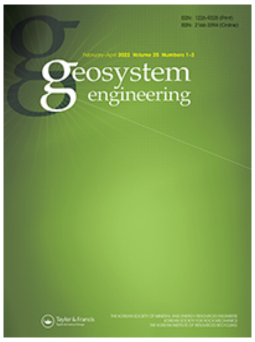

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Potential hydrometallurgical processes to recycle metals from discarded personal computer

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ABSTRACT
Rapid technological modernization has accelerated the replacement of older electronic goods with newer ones, which has led to the generation of huge quantities of discarded electronic items at its end-of-life, known as electronic wastes (e-wastes). The growing quantity of e-wastes has become a major threat to the society as well as environment. On the other hand, e-wastes contain several valuable metals and materials of high economic value, which compels researchers to work in the area for secondary resources for metal recovery. Metal recovery from such secondary resources will not only preserve the primary resources but also reduce the loss of valuable metals/materials, protect the environment from their hazardous effects as well as reduce the demand-supply gap of metals up to some extent. In view of the above, present study is focused on the possible effort to figure out variety of metals present in the component of waste personal computers (WPCs) as well as different recycling processes implemented for the efficient recovery of metals.

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E-wastes; personal computers; components; hydrometallurgical processes; recycling; precious & base metals

1. Introduction

Huge quantities of electronic wastes containing variety of metals and materials are generated as solid waste worldwide. The global e-waste generation in 2019 was 53.6 million tonnes (MT) contributed by Africa (2.9 MT), America (13.10 MT), Asia (24.9 MT), Europe (12 MT), and Oceania (0.7 MT). It was 41.8 MT and 44.7 MT in 2014 and 2016, respectively, and estimated to increase up to 74.7 MT by 2030 (Balde et al., 2017; Forti et al., 2020). The reason for the rise of e-wastes is advancement of technology, increase in replacement of electronic equipment by improved one, short life span, dismissal in the sale of used products (Ilankoon et al., 2018), informal recycling, lack of consciousness among people about the social and environmental impacts (Hale & McAllister, 2020).

The PCs are one of the most widespread electrical and electronic equipment used in corporate/home for work, entertainment and communication placed at the top in waste electronic equipments (WEEs). Printed circuit boards (PCBs) inside a desktop computer is the wide sized motherboard, which is also known as the backbone of all types of electronic components. The PCBs of PCs are made up of 27.00 wt. % polymer, 28.00 wt. % ceramic, and 45.00 wt. % metals (Yamane et al., 2011) including some percentage of toxic metals too. If they are not recycled properly, then it can contaminate the air, soil and groundwater. And when PCBs are burned, dioxin and furan gases are emitted, which causes health and environmental hazards (Bi et al., 2010; Hadi et al., 2013; Owens et al., 2007). In addition to this, scrap PCBs contains all types of precious (Au, Ag, Pd, and Pt), base metals (Cu, Ni, Fe, and Fe) and rare earth metals, which can be recovered using recycling techniques (Guo et al., 2010; Park & Fray, 2009; Veit et al., 2005). The effective collection system and the efficient recycling technologies are still lacking (J. C. Lee et al., 2007). Only 17.4% of e-wastes were properly collected and recycled according to a global report (Forti et al., 2020).

Keeping in view the above, the present paper reports comparative studies among most of the potential processes available and best in commercial scale to recover valuable, base and precious metals from waste personal computers and related e-waste using hybrid process consists of pre-treatment and hydrometallurgical techniques.

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2. Steps for commercial exploitation of metals from PCs

2.1. Dismantling and sorting

In this process, the contents or objects of PCs are dismantled, separated and arranged systematically using simple tools like screwdriver, hot gun, and tongs. The computer cases are separated in order to systematic removal of the different parts of the computer. The materials and components, such as plastic parts, iron components, steel, copper, aluminium, materials and printed circuit boards, and so on, are separated by sorting process to make the recycling process of scrap personal computers easy.

2.1.1. Computer chassis

At CSIR-NML, we have dismantled the scrap computers and from the detached computer chassis or main body, the components such as power supply, Cu wire, cooling fan, CD drive, memory module, PCI card, mother board (PCBs) and CPU, and so on, were separated (Figure 1).

PCBs engraved with a laminated copper sheet onto a non-syndicated substrate using a syndicated pathway track or signal trace are essential part of almost all the electrical and electronic products used to connect electronically and support mechanically electronic components (Becker et al., 2003). The PCBs contain various components such as core component central processing unit (CPU) commonly known as brain of PC, resistors, relays, capacitors and integrated circuits (ICs) associated with it. In basic structure of PCBs, a number of metallic materials including laminated Cu-clad containing fibbers, glass-reinforced epoxy resin and precious metals are used. The concentration of precious metals, that is, Au, Ag, Pd and Pt in waste PCBs is very high compared to primary resources, which are becoming economically attractive sources for recycling of secondary metals. In addition, rare earth elements (REEs)

Figure 1. The dismantled components of waste personal computer.

along with Ta, Ga, and flame retardants including Br and Cl create severe threats to ecosystems as a result of land filling and incineration (C. H. Lee et al., 2004) and loss of valuable metals like Ta and Ga. The value of every scrap PCBs is based on the metals concentration present in it, and also on the size and number of IC chips, capacitors, gold plated connectors, gold pins and area of gold plating (Kida, 2010). Another component is random access memory (RAM) a short-term memory storage device having different types of IC chips populated on it. Such memory module contains very high concentration of precious metals like Au, Ag, Pd, and Pt. Therefore, the value of scrap memory modules is higher than the other components of waste computers.

Apart of the above, each computer has one or more hard disk drives (HDDs) that are partitioned as long-term memory for the PCs. As a bracket shape that occurs in nickel-plated neodymium (Nd-Fe-B) magnet that can also be removed by manual breakup, this scrap has high value metals in its circuit boards. Circuit boards cost more than computer motherboards because circuit boards are made up of trace amounts of many precious and rare earth metals (Cong et al., 2015). It can be recycled for profit as SCSI and IDE connector cables have high value gold-coated pins.

2.2. Pre-treatment of discarded PCs

2.2.1. Mechanical beneficiation

Mechanical pre-treatment process can be classified into three phases (Figure 2.): (I) the process of disassembling all electronic components viz. capacitors, cell batteries, chips, resistors, diodes, transistors, heat sinks, and so on, including mandatory steps to disassemble the hazardous and valuable components present in it. (II) Size reduction and liberation of components by the process of crushing, grinding and shredding. (III) Each of the metals/non-metals should be separated and enriched based on the difference in physical properties (J. Cui & Forssberg, 2003; Luda, 2011) before hydrometallurgical leaching process. The mechanical-physical method was used for metal recovery in view of environmental safety (H. Cui & Anderson, 2016). However, the poor separation and low recycling rate of metals limits the mechanical-physical methods up to pre-treatment and metals enrichment only.

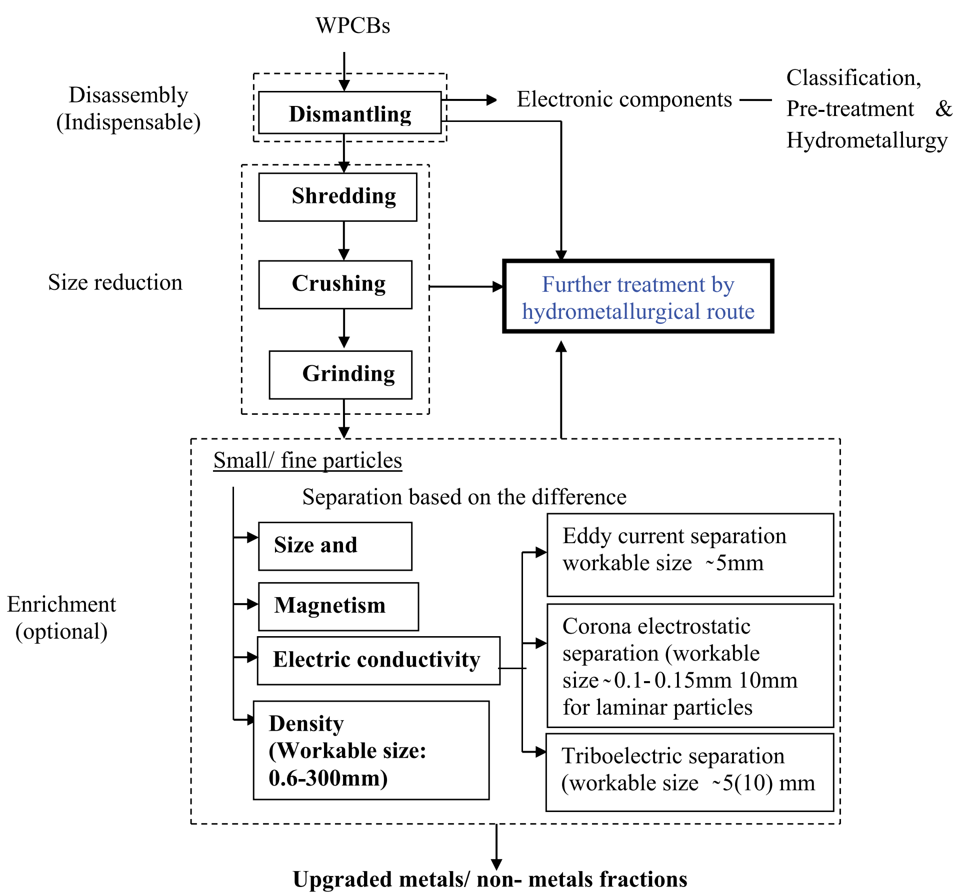

Figure 2. Flow sheet for mechanical pre-treatment of WPCBs, (J. Cui & Forssberg, 2003).

2.2.2. Thermal treatment process

Heat treatment is one of the potential methods that is involved in the initial stage of recycling for size reduction and cage breaking of hindering materials present. Pyrolysis is a type of thermal process under inert atmosphere in which the PCBs of PCs are treated in a furnace at low temperature, after which the metallic and non-metallic fractions are separated for further processing. Pyrolysis is beneficial in terms of reducing the requirement of mechanical-physical method as well as making all the products (oil, gases, carbon powder, etc.) marketable or usable. However, some drawbacks mainly related to environment are also attached with it, but it can be fully minimized using proper condensation and distillation facilities, which makes possible to condense the gases as low-density oil and use of excess gases as fuel to self-sustain the pyrolysis process, as the advance pyrolyser specially designed for e-waste/ plastics treatment has such features.

An attempt was made to enrich the copper grade in PCBs samples. Initially surface mounted components were removed and then the PCBs free from components were crushed. The crushed sample prepared after removal of the mounted components was further put for carbonization process at 873–1073 K in nitrogen atmosphere. After screening, the chars were classified into larger pieces in size, small pieces and powder. The pieces of Cu foil and glass fibres were separated and collected. Ni present in the multi-layered ceramic capacitors were carbonated at 873 K. A process of magnetic separation was carried out at 0.1 T and also at lower magnetic field strength. Then the Ni grade in the magnetic product was increased from 0.16% in the fraction of +0.5 mm size at 0.8 T to 6.7% with 74% nickel recovery. Other useful mounted parts are tantalum capacitors, which were collected and the tantalum-sinuous bodies were separated from the melded resins by the method of heat treatment at 723–773 K, subsequently, 0.5 mm was screened in atmospheric air shown in Figure 3. The silica was removed and a tantalum grade of 70% was extracted after heating and separation over 823 K (Fujita et al., 2014).

In order to recover both, solder and organic materials from waste PCBs, methods of centrifugal separation and vacuum pyrolysis were found to be effective. The scrap PCBs were rotated (1400 rpm) at 240 °C for 6 min to separate the solder material from the waste PCBs by a centrifugation process. The WPCBs without solder coming in Type-A were pyrolysed by vacuum pyrolysis process, which yielded 69.5 wt % residue, 27.8 wt % oil and 2.7 wt % gas. In addition, Type-B without solder was also pyrolysed and yield was 75.7 wt % residues, 20 wt % oil and 4.3 wt % gases. The pyrolysed residue

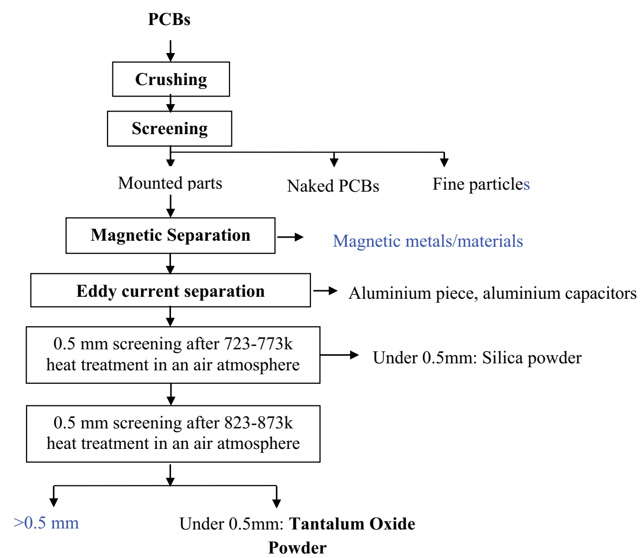

Figure 3. Process flow-sheet to recover tantalum from mounted parts of PCBs (Fujita et al., 2014).

containing various glass fibres, metals and other inorganic materials can be recycled to recover the metals and materials as shown in Figure 4. And the oil obtained through pyrolysis process can be used as fuel or chemical feedstock and collected gases can also be utilised in pyrolysis as fuel or in other application. This process is very important in preventing environmental pollution as well as in the recovery of valuable materials from WPCBs (Zhou & Qiu, 2010).

3. Metals leaching and purification from beneficiated components

3.1. Leaching

In recent years, many researchers have made several attempts to recover precious metals without harming the environment, but many of these techniques are still limited to the laboratory scale. For the recovery of any precious metal as well as base metals, the traditional processes are classified into three steps, leaching, separation and purification of the metals, and product recovery Figure 5. Waste personal computer are made up of various components consisting of different metals, undergo a leaching process to dissolve them in solution (Table 1) after classification and segregation.

3.1.1. Leaching of base metals

Oishi et al. (2007) used ammonium sulfate and chloride solutions to recover Cu from scrap PCBs. Copper leaching was carried out using Cu (II) amines to form Cu (I)

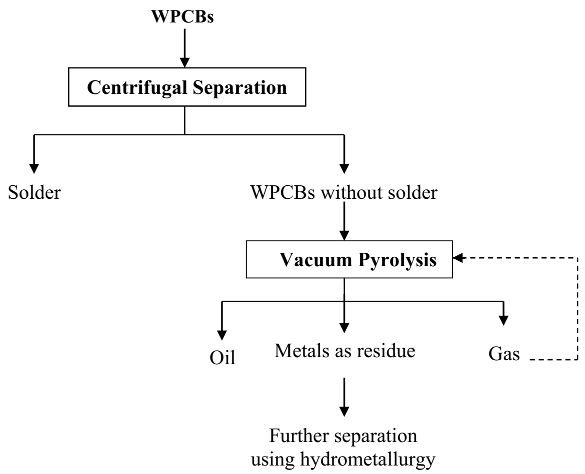

Figure 4. Process for integrated recycling of WPCBs (Zhou & Qiu, 2010).

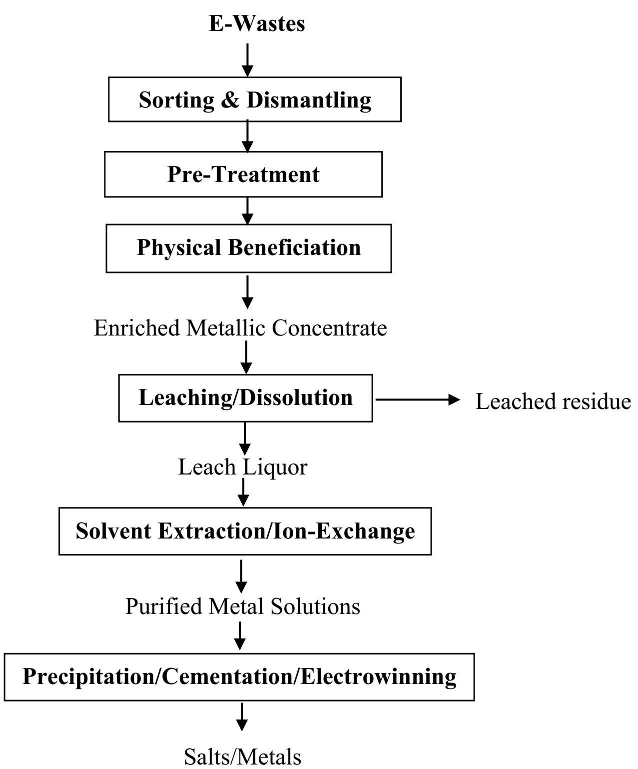

Figure 5. Generalized hydrometallurgical process flow-sheet for the extraction of metals.

amines together with other metals viz. Zn, Pb, Mn, and Ni in which amine complexes are formed. Fe and Al were not dissolved in this process and remained in the residue. In addition, LIX26 was used for the selective extraction and purification of metals present in leach liquor. Jha et al. (2012) reported the recovery of lead from organic free epoxy resin by leaching process. Nitric acid was found to be the most suitable lixiviant for lead leaching, which was confirmed under optimal conditions of 0.2 M HNO_3, 10 g/L pulp density and 90 °C temperature. As shown in Figure 6, total Pb was removed from the solder material in 120 min. After the recovery of Pb, 98.2% of Sn remained in the residue was removed from 3.5 M HCl at 90 °C for 120 min at solid-liquid ratio 1:20 (g/mL). After metals recovery, the metals free epoxy resin was washed with water. So reuse or disposal can be done without harming the environment.

3.1.2. Leaching of precious metals

Panda et al. (2020a) reported gold recovery from small components of e-wastes, where at first; the connectors and integrated circuits were pulverized. Gold leaching was performed using sodium cyanide solution (10 g/L) at 40 °C in mixing time of 15 min. More than 95% of gold was recovered in single step leaching under the optimized condition. Tuncuk (2019) reported the two-stage sequential bench scale leaching for the extraction of Cu, Au and Ag from WEEEs. Extraction of Au and Ag was 96.81% and 99.02%, respectively, using 2% I_2, 3% H_2O_2 as oxidizing agents maintaining 5% pulp density and 2 h of time. The extraction of Au and Ag was increased by increasing the concentration of H_2O_2. While approximately 79.30% of Ag was extracted using 2 M H_2SO_4, 1.5 M $(NH_4)_2S_2O_8$, in 5 h maintaining 5% of pulp density, 79.43% of Cu was extracted using ammonia instead of H_2SO_4 under the same conditions. $(NH_4)_2S_2O_8$. Alzate et al. (2016) reported gold recovery from WEEEs using $(NH_4)_2S_2O_8$. Gold was recovered as a fine coating using substrate oxidation without the shredding/grinding process. More than 98% Au was recovered using 0.65 M $(NH_4)_2S_2O_8$, oxygen supply (0.58 L/min) and L/S ratio (24 mL/g). Birloaga et al. (2013) and Birloaga & Veglio (2016)) reported leaching of gold and silver along with copper from waste PCBs with leaching percentage 69 and 90 for gold and 75% for silver using the lixiviant and condition mentioned in table-1, which not fulfilling the complete leaching of precious metals. Qu et al. (2009) reported 97.5% of gold leaching using iodine and hydrogen peroxide, and it shows that such lixiviant are effective for precious metal gold.

3.1.3. Leaching of platinum group metals (PGMs)

Fontana et al. (2017) reported recovery of Pd present in MLCCs of waste PCBs. Firstly, MLCCs was powdered form by milling process. 100% Pd was recovered under the optimized condition such as aqua regia as a lixiviant, temperature 25°C, solid/liquid ratio 1/10 and time 24 h. Panda et al. (2019) reported the recovery of precious metal from e-waste. In which the PCBs were first desoldered, allowing the integrated circuit (ICs) to be easily disassembled, and then pulverized to obtain

Table 1. Recovery of metals from e-wastes by leaching process.

S.No.	Target Waste	Experimental Condition	Salient Features	Reference
01.	PCBs	0.2 M HNO_3, Time: 45 min, Temp: 90 °C and 10 g/L pulp density for lead leaching. 3.5 M HCl, Temp: 90 °C, Time: 120 min, S: L ratio: 1:20 (g/mL) for tin leaching.	99.99% lead, 98.74% tin was leached.	Jha et al. (2012)
02.	RAM	2% I_2, 3% H_2O_2 as oxidizing agents, Pulp density: 5%, Time: 2 h.	Extraction of gold and silver was 96.81% and 99.02%.	Tuncuk (2019)
03.	PCBs	3 M HNO_3, Temp: 75 °C, Pulp density: 75 g/L, Time: 120 min.	99.99% Cu was leached in two stages.	Dutta et al. (2018)
04.	ICs	10 g/L NaCN, Temp: 40 °C, Time: 15 min.	95% gold was leached in single stage.	Panda et al. (2020a)
05.	Processor	0.88 M $(NH_4)_2S_2O_8$, Oxygen supply: (1.0 L/min) and L/S ratio: 25 mL/g.	More than 99% Au was recovered.	Alzate et al. (2016)
06.	Ceramic microcircuits of PCBs	Aqua regia as a lixiviant, Temp: 25 °C, Solid/liquid ratio: 1/10 and Time: 24 h.	100% Pd was recovered under the optimized condition.	Fontana et al. (2017)
07.	PCBs	$NaCl/CuSO_4$ (mL/g) ratio: 6, [Cu]/ [Cu^{2+}] mole ratio: 0.95, Time: 30 min and Temp: 60 °C.	About 98.5% Cu was recovered from PCBs through two synthesis circles. And about 93.9% Ag and 95.3% Pd were recovered, where Cu^{2+} played the role of oxidant in the system during synthesis.	Zhang and Zhang (2013)
08.	PCBs	2 M H_2SO_4 + 30% H_2O_2, Temp: 30 °C, Time: 3 h. 20 g/L CH_4N_2S, 6 g/L ferric ion, 10 g/L H_2SO_4, Stirring speed: 600 rpm.	75% Cu was removed with particle sizes smaller than 2 mm using double oxidative leaching. Gold extraction rate was 69%.	Birloaga et al. (2013)
09.	PCBs	1.7 M H_2SO_4 + 17% H_2O_2, Solid/liquid ratio: 15 g/L, Temp: room temp., Stirring speed: 200 rpm, Time: 1 h. 20 g/L CH_4N_2S, 6 g/L ferric ion, H_2SO_4: 0.1 M, Stirring speed: 200 rpm, Time: 1 h.	Complete Cu dissolution by two-step counters current leaching procedure. 90% Au and 75% Ag were extract.	Birloaga and Veglio (2016)
10.	RAM	0.8 mol/L $(NH_4)_2S_2O_8$, Solid/liquid ratio: 1/30, 14.45 mL H_2O_2, Temp: 80 °C, Time: 30 min.	Recovery rate of gold was 98.95% with purity 93.10%.	Lu and Xu (2017)
11.	PCBs	4 g/L NaCN, pH: 10.5–11, Time: 15 days.	Recovery rate 46.6% of Au and 51.3% Ag with the particles size 74–180 µm, 47.2% Nb, 62.3% Cu.	Montero et al. (2012)
12.	PCBs	(1) Selective leaching of Cu: 2 M H_2SO_4, 35% H_2O_2, Stirring speed: 200 rpm, Time: 3 h, Temp: 298 K. (2) Au and Ag leaching: 20 g/L CH_4N_2S, 6 g/L ferric ion: 10 g/L H_2SO_4, Stirring speed: 200 rpm, Time: 3 h, Temp: 298 ± 2 K. (3) Pd leaching: 1 % H_2O_2, 10 % NaClO, 5 M HCl, Time: 3 h, Temp: 89.85 °C.	71.36% Ag, 100% Au and 100% Pd was recovered with the particles size <2 mm.	Behnamfard et al. (2013)
13.	PCBs	0.3–0.5 M DTPA, 0.3–0.9 M H_2O_2, pH: 5–9, Temp: 20–50 °C, Stirring: 150–450 rpm, S/L: 1/100-1/10, Time: 0–8 h.	Leaching rate of Cu 99%, Ni 82% and Zn 100%.	Verma and Hait (2019)
14.	PCBs	1.1% Iodine, 1.5% H_2O_2, Solid/liquid ratio: 1/10, Time: 4 h, pH: 7.	97.5% Au recovery by leaching.	Qu et al. (2009)
15.	PCBs	CH_4N_2S 20 g/L, Oxidizing Agent: ferric (III) 6 g/L, H_2SO_4: 10 g/L, Stirring speed: 600 rpm, Time: 3.5 h.	82% Au was recovered.	Zhang et al. (2012)
16.	PCBs	0.5 M EDTA, 0.7 M H_2SO_4, pH: 7, Temp: 100 °C, Stirring speed: 700 rpm, Time: 3 h.	~84% copper was recovered.	Jadhao et al. (2015)

a fine powder. The pulverized ICs analyzed were plastics and ceramics in addition to ~0.8% Au, 0.01% Pd, 12% Cu. Nitric acid was used for the leaching of Cu and Pd, leaving gold in the leached residue. Zhang and Zhang (2013) reported the synthesis of cuprous chloride and simultaneous recovery of Ag and Pd from waste PCBs. Optimized condition $NaCl/CuSO_4$ (mL/g) ratio 6, [Cu]/ [Cu^{2+}] mole ratio 0.95, time 30 min and temperature and 60°C, respectively. About 98.5% Cu was recovered from PCBs through two synthesis circles. During the process of synthesis, recovery of Ag and Pd were attained by the formation of stable chloride complexes. About 93.9% Ag and 95.3% Pd were recovered, where Cu^{2+} played the role of oxidant in the system during synthesis.

3.2. Separation and purification of metals from leach liquor

There are various processes like solvent extraction, ion-exchange and electrolysis to obtain pure precious metals and other base metals solutions.

3.2.1. Solvent extraction of base metals

Choubey et al. (2015) reported the extraction of metals from leach liquor of discarded PCBs using solvent

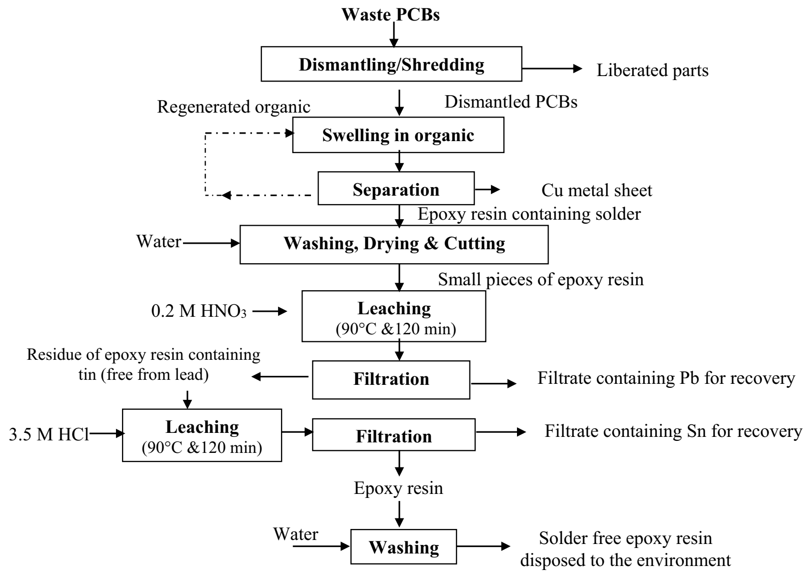

Figure 6. Flow sheet for the recovery of lead from the liberated resin of PCBs swelled by organic (Jha et al., 2012).

extraction process. The waste PCBs were separated and leached using nitric acid. The leach liquor was found to contain Cu (22.97 g/L) and HNO_3 (6.3 mol/L), which was processed for the acid extraction using tri-butyl phosphate (TBP) at phase ratio (O/A) 3/1 in mixing time of 15 min. Further, Cu was extracted using 30% LIX 84IC at equilibrium pH 2, phase ratio (O/A) 1/1 and mixing time of 15 min. 99.9% Cu extraction was achieved.10% sulphuric acid (H_2SO_4), 5 contact times and phase ratio (O/A) 1/1 were used to remove copper from the loaded organics. Wu et al. (2021) reported the selective extraction of nickel from ammoniacal leach liquor by LIX84. Optimized condition was 5% LIX84, pH 11.5 and phase ratio (O/A) 2/1.1 with two steps of counter current, the nickel extraction rate was 99.977%. Stripping of nickel from loaded LIX84 with 0.1 mol/L oxalic acid and phase ratio (O/A) 0.5 was performed. The stripping rate of nickel was 99.9%. Akbari and Ahmadi (2019) reported the recovery of copper from the bioleaching leach liquor of $WPCB_S$. To extract 96% copper, the optimized conditions were 20% LIX 984 N, pH 1.5 (bioleaching solution), 400 rpm stir, contact time 4 min and phase ratio (A/O) 1:1.

3.2.2. Separation of precious metals (gold and silver)

Rao et al. (2021) reported selective separation of gold using 0.1 M tertiary amide extractant dissolved in toluene to perform the selective separation of gold from leach liquor. Lekka et al. (2015) reported the recovery of gold from waste electrical and electronic equipment by electro deposition. In leach solutions containing base metals and precious metals, only Cu hindered the deposition of Au, as the reduction peak for Cu^{2+} ions and auric chloride complex were too close. On the other hand, Au deposition was promising even with low efficiency. The rate of deposition increased with the increase in temperature, that is, > 40 °C along with continuous stirring of the electrolyte. High purity gold as compact nano crystalline was deposited from leach solution by electro deposition at 0.55 V *vs* Ag/AgCl/KCl. Kim et al. (2011) reported the ion exchange involved in the process flow, followed by a two-step leaching by electro-generated Cl_2 to selectively recover gold from cell phone PCBs. The resins used were Bonlite BA304, Purolite A-500 and Amberlite XAD-7HP, all three resins having nearly identical adsorption efficiencies for Cu (95-97.70%), but showed low selectivity towards Au (7–8%). Therefore, in order to concentrate Au in second-stage leaching, ion-exchange was carried out using Amberlite XAD-7HP, which resulted in 95% Au recovery. Subsequently, Cu and Au were eluted using 0.1 mol/L HCl in acetone. Panda et al. (2020b) reported the recovery of Fe, Ag, Cu, and Ni from small components of e-waste using hydrometallurgical route (Figure 7). The process consisted of leaching followed by precipitation and solvent extraction to recover Fe, Ag, Cu, and Ni as value-added products.

3.2.3. Extraction of platinum group metals (PGMs)

Hoh et al. (1985) reported the fundamental aspects of extraction and stripping. Aliquat 336 was used to extract Pt (II) from chloride solution, in which 99.5% Pt (II) was achieved in 30 seconds. $NaHO_3$ was used to remove Pt (II) from the loaded organic. Panda et al. (2019) reported solvent extraction studies for recovery of metals from leach liquor, using low pH and 0.5% LIX84IC to extract

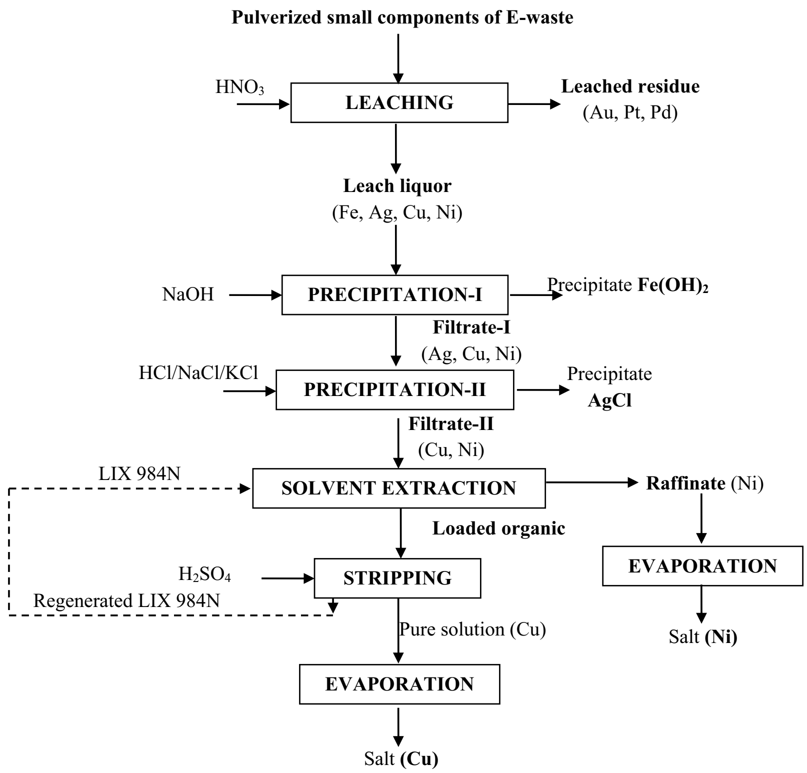

Figure 7. Hydrometallurgical process flow-sheet for the recovery of non-ferrous and precious metals (Panda et al., 2020b).

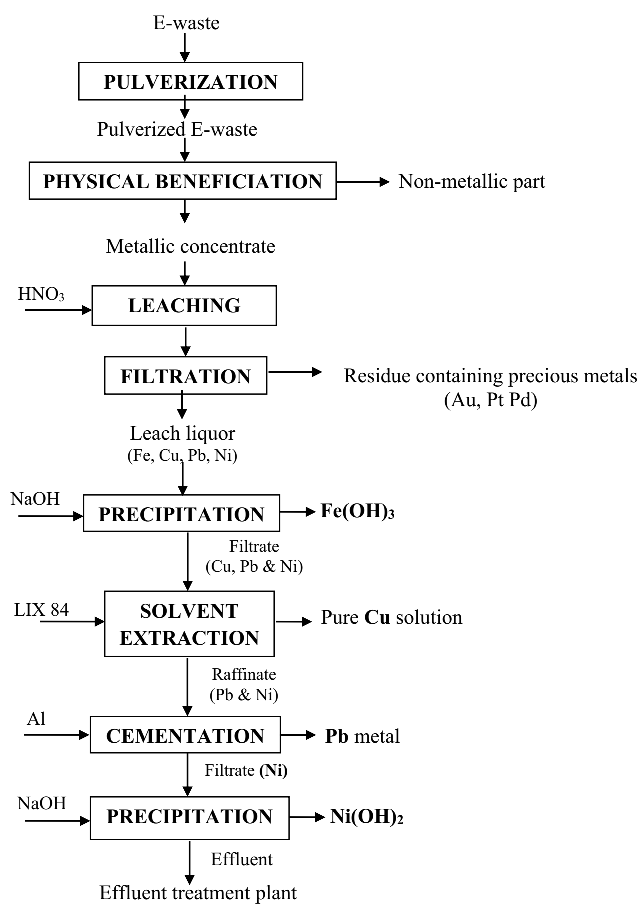

Figure 8. Process flow-sheet to recover non-ferrous and precious metals from e-waste (Panda et al., 2021).

Pd, using low concentration HCl to extract Pd from loaded organic and the copper was released into the raffinate. J. Y. Lee et al. (2009) reported extraction of $PtCl_6^{2-}$ and $RhCl_6^{3-}$ using Alamine 308 from acidic medium. The recovery rates of 98% and 36% for $PtCl_6^{2-}$ and $RhCl_6^{3-}$, respectively were achieved using 0.01 M Alamine 308. A mixture of 5 M HCl and 0.75 M thiourea was prepared and used for the stripping of metals from the loaded extractant (Alamine 308). After twelve cycles of extraction and stripping, the regeneration of Alamine 308 was found to decrease to some extent. The use of phosphonium ionic liquids have been considered potential for the separation and purification of PGMs. Shi et al. (2021) reported the Recovery of Pd (II) in chloride solutions by solvent extraction with new vinyl sulphide polymer extractant. Optimized condition was 0.7 g/L vinyl sulphide polymer as extractant, contact time 20 min and phase ratio (O/A) 1/1. Extraction rate was 99%. Almost 95.6 % Pd was stripped from loaded organic with 1 mol/L HCl + 0.1 mol/L thiourea. Panda et al. (2021) reported a process to generate enriched concentrate of Au, Pt and Pd from small components of e-waste, where other impurities were dissolved in suitable lixiviant and recovered as marketable products (Figure 8).

4. Conclusions

Based on the studies made for the potential processes to recover valuable, non-ferrous, precious and rare metals, the following conclusions have been made:

- Pre-treatment is essentially required in each processes for the effective liberation of metals from dismantled components. Basically, it may be either mechanical pre-treatment/ pyrolysis followed by pre-treatment. Pre-treatment has its own limitations toward liberation and fully separation of metallic and non-metallic components. However, pyrolysis may create hazardous fumes even in closed system. Use of advanced pyrolysis machines with zero discharge of hazardous gas fumes followed by pre-treatment will be more effective.
- For the recovery of individual metals from computer's components/e-wastes, combination of various advanced and effective hybrid techniques consisting leaching, solvent extraction, cementation, precipitation, electro-winning, and so on, are required.
- In future, varieties of e-waste with various metals will be generated and hydrometallurgical metal extraction can play important role. Hence, the presented flow-sheets in the paper have commercial potential after scale-up studies.

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Disclosure statement

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References

Akbari, S., & Ahmadi, A. (2019). Recovery of copper from a mixture of printed circuit boards (PCBs) and sulphidic tailings using bioleaching and solvent extraction processes. *Chemical Engineering and Processing - Process Intensification*, *142*, 107584. https://doi.org/10.1016/j.cep.2019.107584

Alzate, A., Lopez, M. E., & Serna, C. (2016). Recovery of gold from waste electrical and electronic equipment (WEEE) using ammonium persulfate. *Waste Management*, *57*, 113–120. http://dx.doi.org/10.1016/j.wasman.2016.01.043

Balde, C. P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). *The global e-waste monitor 2017. Quantities, flows, and resources*. United Nations University, international telecommunication union, and international solid waste association.

Becker, W., Simon-Hettich, B., & Honicke, P., 2003. Toxicology and ecotoxicology investigations for liquid crystal and disposal of LCDs, Merck brochure, Merck KGaA, Liquid Crystals Division and Institute of Toxicology 64271: Darmstadt, Germany.

Behnamfard, A., Salarirad, M. M., & Veglio, F. (2013). Process development for recovery of copper and precious metals from waste printed circuit board with emphasize on palladium and gold leaching and precipitation. *Waste Management (New York, N.Y.)*, *33*(11), 2354–2363. https://doi.org/10.1016/j.wasman.2013.07.017

Birloaga, I., Michelis, I. D., Ferella, F., Buzatu, M., & Vegliò, F. (2013). Study on the influence of various factors in the hydrometallurgical processing of waste printed circuit boards for copper and gold recovery. *Waste Management*, *33*(4), 935–941. https://doi.org/10.1016/j.wasman.2013.01.003

Birloaga, I., & Veglio, F. (2016). Study of multi-step hydrometallurgical methods to extract the valuable content of gold, silver and copper from waste printed circuit boards. *Journal of Environmental Chemical Engineering*, *4*(1), 20–29. https://doi.org/10.1016/j.jece.2015.11.021

Bi, X., Simoneit, B. R. T., Wang, Z., Wang, X., Sheng, G., & Fu, J. (2010). The major components of particles emitted during recycling of waste printed circuit boards in a typical e-waste workshop of South China. *Atmospheric*

Environment, *44*(35), 4440–4445. https://doi.org/10.1016/j.atmosenv.2010.07.040

Choubey, P. K., Panda, R., Jha, M. K., Lee, J. C., & Pathak, D. D. (2015). Recovery of copper and recycling of acid from the leach liquor of discarded Printed Circuit Boards (PCBs). *Separation and Purification Technology*, *156*(2), 269–275. https://doi.org/10.1016/j.seppur.2015.10.012

Cong, L., Jin, H., Fitsos, P., McIntyre, T., Yih, Y., Zhao, F., John, E. W., & Lande, S. (2015). Modeling the value recovery of rare earth permanent magnets at end-of-life. *Procedia CIRP*, *29*, 680–685. https://doi.org/10.1016/j.procir.2015.02.015

Cui, H., & Anderson, C. G. (2016). Literature review of hydrometallurgical recycling of printed circuit boards (PCBs). *Journal of Advanced Chemical Engineering*, *6*(1), 142–153. https://doi.org/10.4172/2090-4568.1000142

Cui, J., & Forssberg, E. (2003). Mechanical recycling of waste electric and electronic equipment: A review. *Journal of Hazardous Materials*, *99*(3), 243–263. https://doi.org/10.1016/s0304-3894(03)00061-x

Dutta, D., Panda, R., Kumari, A., Goel, S., & Jha, M. K. (2018). Sustainable recycling process for metals recovery from used printed circuit boards (PCBs). *Sustainable Materials Technology*, *17*, e00066. https://doi.org/10.1016/j.susmat.2018.e00066

Fontana, D., Pietrantonio, M., Pucciarmati, S., Torelli, G. N., Bonomi, C., & Masi, F. (2017). Palladium recovery from monolithic ceramic capacitors by leaching, solvent extraction and reduction. *Journal of Material Cycles and Waste Management*, *20*(2), 1199–1206. https://doi.org/10.1007/s10163-017-0684-3

Forti, V., Balde, C. P., & Kuehr, R., 2020. *E-waste statistics: Guidelines on classification, reporting and indicators*, (Second) ed. United Nations University, ViE – SCYCLE. Retrieved 2020, September 22, from https://collections.unu.edu/view/UNU:6477

Fujita, T., Ono, H., Dodbiba, G., & Yamaguchi, K. (2014). Valuation of a recycling process for printed circuit board by physical separation and heat treatment. *Waste Management*, *34*(7), 1264–1273. https://doi.org/10.1016/j.wasman.2014.03.002

Guo, Q., Yue, X., Wang, M., & Liu, Y. (2010). Pyrolysis of scrap printed circuit board plastic particles in a fluidized bed. *Powder Technology*, *198*(3), 422–428. https://doi.org/10.1016/j.powtec.2009.12.011

Hadi, P., Gao, P., Barford, J. P., & McKay, G. (2013). Novel application of the non-metallic fraction of the recycled printed circuit boards as a toxic heavy metal adsorbent. *Journal of Hazardous Materials*, *254-255*, 252–253, 166–70. https://doi.org/10.1016/j.jhazmat.2013.03.051

Hale, B., & McAllister, L. (2020). From treasure to trash: The lingering value of technological artifacts. *Science and Engineering Ethics*, *26*(2), 619–640. https://doi.org/10.1007/s11948-019-00107-1

Hoh, Y. C., Chuang, W. S., & Yueh, P. S. (1985). The extraction of platinum from Pt (II) chloride solution by a quaternary ammonium compound. *Journal of Chemical Technology & Biotechnology*, *35A*, 41–47. https://doi.org/10.1002/jctb.5040350108

Ilankoon, I. M. S. K., Ghorbani, Y., Chong, M. N., Herath, G., Moyo, T., & Petersen, J. (2018). E-waste in the international context – A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. *Waste Management*, *82*, 258–275. https://doi.org/10.1016/j.wasman.2018.10.018

Jadhao, P., Chauhan, G., Pant, K. K., & Nigam, K. D. P. (2015). Greener approach for the extraction of copper metal from electronic waste. *Waste Management*, *57*, 102–112. https://doi.org/10.1016/j.wasman.2015.11.023

Jha, M. K., Kumari, A., Choubey, P. K., Lee, J. C., Kumar, V., & Jeong, J. (2012). Leaching of lead from solder material of waste printed circuit boards (PCBs. *Hydrometallurgy*, *121-124*, 28–34. https://doi.org/10.1016/j.hydromet.2012.04.010

Kida, A. 2010. Elemental analysis methods including rare metals in used products. *Journal of Material Cycles and Waste Management*. Japan Society of Material Cycles and Waste Management. http://jsmcwm.or.jp/recycle/4KidaNIES.pdf

Kim, E. Y., Kim, M. S., Lee, J. C., & Pandey, B. D. (2011). Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process. *Journal of Hazardous Materials*, *198*, 206–215. https://doi.org/10.1016/j.jhazmat.2011.10.034

Lee, C. H., Chang, C. T., Fan, K. S., & Chang, T. C. (2004). An overview of recycling and treatment of scrap computers. *Journal of Hazardous Materials*, *144*(1–3), 93–100. https://doi.org/10.1016/j.jhazmat.2004.07.013

Lee, J. Y., Kumar, J. R., Kim, J. S., Park, H. K., & Yoon, H. S. (2009). Liquid–liquid extraction/ separation of platinum (IV) and rhodium (III) from chloride solutions using tri-iso-octylamine. *Journal of Hazardous Materials*, *168*(1), 424–429. https://doi.org/10.1016/j.jhazmat.2009.02.056

Lee, J. C., Song, H. T., & Yoo, J. M. (2007). Present status of the recycling of waste electrical and electronic equipment in Korea. *Resources, Conservation and Recycling*, *50*(4), 380–397. https://doi.org/10.1016/j.resconrec.2007.01.010

Lekka, M., Masavetas, I., Benedetti, A. V., Moutsatsoub, A., & Fedrizzi, L. (2015). Gold recovery from waste electrical and electronic equipment by electrodeposition: A feasibility study. *Hydrometallurgy*, *157*, 97–106. https://doi.org/10.1016/j.hydromet.2015.07.017

Luda, M. P. (2011). *Recycling of printed circuit boards*. Integrated Waste Management. Vol. II. In Tech.

Lu, Y., & Xu, Z. (2017). Recycling non-leaching gold from gold-plated memory cards: Parameters optimization, experimental verification, and mechanism analysis. *Journal of Cleaner Production*, *162*, 1518–1526. https://doi.org/10.1016/j.jclepro.2017.06.094

Montero, R., Guevara, A., & Torre, E. D. L. (2012). Recovery of Gold, Silver, Copper and Niobium from printed circuit boards using leaching column. *Global Journal of Earth Science and Engineering*, *2*, 590–595. https://docplayer.net/21219676-Recovery-of-gold-silver-copper-and-niobium-from-printed-circuit-boards-using-leaching-column-technique.html

Oishi, T., Koyama, K., Alam, S., Tanaka, M., & Lee, J. C. (2007). Recovery of high purity copper cathode from printed circuit boards using ammoniacal sulfate or chloride solutions. *Hydrometallurgy*, *89*(1–2), 82–88. https://doi.org/10.1016/j.hydromet.2007.05.010

Owens, C., Lambright, C., Bobseine, K., Ryan, B., Gray, L., Gullett, B., & Wilson, V. S. (2007). Identification of estrogenic compounds emitted from the combustion of computer printed circuit boards in electronic waste.

Environmental Science & Technology, *41*(24), 8506–8511. https://doi.org/10.1021/es071425p

Panda, R., Dinkar, O. S., Jha, M. K., & Pathak, D. D. (2020a). Recycling of gold from waste electronic components of devices. *Korean Journal of Chemical Engineering*, *37*(1), 111–119. https://doi.org/10.1007/s11814-019-0412-x

Panda, R., Dinkar, O. S., Kumari, A., Gupta, R., Jha, M. K., & Pathak, D. D. (2021). Hydrometallurgical processing of waste integrated circuits (ICs) to recover Ag and generate mix concentrate of Au, Pd and Pt. *Journal of Industrial and Engineering Chemistry*, *93*, 315–321. https://doi.org/10.1016/j.jiec.2020.10.007

Panda, R., Jha, M. K., & Pathak, D. D. (2019). Recovery of precious metals from PCBs of e-waste. *Journal of Metallurgy and Materials Science*, *61*(4), 213–219. https://www.indianjournals.com/ijor.aspx?target=ijor:jmms&volume=61&issue=4&article=005

Panda, R., Jha, M. K., Pathak, D. D., & Gupta, R. (2020b). Recovery of Ag, Cu, Ni and Fe from the nitrate leach liquor of waste ICs. *Minerals Engineering*, *158*, 106584. https://doi.org/10.1016/j.mineng.2020.106584

Park, Y. J., & Fray, D. J. (2009). Recovery of high purity precious metals from printed circuit boards. *Journal of Hazardous Materials*, *164*(2–3), 1152–1158. https://doi.org/10.1016/j.jhazmat.2008.09.043

Qu, X., Donghui, C., Liang, C., & Manhong, H. (2009). Iodine leaching process for recovery of gold from waste PCB. *Chinese Journal of Environmental Engineering*, *3*(5), 911–914. http://www.cjee.ac.cn/en/article/id/20090530

Rao, M. D., Singh, K. K., Morrison, C. A., & Love, J. B. (2021). Recycling copper and gold from e-waste by a two-stage leaching and solvent extraction process. *Separation and Purification Technology*, *263*, 118400. https://doi.org/10.1016/j.seppur.2021.118400

Shi, W., Hu, Y., Li, Q., Lan, T., Zhang, X., & Cao, J. (2021). Recovery of Pd(II) in chloride solutions by solvent extraction with new vinyl sulphide polymer extractants. *Hydrometallurgy*, *204*, 105716. https://doi.org/10.1016/j.hydromet.2021.105716

Tuncuk, A. (2019). Lab scale optimization and two-step sequential bench scale reactor leaching tests for the chemical dissolution of Cu, Au & Ag from waste electrical and electronic equipment (WEEE. *Waste Management*, *95*, 636–643. https://doi.org/10.1016/j.wasman.2019.07.008

Veit, H. M., Diehl, T. R., Salami, A. P., Rodrigues, J. S., Bernardes, A. M., & Tenório, J. A. S. (2005). Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. *Waste Management*, *25*(1), 67–74. https://doi.org/10.1016/j.wasman.2004.09.009

Verma, A., & Hait, S. (2019). Chelating extraction of metals from e-waste using diethylene triamine pentaacetic acid. *Process Safety and Environmental Protection*, *121*, 1–11. https://doi.org/10.1016/j.psep.2018.10.005

Wu, H., Duan, S., Liu, D., Guo, X., Yi, A., & Li, H. (2021). Recovery of nickel and molybdate from ammoniacal leach liquor of spent hydrodesulfurization catalyst using LIX84 extraction. *Separation and Purification Technology*, *269*, 118750. https://doi.org/10.1016/j.seppur.2021.118750

Yamane, H. L., Moraes, V. T., Espinosa, D. C. R., & Tenório, J. A. S. (2011). Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. *Waste Management*, *31* (12), 2553–2558. https://doi.org/10.1016/j.wasman.2011.07.006

Zhang, Y., Liu, S., Xie, H., Zeng, X., & Li, J. (2012). Current status on leaching precious metals from waste printed circuit boards. *Procedia Environmental Sciences*, *16*, 560–568. https://doi.org/10.1016/j.proenv.2012.10.077

Zhang, Z., & Zhang, F. (2013). Synthesis of cuprous chloride and simultaneous recovery of Ag and Pd from waste printed circuit boards. *Journal of Hazardous Materials*, *261*, 398–404. https://doi.org/10.1016/j.jhazmat.2013.07.057

Zhou, Y., & Qiu, K. (2010). A new technology for recycling materials from waste printed circuit boards, J. *Journal of Hazardous Materials*, *175*(1–3), 823–828. https://doi.org/10.1016/j.jhazmat.2009.10.083