and cancer of the lung and nasal sinus **(Guo, Y. et al. 2010)**. |
| Ag | Capacitors, switches (contacts), batteries, resistors | Very hazardous in case of eye contact, ingestion exposure can result in death. Repeated exposure can deteriorate health by an accumulation in one or many human organs **(MSDS 2005)**. |
| Pt | Hard disks, thermocouples, spark plugs, and other high-tech applications due to their excellent conductivity and resistance to corrosion. | Exposure to platinum salts can cause respiratory problems, including asthma, chronic bronchitis, and other lung conditions **(Ravindra, K. et al. 2004).** |
| Polychlorinated biphenyls (PCBs) | Transformers, capacitors, softening agents for paints, glue, and plastic | Possible cancer, affects the immune system, nervous system, and endocrine system. It accumulates in the fat-rich tissues of almost all organisms. |
| Polybrominated diphenyl ethers (PBDEs) | The plastic housing of electronic equipment and circuit boards reduces flammability | High lipophilicity, and high resistance to the degradation processes. Hepatotoxicity and behavioral effects have been demonstrated. BFRs in general have been shown to disrupt endocrine system functions and may have an effect on the levels of thyroid-stimulating hormone and cause genotoxic damage, causing high cancer risk **(Tsydenova O 2011).** |
| Brominated Flame Retardants (BFRs) | Found in plastic casings, circuit boards, cables, and electrical components for fire resistance. | Interferes with thyroid hormones leading to hormonal imbalances, impairs brain development, causing cognitive and behavioral issues in children, reduces fertility, causes adverse pregnancy outcomes, and birth defects, prolonged exposure increases cancer risk, inhalation of BFR dust can irritate airways and cause chronic lung damage, accumulates in human fat tissues, and increasing long-term health risks **( Bansal, A., & Verghese, S., 2025).** |

Table 1: Common toxic substances associated with e-waste and their impact on human health (Akram, R. et al. 2019, Bansal A. et al., 2023)

## 3. CIRCULAR ECONOMY CONCEPT IN E-WASTE MANAGEMENT

The assimilation of concepts of circular economy (Ellen MacArthur Foundation 2019; Parajuly et al. 2020) and sustainable development goals is among the most important objectives for every organization/institution. According to Sauvé et al. (2016), recycling of the materials and maximum resource recovery from wastes should be ensured to restrict future environmental pollution. Meaning, thereby, maximum use of the Environment Friendly materials must be ensured to reduce waste generation (Ellen MacArthur Foundation 2019), and it can be achieved by adopting eco-friendly technologies and green policy developments, as well as inculcating fruitful innovative corporate cultures (Ghisellini et al. 2016).

## 4. TECHNOLOGIES FOR HEAVY METAL RECOVERY FROM E-WASTE

The recovery of base and precious metals from e-waste can be classified into three types – pyrometallurgical (thermal), hydrometallurgical (chemical), and bio-metallurgical (biological) (Hong and Valix, 2014; Tuncuk et al., 2012). Physical methods have gained popularity in e-waste recycling as a pre-

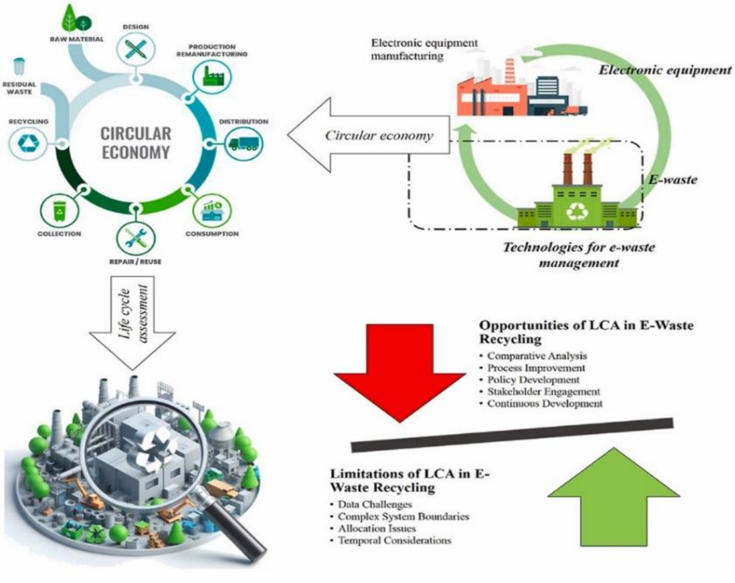


Figure 2: The representation of the concepts of circular economy in e-waste management (He, Y. et al., 2024).

treatment strategy. The physical separation processes applied for the treatment of e-waste entail magnetic separation (MS) (Li et al., 2016), eddy current separation (ECS) (Jujun et al., 2014), air current separation (ACS) (Bedekovic, 2015), corona electrostatic separation (CES) (Xue et al., 2012) and vacuum metallurgy separation (VMS) (Zhan and Xu, 2014). Contrary to the conventional chemical leaching technologies, the bio-hydrometallurgical strategy is largely regarded as a “green technology” for the extraction of metals from e-wastes (Kim et al., 2016).

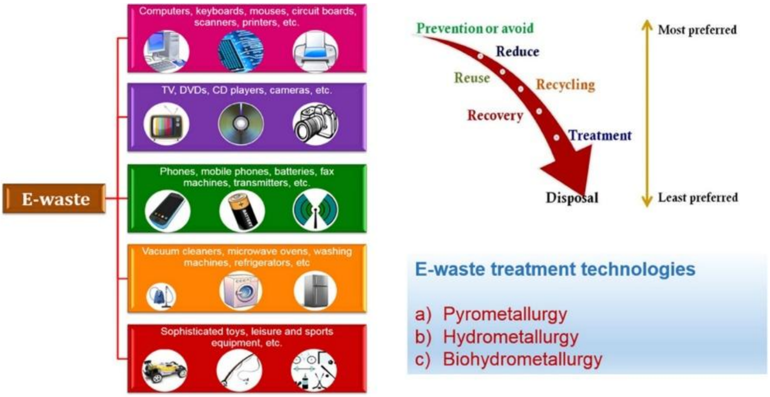


Figure 3: Conceptual Framework for E-waste Management and Treatment Technologies (Forti, V. et al., 2020).

### 4.1. Pyrometallurgy

Pyrometallurgy is a conventional technology wherein non-ferrous and precious metals are leached from WEEE. The pyrometallurgical technique pre-treats the waste by roasting, disassembling, and then smelting the abundant metal fraction. The pyrometallurgical approach engaging the smelter has been a customary tool for the recovery of precious metals and copper from the EoL electronic appliances (Ilyas et al., 2013; Sun et al., 2016). Smelting is the most vital process for pyrometallurgy, and some of the modern smelting equipment used in pyrometallurgy include Outokumpu flash smelting, Noranda reactor system, and the Mitsubishi continuous smelter (Cui and Zhang, 2008; Zhang and Xu, 2016).

The major challenge in pyrometallurgical processes is the enhancement of the purity of the final metal products because e-waste comprises both pure metals and alloys. Pure metallic forms are effortlessly handled by melting in smelters (Hong and Valix, 2014). Pyrometallurgical techniques employ higher temperatures to volatilize specific metals, which are then condensed and recovered. Most of the industrial recycling processes have implemented pyrometallurgical processes and heat treatments. Compared to pyrometallurgical processes, hydrometallurgical techniques endow comparatively low capital cost, minimized environmental impacts, fully recoverable leachates, and less air pollution (e.g., no hazardous gases/dusts) (Tuncuk et al., 2012; Sun et al., 2016).

It is noteworthy to mention that most of the metals (based and precious metals) present in the e-waste can be recycled using this technology; however, further processing (downstream) is required using hydrometallurgical or electrochemical treatments to refine or separate the desired metal of interest. The Kaldo process is the most employed method to treat e-waste, and it involves the following steps: (i) water washing, (ii) pressure acid leaching, (iii) reductive smelting, (iv) oxidative blowing and refining, and (v) electrolytic refining (Hait et al., 2009). The advantages of this process include: (i) high recovery rates for precious metals such as gold and silver, (ii) easy to scale-up and operate because its furnace design and configuration is well established, and (iii) high treatment capacity (Xu et al., 2021).

### 4.2. Hydrometallurgy

Hydrometallurgy is the extraction of metals from solid resources by using chemicals. Hydrometallurgy consists of two stages: (i) leaching, where the metals are solubilized by aqueous chemicals at low pH, and (ii) recovery, where the leached metals are recovered from the polymetallic pregnant leaching solution (Sethurajan et al., 2017; Sethurajan et al., 2018). Hydrometallurgical techniques are advancing rapidly; additionally, they are deemed to be well-established and efficient. From an economic view-point, printed circuit boards, telecom servers and automatic teller machines contain large amounts of precious metals and therefore, such components are more cost-efficient to be used as raw materials in hydrometallurgical processes (Sethurajan et al., 2019) Hydrometallurgical techniques may utilize huge amounts of poisonous, highly acidic or alkaline or inflammable components with the release of large volumes of solid wastes and effluents. Hydrometallurgical methods involve the suspension of the metallic parts of e-wastes in either acidic or alkali solutions, based on the desired recovery of precious metals (Cui and Zhang, 2008).

The majority of the hydrometallurgical processes used for the extraction of metals from e-waste perform cyanide, thiourea, thiosulfate, and halide leaching of valuable metals (Hong and Valix, 2014; Tuncuk et al., 2012). Hydrometallurgical techniques have been extensively studied to recover Cu, Zn, and Mn by leaching and precipitation. Apart from base metals such as Cu and Zn, precious metals such as Au, Ag, and Pt have also been successfully extracted from e-wastes (Petter et al., 2014; Chen et al., 2015;

Zhou et al., 2020). Recently, it has also been proved that ionic liquids could be efficiently extracted from e-waste (Dupont and Binnemans, 2015; Dupont and Binnemans, 2015; He et al., 2019).

WEEE also contains significant amounts of critical metals such as Co, In, Ga, and rare earth elements (REE) such as Nd, Dy, Pr, and Sm. To recover these elements from e-wastes, hydrometallurgy was found to be efficient (Rabatho et al., 2013; Hu et al., 2015; Nayaka et al., 2016; Kristofova et al., 2016). Hydrometallurgical techniques require high amounts of chemicals and impose noteworthy environmental impacts, particularly during the leaching process. Besides, they also require higher energy input, followed by remanufacturing, recycling and reuse (Cui and Zhang, 2008).

The development trend in hydrometallurgy can be summarized as follows (Jia et al., 2020): (i) in recent years, one or more processes and mechanisms have been applied in hydrometallurgy, including leaching, solvent extraction, biohydrometallurgy, electro-hydrometallurgy, ion exchange, precipitation, adsorption, and cementation, (ii) focus of the academic community and industries are inclined towards the development of cleaner and lower-cost processes, (iii) the application of most of the advanced analytical instruments and techniques such as, XRD, SEM, EDS/EDX, IR, XPS, CV NMR, Raman Spectroscopy, TEM, Mossbauer, XAFS and CT has helped to understand the mechanisms, rate limiting steps, and the quality of final product, (iv) the application of ionic liquids instead of toxic lixiviates, offers flexibility and choice in selection, depending on the viscosity, conductivity, hydrophilicity, hydrophobicity, polarity, and hydrogen bonding ability, and (v) in the field of e-waste management, the recovery of precious metals and rare earth elements should focus in scaling up hydrometallurgy based technologies from the lab-scale to the semi-industrial and full scale in order to support circular economy in the (urban) mining sector.

### 4.3. Biohydrometallurgy

Biotechnology is an emerging and promising technology to extract metals from primary and secondary resources. The utilization of microorganisms for the recovery of metals is a relatively economical process for recovering precious metals from secondary resources (Garlapati, 2016; Sun et al., 2016). Biohydrometallurgical processing is an alternate route for the recovery of metals, specifically, from low-grade and lean-grade ores, shales, and secondary resources (Anjum et al., 2012).

Biohydrometallurgy consists of two important phases: (i) bioleaching, and (ii) biorecovery. Bioleaching is the mobilization of metals from the solid phase to the liquid phase with the help of microorganisms, by any one of the three mechanisms, i.e., acidolysis, complexolysis, and redoxolysis (Sethurajan et al., 2018). Acidithiobacillus sp. and Leptospirillum sp. are the most studied bacteria for bioleaching metals from low-grade ore and secondary resources. Organic acid-producing fungi have also been reported to have good leaching efficiency. On the other hand, microbial recovery of metals from the leachate can be done either by biosorption or by precipitation. In biosorption, live or dead biomass can be used to adsorb the metals on its cell wall for its own defense mechanism (Sethurajan et al., 2018).

Bioprecipitation is also one of the simple yet useful strategies for the recovery of metals from the leachate. The metabolites produced by the microorganisms react with the metal ions and precipitate the desired metal. A major advantage of bioprecipitation is the possibility of selective recovery of metals from the poly-metallic leachate (Sethurajan et al., 2018; De Michelis et al., 2010; De Michelis et al., 2010). Bio reduction and bioaccumulation have not been studied intensely, but they can also be considered as a potential option for resource recovery. Over the past few years, bio hydrometallurgical strategy has garnered great interest for metal recovery, since it is simple, eco-friendly, and cost-effective (Chen et al., 2015).

In recent years, several studies have reported the possibility of copper extraction from PCB and shredding dusts (Isıldar et al., 2016; Isıldar et al., 2019; Marra et al., 2018). Critical metals such as cobalt could also be successfully bioleached from the waste batteries (Baniasadi et al., 2019; Mishra et al., 2008; Naseri et al., 2019). There are also a few studies that have reported the bioleaching of REE from WEEE (Marra et al., 2018). Precious metals (such as gold) extraction from the electronic wastes has also been reported in many recent studies (Isıldar et al., 2016; Son et al., 2020; Brandl et al., 2008; Rienzie et al., 2019). Heterotrophs such as Chromobacterium sp. and Pseudomonas sp. are known to produce cyanides, and the biogenic cyanides can be used leach out gold from e-waste.

Biohydrometallurgy can also be used in the ex-situ/on-site recovery of heavy metals from contaminated sediments (Fonti et al., 2016). It is noteworthy to mention that, although biohydrometallurgy of e-wastes is a proven strategy at the lab-scale level, it still requires further research at the pilot-scale to reach the required technology readiness level (TRL). The limitations of biohydrometallurgy are that the bacterial leaching method is slow and, unlike other approaches, once the bioprocess is initiated, bioleaching cannot be rapidly stopped.

## 5. SOLVING THE E-WASTE PROBLEM (STEP)

“Solving the E-waste Problem” or StEP is a UN-led initiative launched in 2007 to enhance and coordinate different efforts around the globe in the arena of reverse supply chain (Sthiannopkao, S, Wong, M.H.2013). This initiative includes 35 members worldwide, including businesses, international organizations, governments, non-governmental organizations (NGOs), and academic institutions (Step 2020). Its main focuses are to (i) promote reuse of the recycled materials; (ii) facilitate research, analysis, and dialogue among the concerned parties; (iii) incorporate a comprehensive view of social, environmental, and economic aspects of the design, production, usage, and final disposal of EEE; and (iv) support cooperation between industrializing and industrialized/post-industrialized countries for global solutions (Sthiannopkao, S, Wong, M.H.2013, Step 2020). StEP contributions are mainly guided by five principles, namely: policy, redesign, reuse, recycling, and capacity building. Its idea of redesigning with disposal in mind has had a growing impact (Sthiannopkao, S, Wong, M.H.2013).

## 6. FUTURE RESEARCH DIRECTIONS

Future research directions in resource recovery from WEEE or e-waste can be aimed at new technology development, process optimization, understanding the mechanism of biocatalyst-mediated metal recovery processes, and the use of new materials and chemicals that can facilitate a bio-circular economy. Some of the emerging research topics include, amongst others: (i) decomposition of waste high-impact polystyrene (HIPS) resin from e-waste using supercritical water oxidation process and recovering resources (Li and Xu, 2020); (ii) application of new adsorbents and the selective recovery of precious metals from the leaching solution (Bui et al., 2020) (iii) characterization of the residues/leaching solution generated, risk assessment and toxicity characterization studies for all the pilot-scale demonstration technologies (Sahle-Demessie et al., 2020),(iv) perform cost benefit/economic analysis and develop a life-cycle modeling framework for the treatment and recovery of valuable materials from e-waste (Jaunich et al., 2020), (v) recovery of resources from toner cartridges, batteries and hard disks (Baniasadi et al., 2019), and (vi) the recovery of resources from lamps, small IT equipments, screens, temperature resistant devices through the application of multiple (integrated) technologies, including electrochemical based techniques (Jadhao et al., 2020).

## 7. CONCLUSION

Electronic waste is a rapidly increasing environmental concern, but also a valuable source of recoverable metals. The adoption of circular economy principles and advanced recovery methods such as physical, hydrometallurgical, pyrometallurgical, and biological processes can improve resource efficiency and reduce environmental impacts. Sustainable e-waste management requires technological innovation, effective policies, and responsible recycling practices to ensure environmental and economic benefits.

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