Review

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Nallely Guadalupe Picazo-Rodriguez * , Gabriela Baltierra-Costeira , Ma. De Jesús Soria-Aguilar , Zeferino Gamiño-Arroyo , Norman Toro , Jesús R. De la Garza de Luna , Francisco Raúl Carrillo-Pedroza *

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E-waste Recycling: An Overview of Hydrometallurgical Processes Used to Metals Recovery

Nallely G. Picazo-Rodríguez [1,*], Gabriela Baltierra-Costeira [1], Ma de Jesús Soria-Aguilar [2], Zeferino Gamiño Arroyo [3], Norman Toro [4], 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 25701, México
2 Facultad de Metalurgia, Universidad Autónoma de Coahuila, Monclova 25710, México
3 Departamento de Ingeniería Química, División de Ciencias Naturales y Exactas, Universidad de Guanajuato, Guanajuato, 36050, México.
4 Faculty of Engineering and Architecture, Universidad Arturo Prat, Iquique 1100000, Chile
* Correspondence: raul.carrillo@uadec.edu.mx; nallely.pr@monclova.tecnm.mx

Abstract: Currently, with the rapid growth of the population, the demand for metals has increased, especially for the manufacture of electronic devices such as cell phones, computer equipment, among others. Once these devices stop working, most are sent to landfills, which represents a danger since these wastes contain metals and other materials that must be properly managed to prevent them from having a negative effect on the environment and the human being. On the other hand, e-waste contains valuable metals such as copper, gold, and silver, the concentration of which in these materials makes it cost-effective to recover. This paper presents a review of the extraction and recovery of valuable metals from electronic waste by hydrometallurgical methods, as well as patents and industrial processes related to the management and treatment of this waste.

Keywords: Recycling; E-waste; hydrometallurgy; valuable metals; extraction; recovery

1. Introduction

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

As reported by Cui & Zhang, the copper content in electronic waste ranges from 20% while in primary metallic resources from 0.5 to 1%, derived from the above, it is profitable to develop feasible and environmentally friendly methods to recover these metallic values [2].

The treatment of electronic waste is an issue that has gained relevance in recent years, especially in developed countries. On the other hand, these will become an important source of metals, especially when the primary sources are running out. [3].

Electronic waste has increased significantly in all regions of the world because the use of electronic devices and equipment occurs massively in the different sectors of human life (industrial, services, economic) [4]. According to Forti et al., the consumption of electrical and electronic devices is strongly linked to the development and economy of countries, this type of device is essential in society since it improves the quality of life, however, for its manufacture a large amount of resources, according to these researchers, in 2019 globally 53.6 Mt of electronic waste was generated (7.3 kg per capita) and it is expected that by 2030 74.7 Mt of waste will be produced, almost double what was generated in 2019 [5]. Dehchenari et al., mentioned that computers, televisions, 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 [6].

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Nowadays, industrial waste is generally incinerated, which is detrimental to the environment due to the large number of metals it contains [7]. As reported by Akcil et al., the incineration and thermal treatment of e-waste have raised concerns because organic pollutants are emitted during these processes, which can cause serious problems due to their toxicity [3]. However, some researchers have found that recovering metals from these wastes could be more economical than extracting them from their primary sources [8].

As reported by Cui & Zhang, PCBs are the components of electronic scrap that have the highest number of valuable metals, around 3300 ppm Ag, 80 ppm Au and 26.8% Cu [2]. Au and Ag must occur on PCBs as native or alloy forms, mainly coated on the pins and holes of electronic components and the board, or inside microprocessors [9]. Hsu et al., mention in their research work that represent 3% of the total mass of electronic waste worldwide and their structure consists of a copper-coated fiberglass and resin laminate. [10].

To obtain an optimal extraction of gold and silver, it is necessary to eliminate the common metals already described and thus avoid the extra consumption of reagents that would be generated by their presence. Derived from the above, Jiménez & Pinilla analyzed the extraction of copper from computer PCBs through the leaching process with inorganic acids and determined that these reagents dissolve other metallic elements such as iron, nickel, lead, and zinc, generating consequently an increase in the concentration of gold from 131.29 g/ton to 345.9 g/ton and silver from 310 g/ton to 864.8 g/ton [11].

To recover valuable metallic elements from electronic waste, these are dismantled and shredded to separate non-metallic elements [12–15]. Subsequently, the recovery of the metals can be carried out through the pyrometallurgical route or the hydrometallurgical route [16]. The pyrometallurgical process involves the incineration, sintering and melting of waste at high temperatures and is efficient in the recovery of metals such as Ti, Zr, Nb, Ta and Mo [7]. However, the recovery of precious metals from electronic waste through the hydrometallurgical route is more attractive because it is cheaper and easier to implement [6].

2. Hydrometallurgical processes: extraction and recovery from electronic waste

The hydrometallurgical process involves chemical reactions carried out in aqueous or organic solutions, it involves steps such as leaching, concentration/purification of metals and recovery, this presents advantages such as the ability to control the level of impurities, low investment cost, lower environmental impact, and high metal recovery potential [7]. If the hydrometallurgical route is to be followed sulfuric acid is used to leach the copper, which is recovered from the solution [17].

It has been observed that, in the case of acid leaching of copper, the use of H2SO4 has made it possible to extract copper in high quantities, in addition to other heavy metals [18]. Park et al., determined that the efficiency of the sulfuric acid leaching process increased with increasing agitation speed, temperature, oxygen flow and initial Cu2+ and established the following as optimal parameters: sulfuric acid concentration (1 mol/L), temperature (90 °C), stirring speed (600 rpm), pulp density (1%), initial copper concentration (10,000 mg/L) and oxygen flow (1000 mL/min) [19]. Dávila-Pulido et al. carried out copper leaching in a 2 mol/L H2SO4-H2O2 0.2 mol/L system, which allowed the copper in the electronic waste samples to completely dissolve [20]. Some researchers have used the H2SO4 and H2O2 leaching system using recirculated solution for up to 5 cycles, managing to reduce acid consumption by 60% [21]. Other acid media that have been used to extract copper is ferric chloride with hydrochloric acid. Barragan et al. used this leaching system to extract copper and antimony from PCBs and later recover them by electrodeposition, managing to obtain 96 % copper and 81% antimony [22].

Wstawski et al., studied the effectiveness of a new leaching system consisting of ionic hydrogen sulphate liquids to dissolve copper from PCBs, their study showed that copper could be leached in large quantities, but with the presence of an oxidant such as H2O2 [23]. In other works where ionic liquids of hydrogen sulphate and hydrogen peroxide were used, they found that the particle size had a great influence on the process [25].

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Other researchers, such as Kavousi et al., used hydrogen peroxide in a HBF4 leaching medium to extract copper at the same time as the solder alloy, managing to extract 99.99% of copper [26]. On the other hand, Segura & Lapidus used hydrogen peroxide in combination with an environmentally friendly leacher, in this case sodium citrate, additionally added ammonium phosphate as a chemical inhibitor to avoid the co-dissolution of base metals, achieving leaching with high copper concentrations (greater than 30 g/L) [27].

On the other hand, other methods have been used to leach copper such as Kim et al., who used electrogenerated chlorine in hydrochloric acid solution, who developed their experiments in two types of reactors, in one of the experiments it was carried out in a reactor a generation of chlorine simultaneous to the leaching of copper and in another experiment two reactors were used, in one the chlorine was generated and in the other the copper was leached, obtaining better results in the separate reactors, achieving a recovery of copper from the 71% together with 98% zinc, 96% tin and 96% lead using a 2 mol/L HCl solution at a current density of 714 A/m2 , 323 K and 400 rpm in 240 min [28]. After leaching copper from electronic waste, the residue of this process is leached to recover the precious metals [17]. The most used chemical reagents during the leaching of precious metals are cyanide, halides, thiourea, thiosulfate, EDTA, oxalates, aqua regia, sodium hypochlorite, nitric acid, ferric chloride, organic solvents [7].

According to Akcil et al., 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 a leaching agent effective, economical, and easy to implement, however, its use implies applying a treatment to the effluents generated in the recovery process. In this sense, in addition to the use of cyanide, several non-cyanide leaching processes have been developed considering the toxic nature and the handling problems of cyanide with non-toxic leaching such as thiourea, thiosulfate, aqua regia and iodine. Therefore, various recycling technologies have been developed using cyanide or non-cyanide leaching methods to recover precious and valuable metals (Akcil et al., 2015) [3].

An example of a process for recovering precious metals from electronic waste through the hydrometallurgical route was implemented by Mudila et al., who treated circuit boards contained in mobile phones, the process they carried out was mechanical grinding to produce powdered samples and delaminated fractions, researchers such as Kaya (2016) recommend a sample size of 150 µm. Two-stage acid leaching consisting of dissolving copper with 3 mol/L nitric acid at 30 °C and extracting gold with a tertiary amide extractant [29].

Torres & Lapidus , investigated the recovery of gold from electronic waste material with a high copper content under ambient conditions, they considered carrying out a chemical treatment before extracting the gold, for which they used inorganic acids (HCl, HNO_3 and H2SO4), organic substances (EDTA and citrate) and oxidants (air, ozone and hydrogen peroxide), obtaining copper extraction of more than 90% of copper in pre-treatments with peroxide and HCl or citrate. For the leaching of the gold, they used thiourea, managing to recover more than 90% of the gold after one hour of testing (Torres & Lapidus, 2016) [30]. Table 1 shows a review on the leaching of electronic waste with cyanide and leaching considered as "green".

Table 1. Electronic waste leaching processes using cyanide and alternative leaching to cyanidation.

Treated sample	*leaching medium*	*Preparation of sample*	*Conditions*	*% Recovery metals*	*Reference*
PCBs	Glycine	pulverized feed	Glycine=0.5 mol/L, 250 ppm NaCN , pH=10.2, t=72 h, O_2=environmental	Au=2%, Ag= 2%, Pb=16%, Cu=96.5%, Al=12.6%, Ni=9.3%, Zn=92.5%, Co=3.1%	[31]
PCBs	Sodium ammonium	Particle size less than 1 mm	1. Preparation of 1:3 nitric acid. 2. Sodium ammonium	1. Nitric acid=100 Ag. 2. Sodium ammonium thiosulfate=15% Au	[32]

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	thiosulfate	obtained in a blade mill	thiosulfate 0.1 mol/L, pH=9.5-11, S/L=1:20		
PCBs	Sodium ammonium thiosulfate and cyanide based pickling solution	Intact PCBs were used	Sodium and ammonium thiosulfate 0.12 mol/L, t=4 and 24 h, T=30 °C, pH=10	Cyanide base pickling solution=88% Au, sodium ammonium thiosulfate=75% Au	[33]
PCBs	Sodium thiosulfate	Crushed and toasted material at 800°C	1. 4.0 mol/L HNO_3 at 40 °C for 6 hours to dissolve copper from plate dust up to 1%. no. 2., 0.7 mol/L Sodium thiosulfate, 5% solids, $[Na_2S_2O_3]$ = 0.7 mol/L, pH = 10.5, shake=6h, T=25 °C.	81% gold, 88% silver, 32% copper	[34]
PCBs	Cyanide solution for characterization and sodium ammonium thiosulfate	Intact PCBs were used	123.5 g/ton Ag. 0.1 mol/L thiosulfate and 0.2 mol/L ammonium hydroxide, 0.1 mol/L H_2O_2	1. Commercial cyanide: 86.23 g/ton of Au. 2. Sodium ammonium thiosulfate=11% Au	[35]
PCBs	Thiourea	PCBs less than 106 microns	1 mol/L H_2SO_4 and 0.25 ~~M~~ mol/L thiourea	17.3% Au and 49.5 % Ag	[36]
PCBs	Thiourea	100 mesh size	24 g/L thiourea, Fe^{3+}=0.6%, T=ambient, t=2 hours	90% Au, 50% Ag	[37]
PCBs	~~I~~Iodine-iodide	PCBs incinerated at 800 °C	Iodine-iodide ratio=1:6, pulp density=10%, stirring speed=500 rpm, T=40 °C, t=24 h	99% Au, 1% Ag, 1% Pd	[38]

PCBs	Iodine-iodide	Particle size less than 0.75 mm	I_2=8 mmol/L, KI=70 mmol/L, H_2O_2=30 mmol/L	31.5% Au	[39]

The table above shows hydrometallurgical processes under acid and alkaline conditions. In the case of the processes carried out under basic pH conditions, we can see that leaching media such as cyanide, glycine, sodium, and ammonium thiosulfate are used. In the case of glycine, Huan et al. used it for the extraction of copper under alkaline conditions. These researchers mentioned that the first step is a good preparation of the sample, since metallic values can be trapped in the weld, so they recommend a pre-treatment prior to spraying with HNO3. On the other hand, in alkaline conditions it is found in solutions as glycinate ion (H2NCH2COO-), which can form complexes with cuprous (Cu+) and cupric (Cu2+) ions when in the presence of an oxidant such as ambient O2 at room temperature. However, simultaneously in the process base metals such as Ni, Al, Sn, Zn, Co is extracted, whose extraction is favored under alkaline conditions. In the case of gold and silver, its extraction does not exceed 2%, since it would need a catalyst such as cyanide, which could be mixed with glycine in minimum permissible proportions to be recovered. This would have to be after having recovered the copper and other base metals since they are related to cyanide [31].

On the other hand, acid leaching in the presence of an oxidant such as H2O2 has been used for the leaching of copper, gold, and silver [32]. Petter et al., determined that nitric acid can dissolve up to 100% of the silver contained in PCB residues and using aqua regia they were able to dissolve 882 g/ton of gold and 417.9 kg/ton of copper, in the case of silver, a low recovery was obtained since it tends to form AgCl which is an insoluble compound. 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 [32].

Batnasan et al., used 1 mol/L thiourea and 0.25 mol/L H2SO4 at acidic pH, achieving a 17.3% and 49.5% Au and Ag dissolution, respectively. These authors found that a high redox potential and acidity of the solution produce an increase in the leaching of Au and Pd, in contrast to a decrease in Ag leaching [36]. Jing et al., determined that the thiourea gold and silver leaching process can be optimized by decreasing the particle size, because there is better exposure of gold and silver to the reagent. These researchers managed to extract 90% gold and 50% silver from PCB samples using the following conditions: 24 g/L solution of thiourea and Fe3+ at room temperature and 100 mesh particle size, despite having good results, they mention. that the thiourea process is expensive compared to conventional processes such as cyanidation [37]. 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 [38].

Petter et al., used sodium and ammonium thiosulfate, however, they did not obtain positive results since they reached a maximum gold extraction of 15%, and they concluded that more than one leaching agent is needed to extract all the metals from the PCBs (Petter 32). Kasper & Veit also treated intact PCBs using sodium and ammonium thiosulfate, achieving 70 and 75% of the gold respectively, which they attribute to the size of the PCB samples since, according to their research, the use of intact PCB samples inhibits the dissolution of base metals, whose release is favored by grinding and once in solution they compete for the leaching reagent with gold [38]

On the other hand, Gamez et al., found that dissolving copper with nitric acid before carrying out leaching with thiosulfate improved the recovery of gold and silver, reaching an extraction of 81 and 88% respectively (Gamez 34). With the addition of H2O2 to the thiosulfate system a slight increase in the extraction of gold and silver can be achieve [35]. When the base metals are completely separated, gold recovery is greatly improved, and cyanide also achieves efficient gold recovery. According to Birich et al, thiosulfate and thiourea are less sensitive than other leaches to metallic impurities, however, when these are removed from PCBs, gold recovery improves [39]. Based on the above, it could be determined that the leaching of PCB samples at acidic pH, although it gives good

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results, presents the drawback of high cost of reagents and toxicity. On the other hand, glycine is an alternative that offers advantages such as low cost, friendly to the environment, in addition, it can be used in two stages, in one the base metals and the work can be eliminated, and in a second stage it is they can add a small amount of cyanide that would work as a catalyst to extract metals such as gold and silver

According to some researchers, the recovery of metals from the solutions generated from leaching processes can be carried out through different methods, among which stand out; solvent extraction, ion exchange, adsorption, precipitation and cementation, the choice of method depends on the characteristics of the electronic waste and the solution from leaching [2,16]. Examples of some metal recovery work from e-waste leach solutions are shown in Table 2.

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

Treated sample	*Recovery method*	*Conditions*	*% Recovery of valuable metals*	*Reference*
Thiosulfate leach solution	Solvent extraction (SX) and electrowinning (EW)	LIX984 N with kerosene for copper	SX Cu = 92 %, EW Cu =99%, EW Au=87%	[40]
3M nitric acid solution used for Cu and 3 mol/L H_2SO_4 and Sodium Bromide solution used for Au.	Solvent Extraction (SX)	ACORGA M5640 dissolved in kerosene and Tertiary amide extractant 0.1 mol/L dissolved in toluene.	Cu=99%, Au=99.9%	[41]
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	Cu=90%	[42]
Mixture of chlorate and chitosan in HCl	Adsorption	Chitosan granules cross-linked with glutaraldehyde (GCC) were used as adsorbent at a dose of 1g/L.	Au=100%	[43]
Leaching solution with hydrophilic quaternary salts from a CPU	Precipitation	Tetrabutylammonium based salts were added	Au=91.4 %	[44]
16% HCl leach solution	Cementation	Iron powder was used in a 1:1 stoichiometric ratio at room temperature.	Cu=85%	[45]

Murali et al., used the extractant LIX984 N with kerosene and determined that there are two parameters that significantly influence the solvent extraction of copper; the pH, whose increase can increase the formation of complexes with the extractant, so they recommend carrying out the process below pH 2, to avoid the risk of coprecipitation of other metals. In addition to pH, these researchers recommended carrying out copper recovery at room temperature, since by increasing the temperature from 30 °C to 45 °C they noted a decrease in copper extraction, from 94 to 87 % [40]. Rao

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et al., used the solvent extraction method with the ACORGA M560 reagent in kerosene to recover copper and gold, they found that the best pH to carry out the process was 1 to 2.5, which coincides with as established with Murali et al., with the extractant in a ratio of 1:1, pH2 and 4 mol/L H2SO4 as extraction agent, they managed to recover 99.9 % of copper. As for gold, the use of a secondary amide allowed them to recover 99% of gold [41].

Nekouei et al., mention that another option for the recovery of metal ions from leaching solution is the sorption process, which is efficient and easy to operate, using an ion exchanger that is commonly a porous resin [42]. On the other hand, Mahapatra et al., proposed that cementation was an efficient method to recover copper, they managed to recover 90% of which they cemented with iron. Additionally, they recovered Al (5.8 %), Co (0.8 %) and Ni (1.5 %) [45], other authors have proposed that the precipitation method is an effective and economical option for the recovery of metals, since using a precipitating agent they can be separated by stages [45].

According to Hsu et al., the 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 the combination of individual electrowinning steps, to carry out this process takes advantage of the differences in potentials, E(V) [10]

The mentioned recovery techniques are effective; however, each has its advantages and limitations. In the case of the solvent extraction technique, some disadvantages are that a wide variety of additives are required. In cementation, in addition to the high consumption of reagents, the coprecipitation of base metals occurs. During the ionic exchange there is the drawback of the regeneration of the adsorbents and during the electrowinning the metals obtained are of high purity, but a disadvantage of the process is the high energy consumption.

3. Patents and industrial processes

According to Arya & Kumar, urban mining has recently gained significant relevance because it offers a commercial, economic, social, and environmental opportunity. According to these researchers, many developed countries have e-waste management technologies, know-how and systems in place [46]. Developed countries export this waste to developing countries [47]. Arya & Kumar refer to the country of India in which there are still no adequate waste management services, mainly collection, which makes it difficult to implement industrial processes for its treatment because the estimation of the generation of electronic waste must be consistent. On the other hand, they mention that the electronic waste management model in China is one of the preferred methodologies which consists of collection, recycling, and recovery of values [46].

As mentioned above, millions of tons of electronic waste are generated every year, so recycling it is important for environmental protection. Current industrial processes for the treatment of these materials involve dismantling and granulation to grind materials from 0.17 mm to 5 cm, which are used to recover plastics and non-ferrous materials. Additionally, industrial-scale circuit board recycling machines have been implemented that use drum-type screwdrivers to separate metals such as copper from other components [48]. Table 3 shows some industrial processes applied for the recycling of electronic waste.

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Table 3. Industrial processes for recycling electronic waste.

Company	*recovered items*	*Types of electronic waste*	*recovery method*	*Establishment date*	*Birthplace*	*Reference (URL)*
Sun technology (Electronic recycling) ISO certified and follows R2 standards	Plastics, ferrous and non-ferrous materials;	General scrap	On-site dismantling (Safe and ecological)	2008	Canada	[49]
Eco-clean (Environmental Services) Certification ISO 9001:2015 ISO 14001:2015	Ferrous and non-ferrous metals, plastics.	Industrial scrap	All rights reserved	25 years	Mexico	[50]
Recupera (Recycling Centers) Support with Jornada Reciclatrón . Authorized by SEMARNAT	Ferrous and non-ferrous metals, cathode ray tubes (CRT), plastics.	Electronic cards, data processing units, monitors (LCD), computer equipment, household appliances.	Separation of waste for recycling sent to other companies	40's	Mexico	[51]
E- Waste Solutions, SA de CV Authorized by SEMARNAT	All rights reserved	Industrial and private scrap	Smelting, crushing or confinement as established by NOM-161	2020	Mexico	[52]
Mint Innovation (Clean Tech)	Gold, copper and silver	General scrap	Technology from a biological process	2020	New Zealand	[53]
Evernex (Life services)	All rights reserved	Electrical and electronic waste	Hardware and software recycling	37 years	Mexico	[54]
SA recycler CV Authorized by SEMARNAT SEDEMA SEDESU	All rights reserved	Industrial and private scrap	Recycling of a wide range of all types of e-waste	30 years	Mexico	[55]

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Relmex Group Experts in electronic recycling Authorized by SDS SEMA	All rights reserved	General scrap	Valuation and recycling Management of electronic waste with NOM-161-SEMARNAT-2011	2020	Mexico	[56]
MAC Ecological Group Authorized by SERMANAT SE Certification ISO 18001:2007 ISO 14001:2004	All rights reserved	Desktop computers. Laptops. Cell phones (smartphones). tablets.	Collection and destruction	20 years	Mexico	[57]
Revertia in IQ NET	All rights reserved	Computers, laptops, screens, mobiles, printers, hard drives	Waste treatment to convert it into a new resource	10 years	Spain	[58]

In Table 3 we observe companies dedicated to the field of electronic waste recovery by different methods and obtaining, in which they carry out a complete evaluation of their organization by mostly creating a strategic plan that promotes the environmental commitment of their organization, focusing on effective solutions. Each one has an initial handling process, normally they go to the facilities to collect the waste and complete the entire process safely: in-formation processing, repurchase, recycling, deletion, disposal, certification, etc. Granting regulatory advice and processing of all the necessary documentation to understand the obligations as a producer of WEEE complying with certifications, recognitions, awards, medals and endorsed by entities for the proper use of electronic waste.

Notably, Mint Innovation's recovery process uses only 2% of the energy and water per kilogram of gold compared to conventional mined resources and more than $80 billion worth of valuable metals are discarded in waste streams each year. industrial and consumer [53]. Industrial processes provide security, ethics, trust, financial and personalized solutions for each user, public or private organization, providing not only the treatment and recycling of WEEE but also the future use of waste, providing good news for the planet and enhancing brand image with high green scores sought after by investors.

The extraction of metals from electronic waste can be dangerous [59], it is important that in this type of industrial operations personal protective equipment is used and to minimize the presence of dust in the air through dust col-lector systems, since the recycling of electronic waste exposes workers to toxic metals, in a study carried out by Grava et al., six electronic and commercial recycling facilities were investigated for which they measured metal exposure, finding the presence of metals such as lead, beryllium, mercury, arsenic, barium, cadmium and chromium. in the blood of the workers, as

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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 [60].

Regarding the business models that involve the treatment of electronic waste, Marconi et al., that many related industries operate as isolated systems that are not related to other production chains, which generates a loss of a consistent residual economic value, a solution proposed by these researchers is to implement an industrial symbiosis system [61]. According to Zeng et al., an eco-industrial park is the management of the practical application of a supply chain at the industrial park level [62]. Park et al., carried out a review of the first phase of the National Ecological Program of South Korea, which consists of the development of an industrial park, one of the axes of this program was to achieve industrial symbiosis and the main focus was to bring together interested parties from companies, governments and research centers, these researchers mention that the joint work of these three figures allowed the development of industrial symbiosis projects, which brought incalculable benefits to the environment, such as the re-duction of greenhouse gases that reached 51% of the established objective [63].

The recycling industries are looking for alternatives to reduce the environmental impact and the operation of a business model; In addition to this, in Table 3 it can be seen companies dedicated to the field of electronic waste recovery by different methods and obtaining, such as ferrous, non-ferrous and in turn precious metals. In general, most provide advice, maintenance and services to a variety of users; which are diverse in size and nature and include private companies, government agencies and international aid agencies; the concerns are varied, they approach each project as a partnership and make sure to offer each user a personalized service, independence and confidentiality, a large part of these have global locations as well as certifications, awards and medals for their commitment to Quality, Safety and Environment. Some companies offer to develop and implement intelligent, professional, innovative, financial, and sustainable solutions to effectively achieve the objectives of environmental protection and responsibility of our environment.

Today the academy and the industry have combined theoretical and practical knowledge to provide practical solutions for society, which is reflected in the publication of research and registration of patents, this in the long term will allow the transformation of a linear vision to a circular one about waste management [64]. Table 4 shows some of a recent patent that have been implemented for the treatment of electronic waste.

Table 4. Related patents electronic waste recycling.

Patent Number	*Patent Title*	*Invention*	*State*	*Country*	*Date*	*Reference*
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	[65]
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	Application	Mexico	November 2019	[66]

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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	[67]
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	[68]
US202217583385 A	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	[69]
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	[70]
US11608544B2	Recovery process from electronic waste	Use of biohydrometallurgica l techniques; microorganisms	Granted	USA	March 2023	[71]
CA3189365A1	Method for the recovery of metals from electronic waste	Obtaining metals from group 8 to 14, particularly Cu; by means of a smelting	Earring	Canada	January 2022	[72]

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		reactor and 5 steps during the process				
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 2023	[73]
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	[74]

In the invention carried out by Alarcón et al. Reference is made to an ionic solution that implies a low environmental and energy impact for the recovery of Au and Cu from Printed Circuit Boards (PCI) from electronic waste. Said solution is made up of inorganic salts as a leaching mixture to recover the metals. With which an Au/Cu precipitate is obtained, this methodology offers an innovative alternative to the existing ones for the recovery of these metals, with the advantage of having fewer toxic residues than traditional processes [65].

On the other hand, Berrueta et al., focused on non-ferrous metals obtained from electronic scrap through a physical-mechanical refining due to its multiple processes, they formed a production line made up of different mechanical and wind equipment, the process consisted of four stages, the first consisted of reduction, pre-cleaning and cleaning of light polluting materials, during the second stage the heavier materials such as ferrous and other contaminants were eliminated, the third stage which consists of drying and a size homogenate and the fourth stage which is final cleaning and classification [66].

Zhang Hengwang et al., provide in their invention a clean treatment method to efficiently recycle beneficial sub-stances in electronic waste (WEEE), thus achieving clean treatment and saving resources without generating secondary pollution; it also shows a completely new treatment technology and a completely new processing device, which can almost completely recycle all useful substances in e-waste except filters, and does not produce secondary pollution in the treatment process. 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 [67].

According to Minjie et al., in the invention they refer to pyrolysis to treat electronic waste (WEEE), to systems and methods. The system consists of a material treatment system, a metal recovery system, and an organic matter reaction system, where the material treatment system consists of grinding equipment and classifying equipment; the metal recovery system consists of an acid leaching tank and an electrolytic tank; the organic matter reaction system consists of an electronic waste pyrolysis reactor, a heat accumulator type gas fuel heating system, and a refrigerant separation system. Therefore, according to the system, the goal is the recovery of metals in e-waste, the pyrolysis recovery process of non-metallic parts, and the effective resources in e-waste are fully utilized [68].

Lynn et al., in the present invention mention a two-step method for recovering gold from electronic waste (WEEE), in a first step using a solution containing a weak acid in combination with an oxidant. The second step isolates and purifies the delaminated gold from chip debris using solvents, water, and a wetting agent/surfactant which is effective without the need for leaching or harsh or expensive chemicals [69].

Bin et al., present the invention relating to the field of resource recovery and reuse, it relates to methods for preparing hollow polyaniline microspheres for recovering and reusing precious metals in electronic waste (WEEE). The developed polyaniline hollow microspheres can efficiently recover precious metal materials into WEEE without energy consumption, and the polyaniline/precious metal nanocomposites obtained through recovery can also be used as new electroactive materials to prepare electronic devices, thus achieving green circulation. of the devices [70].

According to Reece et al., the invention relates to a method for recovering precious metals from electronic waste (WEEE) using bio-metallurgical techniques. In one aspect, a method for recovering one or more metals, includes (a) removing at least a portion of the non-target material from e-waste or grinding it to a preselected particle size to obtain pre-processed e-waste; (b) contacting the preprocessed e-waste with a leach such that at least a portion of the target metal dissolves in the leach to produce an impregnated solution; (c) contacting a microorganism with the impregnated solution such that at least a portion of the metal ions are bio-absorbed into the microorganism, where the microorganism becomes metal-laden and the impregnated solution is rendered sterile; (d) substantially separating the metal-laden microorganism from the sterile solution; and (e) recovery of the target metal(s) from the metal-laden microorganism[71].

The innovation of Frank Marlin et al. refers to a method for obtaining metals from group 8 to 14, in particular raw copper, comprising the steps of: i) providing and melting a mixed feed comprising electronic waste (WEEE) in a smelting reactor, so that a first melting with a first metallic phase and a first slag phase is formed, ii) separating the first slag phase from the smelting reactor, iii) refining the remaining first metallic phase by means of an oxygen-containing gas, possibly with the copper-containing addition remains, so that a second copper-enriched slag phase is formed, iv) eventually separate the second slag phase and repeat the step, v) separate the first refined metal phase from the smelter reactor, and vi) add an additional feed mixture containing e-waste to the remaining second, copper-enriched slag phase and repeat process steps i) to vi) [72].

The present techniques, which are mentioned by Mohamed et al., include recovering organic and metallic fractions of e-waste (WEEE) by conditioning the e-waste to produce a conditioned material; pyrolyzing the conditioned material to thermally decompose the conditioned material into a gaseous component and a solid component, wherein the solid component comprises an organic fraction and a metal fraction. The recovery further includes separating the metal fraction from the solid component to recover at least one of Al, Zn, Ni, Cu, Au, Ag, Pt and Pd; in which at least 95% by weight of the e-waste can be recovered in the form of recovered metals, pyrolysis oil and value-added products [73].

Xiaohui et al., in their invention provide an integral method of separation and recovery of electronic waste (WEEE), belonging to the technical field of exploitation of solid waste resources. Mixing e-waste particles with acid liquor, low-temperature roasting, mixing a product obtained by low-temperature roasting with water, performing first leaching, and performing solid-liquid separation to obtain first leaching solution and first leaching residues; when e-waste contains noble metals, HCl/Cl is used for the first leach slag. The system is subjected to a secondary leaching and then to a solid-liquid separation, separating to obtain a second leach solution and a second leach residue; filtering the second leach residue, in which the oversized products are glass fibers and the undersized products are polymer roasting products; and when the e-waste does not contain precious metals, screening the first leach slag, where the oversize products are glass fibers and the undersize products are polymer roasting products. The method separates precious metals, base metals, glass fibers, and polymer roasting products in e-waste, thus achieving comprehensive separation and recovery of e-waste [74].

4. Conclusions

From an environmental and circular economy perspective, the search for alternatives to find new applications or use of waste will become a key factor that will impact the social, economic, and environmental aspects of society. With technological advances and the increase in the population, the use of electronic devices has been increasing at accelerated rates, the waste generated contains materials that are harmful to the environment and health, however, they contain high concentrations of valuable metals such as copper gold and silver. There are pyrometallurgical, bio-hydrometallurgical and hydrometallurgical processes to extract and recover these metals, however, the hydrometallurgical route is the most used because it is cheaper, easy to implement and friendly to the environment. In the present work, the main leaching media to extract valuable metals from electronic waste were reviewed, but it is necessary to optimize these processes with the use of chemical reagents that are not harmful to the environment and that are also feasible to implement at an industrial level.

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