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CONSIDERATIONS FOR RECOVERING VALUABLE MATERIALS FROM ELECTRONIC WASTE

BY

ȘTEFAN LEONTIN MARTINAȘ-IONIȚĂ*,
GABRIELA ANTOANETA APOSTOLESCU and MARIA HARJA

“Gheorghe Asachi” Technical University of Iași, “Cristofor Simionescu” Faculty of Chemical Engineering and Environmental Protection, Iași, Romania

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Abstract. The production of electrical and electronic equipment has increased significantly in recent years because of an increase in consumer demand, yet their life expectancies have shortened as a result of the rapid advancement of technology. As a result, a significant amount of electronic waste (or “e-waste”) is generated every day. Most of these wastes are made up of materials that, if managed improperly, can affect the habitats in which they are placed as well as implicitly the species that inhabit those environments. These wastes typically include refractory oxides, polymers, and metals. If correctly separated and recovered, these materials can have significant economic value. In this study, the primary methods for separating and extracting valuable elements from electrical and electronic trash were evaluated, and the efficiency of these techniques was evaluated in terms of removing the waste. Processes like pyrometallurgical, hydrometallurgical, pyro-physical, and biological have been analysed.

Keywords: e-waste, extraction, environment protection, recovery, valuable metals.

*Corresponding author; *e-mail*: martinasstefan@gmail.com

1. Introduction

E-waste is produced as a result of technological development and a consequent decrease in the average age of electrical and electronic equipment. Metals like aluminium and copper as well as non-metallic elements like plastic, printed circuit boards, and glass are among the numerous recyclable components found in e-waste. For the purposes of resource recovery and material recycling, the classification of metallic and non-metallic fractions in e-waste is crucial (Gundupall *et al.*, 2018). Recycling used electrical and electronic equipment helps to recover valuable materials and lowers the amount of waste that needs to be processed. Electrical and electronic materials are diverse and intricate in terms of the materials and components employed, as well as the waste streams from manufacturing operations. The classification of these wastes is essential for developing a recycling system that is both cost-effective and environmentally (Taurino *et al.*, 2010). According to estimates the annual global production of e-waste is 40 million tons, or 5% of all solid wastes (Vermeşan *et al.*, 2020).

Electronic waste usually includes a variety of materials, like metals, polymers, and refractory oxides (Kaya, 2019). According to Ari (2016), up to 60% of the metal in e-waste can be found among them. As a result, e-waste recycling and resource recovery are crucial (Kaya, 2019; Gundupall *et al*., 2018; Guo *et al*., 2009), lead (Pb), mercury (Hg), nickel (Ni), cadmium (Cd), chromium (Cr), iron (Fe), and copper (Cu) are common metals found in e-waste, along with some precious metals like rare earth metals, Pt group elements, alkaline metals, and radioactive metals. E-waste is deemed dangerous if the amount of metals exceeds the allowable standard. For instance, a higher concentration of Cr might result in disorders of the respiratory system and renal damage (Chen *et al.*, 2011).

Techniques for the recovery of valuable materials from electrical and electronic waste can be grouped according to the nature of the processes used to separate the materials. These can be physical, chemical, thermochemical, pyrometallurgical, hydrometallurgical and biometallurgical methods. These techniques can be used individually or in combination (Dolker and Pant, 2019). The most popular technique for recovering valuable materials from electrical and electronic waste is pyrometallurgy. But this is not the most suitable used in this activity because it uses high temperatures, large amounts of chemicals, pollution resulting from processing is high (dust, toxic gases), that affects health, and determine ecologically problems (Khaliq *et al.*, 2014). Physical recovery methods are considered traditional but they have low efficiency but many methods of technological flow and high energy consumption (Islam and Iyer-Raniga, 2023). Hydrometallurgy is a large range of separation of valuable materials considered to be ineffective from high production costs that come from the fact that to obtain a high yield they are a series of treatment with different types of chemicals and reagents for time (Gorain *et al.*, 2016).

The technique with the most promising results is shown to be that in which several separation methods are used in the same technological flow (hybrid method). Thus, depending on the needs, physical, chemical, and biological methods can be used (Cheikh *et al*., 2010). Thus, the techniques for separating materials from electrical and electronic waste can be based on an objective or a specific separation. In their study, Pant *et al.* (2012), reported the extraction of metals from e-waste by physical and biological extraction and proposed a hybrid method that gives higher efficiency to the separation of metals from plastics in e-waste. Hsu *et al.* (2019) researched and highlighted aspects of the separation and recovery of metals from electronic waste. The purpose of this analysis is to briefly present different methods of separating materials that can be recovered from electrical and electronic waste, but also the recovery of valuable materials that it can contains together with the difficulties, advantages and disadvantages of them.

2. Separation and Extraction Methods

Many valuable products can be obtained from electronic waste, sometimes recycling waste is more profitable than the actual mining process. Table 1 shows some aspects regarding the recovery of some metals from electronic waste.

Table 1

Overview of valuable e-waste recovery employing diferent methods

	Extraction process	Advantages, limitations and observation	Recovery (%)	Ref
Cu	hydrometallurgical method	Expensive and corrosive reagents are required, the yield varies depending on the reaction conditions	60.96% to 69.32%	Zhang *et al*., 2018
	nitric acid leaching	TV board scraps	88.5% to 99.9%	Bas *et al*., 2014
	leaching, purification, and electrolysis	waste printed circuit boards	Up to 99.9%	Xia *et al*., 2023
Zn and Pb	chemical leaching + complexing techniques	High yields can be obtained, but the process is unprofitable	Up to 46% - Zn and 75% for Pb	Cheikh *et al*., 2010
Ga, In and Zn	acid-leaching resin separation and purification	gallium and indium are uneconomical to mine	high recovery value	Li *et al*., 2023
Li and Co	leaching in hybrid system (chemical-biological)	metal recovery from lithium-ion battery	not specified	Dolker and Pant, 2019

Au and Ag	hydrometallurgical process	Process tested at pilot scale	upwards of 80%	Vlasopoulos *et al*., 2023
	Thiosulfate leaching	waste mobile phone printed circuit boards	93.8 % Ag, 99 % Au	Zhang *et al*., 2022
Cu, Ni, Au, Ag, Zn	leaching, solvent extraction and cementation	Waste printed circuit board	high	Rao and Singh, 2023
Ta, Mn, Ni, Ag	hydrometallurgical method	waste tantalum capacitor	high	Agrawal *et al*., 2023

Considering that recycling can be done in several places: (at the point of production, at the point of assembly and at the level of the consumer after the end of the life of the item), it is important to choose the method or the combination of methods that bring the greater economic benefits and for the environment. The recovery of materials from electrical and electronic waste presents a potential economic source, various techniques for the recovery have been developed and used (Chakraborty *et al*., 2022). The sustainable recovery of valuable materials requires the use of two main extraction processes. These are represented by processes that will separate the materials subject to recycling into two classes of materials, metals, and non-metals.

Physical extraction processes

The main purpose of this process is to separate the non-metallic fractions from the metallic ones without losing the valuable metallic fractions. Physical properties of particles such as size, shape, specific gravity, magnetic properties, and others are used to separate non-metallic particles from metallic ones.

In the recovery processes three physical extraction techniques are most often used, which are particle shape separation, electrostatic separation and magnetic separation (Fig. 1) (Chakraborty *et al*., 2022; Hsu *et al*. 2019).

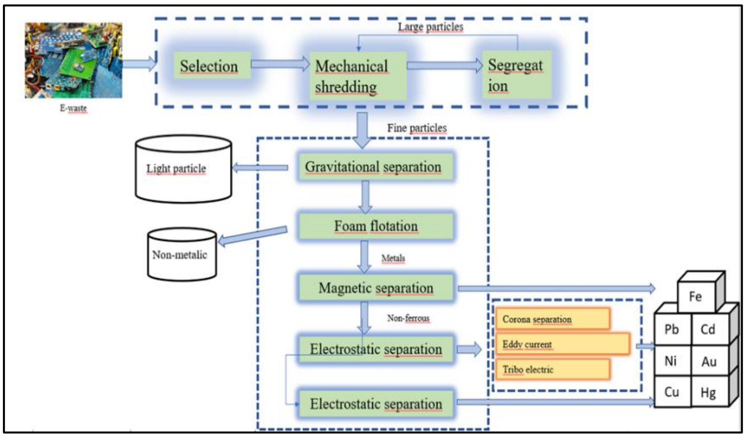

Fig. 1 − Physical methods for recovering valuable materials from electrical and electronic waste.

Physically recovering valuable materials is common since it requires only minor exploitation, little pollution, and low startup and operating costs (Kaya, 2016). This recovery process is widely used, although it is most frequently used as a method of pretreatment to recover valuable metals from electrical and electronic devices. Physical separation can achieve separation efficiency of up to 99% (Kaya, 2016), however this percentage can be increased by using the preparatory techniques of cutting, chopping, trimming, and striving. Several types of machinery, such as tocsin', pregranulating, and granulating machines, are used to carry out these processes (Dalrymple *et al.*, 2007; Debnath *et al.*, 2018).

Sorting refers to any systematic organization of articles and has two distinct meanings: categorizing and grouping objects with comparable properties into a single category in accordance with predetermined criteria. It is a preliminary separation process for components containing electronic metals, such as printed circuit boards (PCBs) or electrical and electronic equipment (DEEE) (Yamane *et al.*, 2011). The recycling of electronic waste involves both manual and automated processes (Chi *et al.*, 2011). New technologies are equipped with intelligent sorting equipment, sensors that can see the shape of objects, and robotized technologies that can increase the efficiency of these processes (Laszlo *et al.*, 2019). In order to separate electrical components from the PCB, Lu *et al*. (2022) created an intelligent sorting system that works in an environment of inert nitrogen and is controlled by a newly designed image detection algorithm.

The process of separating small particles from those with larger dimensions by using a site is known as sieving. Sieving is a technical tool used to establish the dimensions so that it can be used in a specific subsequent process in accordance with those dimensions as well as to increase the metal content of the feed metal. Electric and electrical equipment is used to rotate screens or tramlines during the recycling of desecrated objects (Kaya, 2016). Gravity separation works based on differences in specific densities of metals. This process has an efficiency of about 95% (Eswaraiah *et al.*, 2008). This technique also depends on the size of the waste. Separating metals from plastics is relatively easy and can be done using heavy liquids. The Mozley concentrator (Fig. 2) is one of the most widely used concentrators.

Another gravity separation method is the separation of suspended powders when they pass through an air current. Thus, the particles can be separated using density differences. In this process, two forces are used: gravitational force and traction force, they act in opposite directions from each other (Hadi *et al.*, 2015). This separation technique is very widespread in the electrical and electronic waste processing and recycling industry because it mainly contains plastics with a density of less than 2.0 g/cm^3, light metals with a density of 2.7 g/cm^3 and metals (such as Pb, Cu, Sn, Au, Ag, Ni) that have density greater than 7 g/cm^3 (Veit *et al.*, 2014).

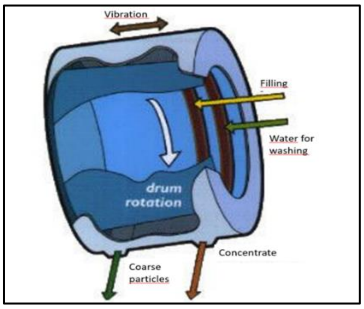

Fig. 2 − Mozley concentrator.

Magnetic separation is used to separate magnetic particles (Fe, Ni, Co) from non-magnetic particles (Hsu *et al.*, 2019). The design and operating procedures describe several advantages for high intensity magnetic separation, the main advantage being that permanent magnets are used to create a strong magnetic field for efficient extraction. The low efficiency of this method is due to agglomeration of metal particles on the surface of the magnetic surface (Yamane *et al.*, 2011).

Electrostatic separation

This method involves separating materials from electrical and electronic waste based on their conductivity or resistivity. Based on this property (electrical conductivity), several methods of metal separation are highlighted such as corona electrostatic separation, triboelectric separation and eddy current separation. Electrostatic corona separation is one of the most efficient methods for separating metallic from non-metallic materials (Qiu *et al.*, 2020). The performance of this method is influenced by the electrode system, rotation speed, humidity and particle size (Chakraborty *et al.*, 2022). However, this separation method is ineffective when the metals have the same electrical conductivity properties, thus the triboelectric separation method or eddy current separation can be used. These are considered more advantageous in terms of recovery percentage because they can separate both fine and larger particles (Hsu *et al.*, 2019).

Pyrometallurgical methods

Metals can be recovered by this method using very high temperatures. Thus, pyrometallurgy involves melting or incineration in a blast furnace or plasma arc furnace or by reaction at high temperature in the gas phase (Lee *et al.*, 2007). In these processes the emphasis is on the recovery of metals and not on a separation of the component materials of electrical and electronic waste. The crushed scraps are burned in a furnace or molten bath to remove the plastics. Refractory oxides form a slag phase with the oxides of some metals (Cui and Zhang, 2008). The smelting process involves materials entering the reactor being submerged in a 1250°C molten metal bath that is being stirred by a mixture of supercharged air (up to 39% oxygen) (Ma, 2019). Certain precious metals with

Cu and iron sulfide generated liquid matte by this process in the Cu recovery from e-waste, whereas other metal sulfides oxidized to metal oxides and produced slag (Ramanayaka *et al.*, 2020).

As the converter upgrades the copper content, blister copper is further refined in the anode furnace before being cast into anodes, which can have a purity of up to 99.1%. The remaining 0.9% is made up of recoverable metals including Se, Te, and Ni as well as valuable metals like Au, Ag, Pd, and Pt. These marketable metals are then recovered by electro-refining the anodes (Cui and Zhang, 2008; Thakur and Kumar, 2020). According to Khaliq e*t al.* (2014) study on metal extraction from e-waste, 99.99% of the lead was recovered during the smelting process. The pyrometallurgical method of recovering metals from e-waste has another use (Cui and Zhang, 2008).

Hybrid methods

The hybrid methodology, which combines many technologies, is a more effective and efficient way to recover metals from e-waste (Pant *et al*., 2012). This technique offers a higher extraction efficiency and needs less time. This method may offer a fresh and developing field of metallurgy that could make it easier to remove metals existing in trace amounts from their ores (Pant *et al.*, 2012). Although if biological leaching is a practical way for cost effectiveness, total metal extraction using purely biological methods is occasionally difficult and time-consuming (Ren *et al.*, 2009). Yet, despite these challenges, chemical leaching is a process that is often quick and efficient compared to other methods. Hence, combining various kinds of approaches can lead to more effective outcomes. The hybrid hydrometallurgical and biometallurgical metal extraction methods each offer distinct advantages over others.

Bioaccumulation, bioleaching, biosorption, chemical alterations, and chelation are the primary chemistry principles upon which the hybrid approach for metal extraction operates. Thus, the hybrid technique can follow the processes of separation and recovery of materials such as the flow shown in Fig. 3.

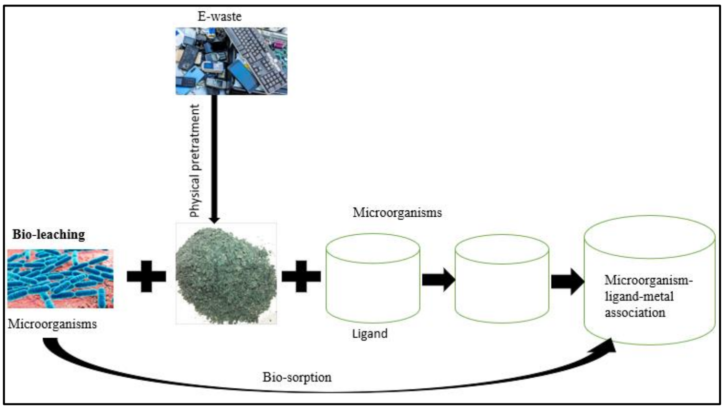

Fig. 3 − The hybrid method of extracting metal.

Comparative analysis of different extraction methods

Cathodic electrodeposition, flotation, electrostatic, magnetic, and gravity separation techniques are among the several physical extraction methods that are extremely effective, while other methods serve as the initial steps in the extraction. Sorting, sieving, or crushing/shredding are frequently used as the first stage in other processes, such as pyrometallurgical, hydrometallurgical, biological, and hybrid ones. Rarely isn't possible to extract metals from e-waste using a certain technology (physical, chemical, hydrometallurgical, or biological) because of the recovery rate, capital investment, environmental impact, and safety and health concerns. To design an effective strategy for metals extraction, an integrated approach (hybrid method) combining two or three processes (for example, combining biological and chemical process) can be utilized.

3. Conclusions

The amount of electrical and electronic waste is increasing daily due to the increasing demand for new electronic devices or the fact that they are designed to work for a shorter period of time and people are becoming more dependent on their use. These devices contain substances that are harmful to the environment, but many of them (metals or plastics) can be reused by applying a proper recovery management of these materials, which also prove to be valuable because they already exist as material and do not require other production costs. Through this recovery process, a better mitigation of the impact of these materials on the environment is achieved. The processes of separation and recovery of these materials are different both from the point of view of the methods applied, which can be harsher or gentler on the environment, and from the point of view of economic efficiency. The researchers analysed all these aspects and concluded that none of these methods can be considered ideal from an economic and ecological point of view at the same time. Thus, they seek to develop a technological flow that provides a balance between the mentioned factors. It was concluded that biochemical and biochemical processes have the highest performances, but research in this segment is ongoing and more future research is needed because electrical and electronic waste, at a global level, is a problem that must be followed by very close to both ordinary people and governments.

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RECUPERAREA MATERIALELOR VALOROASE DIN DEȘEURILE ELECTRONICE

(Rezumat)

Una dintre activitățile globale de producție cu cea mai rapidă rată de creștere este producția de echipamente electrice și electronice. Deșeurile de echipamente electrice și electronice au crescut ca urmare a acestui progres. Atât consumul, cât și producția de

deşeuri electrice şi electronice, care pot fi o sursă de deşeuri periculoase care pun în pericol mediul şi împiedică progresul economic durabil, au crescut ca urmare a expansiunii economice rapide, a urbanizării şi a cererii în creştere a consumatorilor. Multe națiuni şi organizații au elaborat legislație națională pentru a îmbunătăți reutilizarea, reciclarea şi alte forme de recuperare a materialelor din deşeurile electrice şi electronice pentru a reduce cantitatea şi tipurile de materiale aruncate în gropile de gunoi. Acest lucru se face pentru a aborda potențialele probleme de mediu care ar putea rezulta din gestionarea necorespunzătoare a deşeurilor.

Reciclarea echipamentelor electrice şi electronice uzate ajută la recuperarea materialelor valoroase şi reduce cantitatea de deşeuri care trebuie procesate. Materialele electrice şi electronice sunt diverse şi complexe în ceea ce priveşte materialele şi componentele utilizate, precum şi fluxurile de deşeuri din operațiunile de producție. Clasificarea acestor deşeuri este esențială pentru dezvoltarea unui sistem de reciclare care este atât rentabil, cât şi ecologic. Conform estimărilor producția globală anuală de deşeuri electronice este de 40 de milioane de tone, sau 5% din toate deşeurile solide. Plumbul (Pb), mercurul (Hg), nichelul (Ni), cadmiul (Cd), cromul (Cr), fierul (Fe) şi cuprul (Cu) sunt metale comune găsite în deşeurile electronice, împreună cu unele metale prețioase.

Tehnicile de recuperare a materialelor valoroase din deşeurile electrice şi electronice pot fi grupate în funcție de natura proceselor utilizate pentru separarea materialelor. Acestea pot fi metode fizice, chimice, termochimice, pirometalurgice, hidrometalurgice şi biometalurgice. Aceste tehnici pot fi utilizate individual sau în combinație. Cea mai populară tehnică de recuperare a materialelor valoroase din deşeurile electrice şi electronice este pirometalurgia. Hidrometalurgia reprezintă o gamă largă de separare a materialelor valoroase considerate a fi ineficiente din cauza costurilor ridicate de producție. Tehnica cu cele mai promițătoare rezultate se arată a fi aceea în care se folosesc mai multe metode de separare în acelaşi flux tehnologic (metoda hibridă).