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ORIGINAL ARTICLE

Evaluating the optimal digestion method and value distribution of precious metals from different waste printed circuit boards

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Abstract

Knowing the metal content of electronic waste is essential to evaluate metal recovery. Lack of a standard method for digestion of precious metals from electronic waste has resulted in difficulty in comparison to the efficiency of recovery. In this study, different precious metal digestion methods and economic value of precious metals from different types of waste printed circuit boards in different fraction sizes, including computer printed circuit boards, mobile phone printed circuit boards, television printed circuit boards, fax machine printed circuit boards, copy machine printed circuit boards, and central processing unit were examined. The optimal digestion method using aqua regia, hydrogen peroxide, hydrofluoric acid, and boric acid was adopted. The precious metal content was analyzed to answer what precious metals and types of printed circuit boards is preference. The results presented the following order of total value of precious metals ($\sum W_{ti} \mathrm{Pr}_{ti}$): central processing unit > Mobile phone > Copy > Fax > Computer > Television. Among the precious metals, gold and palladium were, respectively, attributed to the highest value distribution. The average values of the precious (gold and palladium) and all of the metals of electronic waste are about 19 and 21 times higher than the average cost of the world's top ten mines.

Keywords Waste PCBs · Acid digestion · Precious metal recycling · Value distribution

Introduction

With the development of electronic instrument industry and consumer market in recent years, electronic waste (E-waste) has created a great concern worldwide and has a significant impact on the environment. The increase of E-waste is quite fast, and its generation rate is three times more than other solid municipal waste streams [1–3]. The global trend in E-waste goes upwards, and it estimates to be continued for a long time [4]. United States Environmental Protection Agency (EPA, 2004) estimated a mobile phone is held by the users for a period of 9–18 months [5]. The lifespan of personal computers between 1992 and 2005 decreased from 5 to 3 years [6]. It is estimated that approximately 72 million tons of E-waste was generated in 2017 worldwide [7]. E-waste embodies a vast range of electrical and electronic instruments generated from industries as well as homes, including laptops, tablets, MP3 players, computers, mobile phones, refrigerators, televisions, air conditioners, etc., [8]. It contains more than 1000 different elements, including wood, plywood, glass, concrete, ferrous metals, non-ferrous metals, plastics, rubber, ceramics, and other items [9]. E-waste materials are categorized into hazardous materials (such as brominated and chlorinated flame retardants) [2], toxic metals (such as mercury (Hg), Lead (Pb), chromium (Cr), and cadmium (Cd)), [1] and precious metals (gold (Au), silver (Ag), copper (Cu), and palladium (Pd)) [8]. The considerable presence of precious metals in E-waste has caused naming E-waste as "urban mining" ore [4]. For example, every 6000 handsets of the mobile phones consist of 340 g Au, 3500 g Ag, 140 g Pd, and 130,000 g Cu [10]. While mines include 0.5 to 13.5 ppm Au [11], E-waste contains 10 to 1000 ppm Au [11]. Recovery of metals from urban mining is a necessary undertaking in the twenty-first century that can save mines and reduce environmental problems that have resulted from metal extraction [4]. The cost of energy consumption for metal recovery from E-waste is only 10–15% of the expense of mining ore [6]. Printed circuit boards (PCBs) are the most important, precious, and hazardous part of e-waste [3] and represent approximately 3wt% of E-waste [12].

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Knowledge of the metal content of E-waste is critical to evaluate the efficiency of metal recovery by different recycling methods [13]. To know the metal content of e-waste, usually, the sample is digested using different acid protocols, and then the amounts of released metals are identified by inductively coupled plasma (ICP) analysis. Most base metals can dissolve in aqua regia, fast and complete. For Au and precious metals, digestion using only aqua regia cannot be sufficient. Some researchers have studied Au leaching from E-waste and have reported metal content [14–19]. Sometimes their reports are very controversial. For example, about Au content of mobile phone printed circuit boards (MPPCBs), researchers have reported 1800 ppm [18], 350 ppm [20], and 0% [21]. So, the concentrations of Au differ significantly; data reported by different researchers are not compatible. The reason is that they had used different samples and analysis methods. In our previous studies [18, 19], we have faced the fact that Au extraction requires an application of an additional method rather than using aqua regia.

Some researchers examined the metal content of E-waste using aqua regia. They digested the E-waste samples using aqua regia. The residue was dried and was weighted to determine the amount of solubilized metal. Also, the supernatant was analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) [16, 22]. Another researcher used aqua regia in a high pressure sealed vessel [23]; some others digested the remained material in sulfuric acid (H_2SO_4) after using aqua regia [24, 25]. In some other researches, the principal acid for digestion of the E-waste sample was nitric acid (HNO_3). In these procedures, the sample was mixed with 65% HNO_3 and shaken until complete nitrogen dioxide (NO2) release was accomplished [14]. Moreover, for better digestion Xiang et al. (2010) suggested a mixture of 3 (v/v%) HNO_3, 1 (v/v%) hydrochloric acid (HCl), 1 (v/v%) hydrofluoric acid (HF), and 1 (v/v%) hydrogen peroxide (H_2O_2) using a microwave system [17]. The main oxidant that was used by Fogarasi et al. (2015) was 0.3 M ferric chloride ($FeCl_3$); they added 0.5 M HCl to ensure the acidic pH of the waste solution [15]. Das et al. (2001) applied H_2O_2 as the main oxidant. HF was employed after H_2O_2 digestion [26]. However, it should be noted that using H_2SO_4 instead of HCl causes difficulties in the interpretation of results [27]. The outlined metal analysis methods and the results are summarized in Table 1.

Knowing the metal contents of the waste is essential to evaluate the efficiency of metal recovery by different recycling methods [28]. The gap of the study is that a standard acid digestion method is needed to evaluate the effectiveness of a metal recovery process. Unfortunately, different digestion methods were applied for measuring metal content of E-waste, thus rendering it difficult for comparison in precious metal efficiency [28]. The gap of the study is that no study compares the precious metal content of the different types of e-waste simultaneously. The researches on the metal characterization of e-waste studied just one or a few numbers of different types of e-waste. No research indicates the precious metal content of other major e-wastes excluding computer printed circuit boards (CPCBs), MPPCBs, and television printed circuit boards (TVPCBs). Central processing unit (CPUs), fax machine printed circuit boards (FPCBs), and copy machine printed circuit boards (COPCBs) are important e-wastes that have not been considered for precious metal recovery. The gap of the study is that the metal content of definite e-waste is not compatible with different studies due to differences in brand, make, model, manufacturer, obsolescence age of PCBs, and the different

Table 1 Summary of different methods for the metal analysis of E-waste

References	Fogarasi et al. [15]	Ilyas et al. [22]	Yang et al. [23]	Natarjan and Ting [16]	Dangton and leepowpanth [14]	Shah et al. [24]	Xiang et al. [17]
Type of Waste	Waste PCBs	Industry E-waste (120 µm)	Waste PCBs	Untreated electronic scarp materials (mainly PCBs)	Untreated electronic scarp materials	CPCBs	Waste PCBs
Au (ppm)	110	–	–	280	2200	140	14
Ag (ppm)	180	–	–	560	–	230	217
Ni (ppm)	11,100	28,000	5310	16,000	–	78,200	1920
Cu (%)	18	6	26	15	33	–	23
Pd (ppm)	–	–	–	–	–	270	4
Al (%)	–	1	6	5	–	6	3
Sn (%)	4	–	3	2	–		2
Zn (%)	2	5	6	1	–	5	2
Fe (%)	3	4	-	3	–	14	1

adopted methods for analysis. It is more logical to comprise different types of e-waste with the same analysis method and by selecting sample existed in a defined country which affects the age, model, etc. However, the metal contents of the same e-waste used in a definite country but produced by different countries or different brands are varied, but these differences are much lower than the variation between metal content of different types of PCBs; by combining the diverse kinds of a definite PCBs, a valuable average of that PCBs is gained (For example, in this research, about 10 kg of different types of CPCBs was purchased).

In this research, several digestion protocols were evaluated to determine the optimal digestion method to determine the precious metal content in different types of PCBs in different fraction sizes. In this respect, CPCBs, MPPCBs, FPCBs, COPCBs, TVPCBs, and CPUs were selected as the most important types of E-waste. Precious metals of the different kinds of E-waste in different fraction sizes were analyzed using ICP-OES. Furthermore, the value distribution study was carried out to find the most economical types of E-waste and metals for recovery. Finally, to complete data about the properties of the studied E-waste, X-ray diffraction (XRD) analysis was used. It has to be noted our previous article examined base metals and the structure of different waste PCBs [29].

Materials and methods

Preparation of different types of PCBs.

CPCBs, MPPCBs, FPCBs, COPCBs, TVPCBs, and CPUs were selected as the most important types of E-waste. They were crushed into particles with dimensions lower than 2 cm using a hammer mill; then, an industrial hammer mill (Gharegozlu, Iran) was used, and they were minified to lower sizes. Some portions of the E-waste samples were trapped in the hammer mill; they were minified to particles less than 8 mm. The output was sieved to two sizes smaller than 3 mm and less than 1 mm. In this way, three fraction sizes of $F_1 < 1$ mm, $1 < F_2 < 3$ mm, and $3 < F_3 < 8$ mm were produced. The F_3 part has not been generated from the PCBs that contain a low percentage of plastic. After fragmentation, the plastics of the PCBs were separated through the shaking table method based on the density difference of the sample materials. In the third step, a micronizer (Herzog, West Germany) was employed to powder fractions of each PCBs type to particles smaller than 150 µm. The details of the PCB pretreatment were reported at our previous research that examining base metals, polymer content, recovery priority, and economic value of base metals [29].

It has to be noted that throughout the text, the reported values for F1, F2, and F3 were measured after plastic separation. The reported values for CPCBs, MPPCBs, and other waste PCBs are related to the initial samples with no pretreatment (without plastic separation and classification).

Different digestion methods for the analysis of precious metals.

Concerning other researches reports outlined in the "Introduction" section and Table 1, five methods were selected and were followed for analysis of precious metals. As time and temperature increase, the dissolution of some metals (such as Cu) increases in HNO_3, H_2SO_4, and HCl. Using additive (such as H_2O_2) increases the dissolution of Cu. Also, some metals such as Cu are soluble in HNO_3, and some others (such as iron (Fe)) are soluble in H_2SO_4 [30]. So, high temperature, a long time, the presence of an additive, and a two-stage leaching process were tried.

The treated solutions were analyzed using ICP-OES (730-ES, Varian). The used reagents were concentrated HCl (37% w/w), H_2O_2 (30% w/w), HF (49% w/w), and HNO_3 (69% w/w). The investigated methods are as follows:

Aqua regia.

In this method, a definite weight of the sample was dissolved in aqua regia with HNO_3: HCl ratio of 3:2, and was heated about 5 h, at 90 °C.

Furnace + Aqua regia.

1 g of the sample was heated in a furnace for 4 h at 700 °C. The furnace helps to vaporize the existing organic materials, such as plastics. Then 20 mL of aqua regia (with a high HNO_3: HCl ratio (3:1)) was added to the residual sample. The solution was heated on a hot plate.

Aqua regia + H_2SO_4.

In this method, 1 g of the sample was dissolved in 20 mL aqua regia and was heated at 150 °C to 180 °C until the solution evaporated completely. The remaining sample was digested in dense H_2SO_4 for 15 min. After cooling, the suspension was filtered through Whatman filter paper No. 42. This method was introduced by Shah et al. (2014) [24].

Aqua regia + H_2O_2 + HF + boric acid (H_3BO_3).

1 g of the sample was digested in a mixture of aqua regia, H_2O_2, and HF with a 1:1:3 ratio. Also, H_3BO_3 was added to the digestion solution to reduce the corrosive effect of HF [24]. The suspension was cooled and then filtered using filter paper. This analysis was operated in a PTFE reactor. This approach was inspired by the methods developed by Xiang et al. (2010) [17] and Ilyas et al. (2014) [22].

Aqua regia + H_2O_2 + HF + H_3BO_3 + perchloric acid ($HClO_4$).

This method is similar to the fourth method. However, $HClO_4$ was also added to the digestion solution since Ghosh et al. (2015) have stated that using oxidative chloride is effective in Cu and Pd extraction [31].

Results and discussion

The optimal precious metals digestion method.

The MPPCBs powder (≤ 150 µm) was analyzed through five methods introduced previously, and the results are presented in Table 2. This Table implies that the fourth method is the best approach for the metal analysis of PCBs. Results of the first method indicate using only aqua regia is not a suitable method, while many researchers performed their metal analyses with only aqua regia. The second and third methods emphasize that using the furnace and H_2SO_4, along with aqua regia, is not effective. The fourth method is the best one that aqua regia is the main acid for metal digestion. In the fourth method, HF helps to eliminate the plastic content, leads to release metal bounds to silicate fractions [28], and achieves improved metal digestion; meantime H_3BO_3 decreases the corrosive effect of HF. In this method, to increase the reaction kinetics and for improving metal recovery, H_2O_2 was used as an oxidant [30]. Based on the results of the fifth method, while the metal recovery is expected to enhance with the addition of an oxidative chloride but the application of $HClO_4$ gives a more complex matrix and decreases the efficiency of metal analysis.

Table 2 The detected metal content of MPPCBs using different methods, in ppm

Method	Au (ppm)	Pd (ppm)	Pt (ppm)
#1	245.24	129.37	ND**
#2	205.79	152.59	ND
#3	287.31	134.25	ND
#4	606.01	185.33	ND
#5	289.60	189.03	ND

**Not detected

Precious metal analysis for different fraction sizes of different PCBs.

The optimal digestion method was chosen to analyze the precious metal content of different fraction sizes of different types of PCBs. The results are presented in Table 3. It is found out that all samples are platinum (Pt) free. Table 3 shows Au concentration is greater in F_1 fraction. However, the amount of Pd is more in F_3. Therefore, when PCBs wastes are crushed, the smaller parts include more Au while the bigger particles contain more Pd, and none of the fractions have to be ignored. Another point is that by separating plastics, concentrations of all metals increase more than two times. Figure 1 illustrates the amount of Au and Pd in different six PCBs without any pretreatment. First, CPU and then MPPCBs contain the highest concentration of Au and Pd. CPU is a part of computers that is smaller than MPPCBs. Mobile phones are produced four times more than computers [32]. The weight of CPUs is too lower than MPPCBs, so MPPCBs is more valuable. It is worth noting that the amount of Au and Pd in COPCBs and FPCBs is close to MPPCBs, and is higher than CPCBs and TVPCBs. Another point refers to the average Au content of the world's top ten Au mines, i.e., 18.98 ppm [33]. The amount of Au that can be extracted from the E-wastes is noticeably higher than Au mines. E-waste contains Au averagely 605.67 ppm. In other words, the average Au concentration of different types of PCBs is about 32 times higher than the average Au content of the world's top ten Au mines; this amount increases to

Table 3 Precious metal analysis of different fraction sizes of various PCBs

PCBs	Au (ppm)	Pd (ppm)	PCBs	Au (ppm)	Pd (ppm)
MPPCBs*	1269.90	170.09	TVPCBs*	90.95	25.67
F_1*	1484.87	98.96	F_1	129.80	25.12
F_2*	1164.63	302.50	F_2	64.59	20.43
F_3*	145.55	323.49	F_3	64.44	40.89
MPPCBs WOP*	606.01	189.03	TVPCBs WOP	111.32	40.87
CPCBs*	482.03	21.93	COPCBs*	1254.73	195.12
F_1	600.36	17.93	F_1	1621.19	265.06
F_2	387.14	28.75	F_2	671.28	79.20
F_3	41.10	18.17	COPCBs WOP	412.59	217.89
CPCBs WOP	271.29	39.35	CPU*	2203.85	557.32
FPCBs*	1038.29	131.13			
F_1	1137.19	132.04			
F_2	892.36	142.42			
FPCBs WOP	446.20	165.81			

*WOP** without pretreatment and plastic separation, *MPPCBs** mobile phone PCBs, *CPCBs** computer PCBs, *FPCBs** fax machine PCBs, *PCBTVs** television PCBs, *COPCBs** copy machine PCBs, *CPU**, central processing unit, $F_1 < 1$ mm, $1 < F_2 < 3$ mm, and $3 < F_3 < 8$ mm

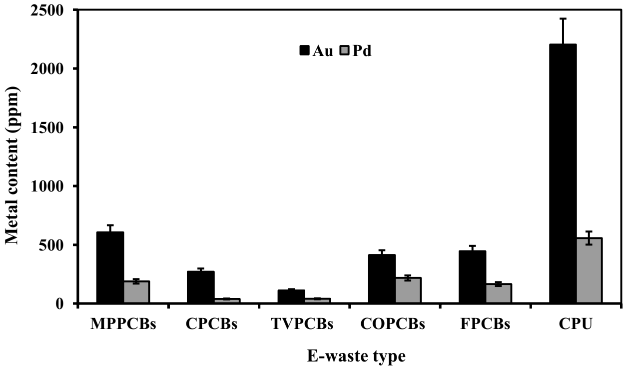


Fig. 1 Au and Pd concentrations in different PCBs without waste pretreatment

about 883 times for Au concentration of all reported samples in Table 3 (before and after plastic separation). It validates that in the past four decades, a significant portion of Au has been consumed to produce electrical instruments [34].

Value distribution.

Value distribution defines how much is the share of each metal in the economic value of a sample. The amount of value distribution was computed according to Eq. 1 [29]. In this equation, W_{ti} is the weight percent of each metal in the sample that is presented in Table 3. Pr_{ti} is the price of metal i that was obtained on 15 January 2020, the values of Au and Pd were, respectively, 1502.00 ($/fine troy ounce) and 1808.80 ($/fine troy ounce) [35]. One troy ounce is equal to 31.1034768 g [36].

$$V_i = \frac{100 W_{ti}\,\mathrm{Pr}_{ti}}{\sum W_{ti}\,\mathrm{Pr}_{ti}} \tag{1}$$

By using Eq. 1, Table 3, metal price value distributions for each metal and PCBs were calculated. The results are outlined in Table 4. Also, the value distribution of base metals was computed using the base metals' concentration that was reported in our previous study [29]. The base metal prices were obtained on 15 January 2020, and the values of Cu, silicon (Si), tin (Sn), aluminum (Al), nickel (Ni), Ag, zinc (Zn), Pb, manganese (Mn), molybdenum (Mo), cobalt (Co), and titanium (Ti) were, respectively, 5757.3 $/ton, 2576.102 $/ton, 16,603.39 $/ton, 1725.96 $/ton, 17,046.22 $/ton, 551,063.8 $/ton, 2451.65 $/ton, 1921 $/ton, 2060 $/ton, 26,000 $/ton, 33,000 $/ton, and 4800 $/ton [35].

Table 4 Value distribution of metals for different types of PCBs and fractions

Waste PCBs	V_{Au}%	V_{Pd}%	V All other metals%	$\sum W_{ti}Pr_{ti}$ ($Au\&Pd$) ($/ton)	$\sum W_{ti}Pr_{ti}$ (All metals) ($/ton)
MPPCBs*	67.86	25.49	6.66	40,257	43,128
F_1*	85.92	6.90	7.19	77,460	83,459
F_2*	72.62	22.72	4.67	73,832	77,445
F_3*	24.89	66.62	8.48	25,841	28,236
CPCBs*	77.55	13.55	8.90	15,389	16,893
F_1	82.27	2.96	14.77	30,034	35,239
F_2	84.69	7.57	7.74	20,367	22,075
F_3	46.57	24.79	28.64	3041	4262
TVPCBs*	55.49	24.53	19.98	7752	9688
F_1	47.40	11.04	41.55	7729	13,223
F_2	32.59	12.41	55.00	4307	9571
F_3	41.49	31.71	26.80	5490	7500
FPCBs*	63.01	28.20	8.79	31,190	34,196
F_1	80.58	11.27	8.16	62,594	68,153
F_2	77.44	14.88	7.68	51,375	55,646
COPCBs*	56.28	35.80	7.92	32,595	35,399
F_1	79.53	15.66	4.81	93,702	98,435
F_2	77.30	10.98	11.72	37,022	41,935
CPU*	73.94	22.52	3.55	138,835	142,774

*MPPCBs** mobile phone PCBs, *CPCBs** computer PCBs, *FPCBs** fax machine PCBs, *TVPCBs** television PCBs, *COPCBs** copy machine PCBs, *CPU** central processing unit, <1 mm, $1<F_2<3$ mm, and $3<F_3<8$ mm

Based on Table 4, though the concentration of Au is too lower than other metals, Au makes the bulk value of these wastes. This table clarifies that Au and Pd, respectively, have the highest value distribution. This trend of value distribution is observed in almost all data related to the three fractions of all PCBs. The average value distribution of all other metals for all samples is about 15%. Among all PCBs, Au value for TVPCBs is the lowest, and the share of the other metals is the highest. $\sum W_{ti}\,\mathrm{Pr}_{ti}\,(Au\&Pd)$ indicates the total price of Au and Pd in each E-waste. $\sum W_{ti}\mathrm{Pr}_{ti(Metals)}$ shows the cost of all metals in each E-waste. $\sum W_{ti}\,\mathrm{Pr}_{ti}$ values for the PCBs without any pretreatment and plastic separation are as follows: CPU > MPPCBs > COPCBs > FPCBs > CPCBs > TVPCBs. This trend is as same as the obtained trend for the PCBs that were analyzed after plastic separation and pretreatment. The higher the total price of a PCB, the more precious metals it contains, and the more economical it will be to recycle. So, the order of the PCBs for metal recovery is as follows: CPU > MPPCBs > COPCBs > FPCBs > CPCBs > TVPCBs. These data show COPCBs and FPCBs are more valuable than CPCBs and TVPCBs. However, few studies have focused on them. Also, Table 4 suggests F_1 is more precious, and almost all $\sum W_{ti}\,\mathrm{Pr}_{ti}$ values for F_1 are higher than the F_2 and F_3 values.

Figure 2 displays the value distributions regarding different metals of the PCBs. This figure describes the importance of Au extraction from all PCBs; Au recovery from TVPCBs and COPCBs is of less importance. For TVPCBs, recovery of the base metals is more economical than the other PCBs. This figure illustrates the value of all metals without Pd and

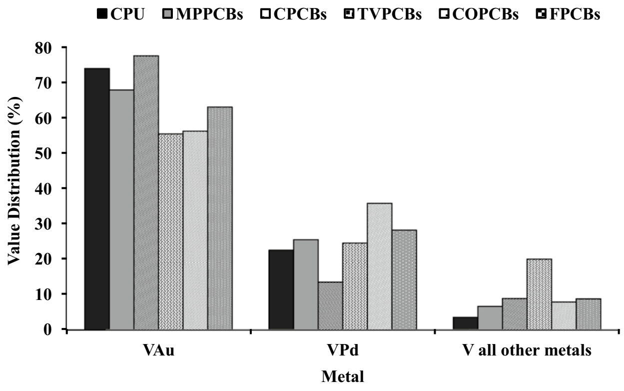


Fig. 2 Comparison between value distributions of different PCBs

Au is too lower than the Au value and even is lower than the Pd value.

The average value of the world's top ten mines is about 2096.8 $/ton. The fifth-largest mine in the world locates in Canada, and its reserves are about 846 $/ton. Cu, Ni, Pd, Pt, and Au share the value of this ore. The world's first mine that is just uranium-rich is worth about 8430 $/ton [37]. The average values distribution of precious metals (Au and Pd) and all of the metals of E-waste, respectively, are 39,937.61 $/ton and 43,539.93 $/ton that are about 19.05 and 20.76 times greater than the average value of the world's top ten mines in the world. This fact emphasizes the E-waste recovery importance. Therefore, recycling E-waste is necessary for both reducing environmental pollutions and saving natural ores [38].

XRD analysis.

Since E-waste is heterogeneous in composition, for standardizing the digestion protocol knowing the chemical forms of the metals present in the waste matrix is very important [28]. When X-rays interplay with a crystalline substance, it gives a XRD pattern of the materials. About 95% of all solids enumerate as crystalline materials, and the rest are amorphous, which means that their atoms are arranged randomly. XRD is a powerful analysis tool because every crystalline substance has a unique pattern. The same element produces the same patterns. In a mixture of crystalline materials, each material results in its unique pattern independent from the other substances. The main application of XRD is to identify components of a sample while the area under each peak shows the amount related to each phase [39]. In this research, XRD (EQUINOX 3000, Inel, France) was used to determine the comprising phases of each sample within the scanning range of 5° to 118°. The tube voltage and current of the XRD spectroscopy were 40 kV and 30 mA, respectively.

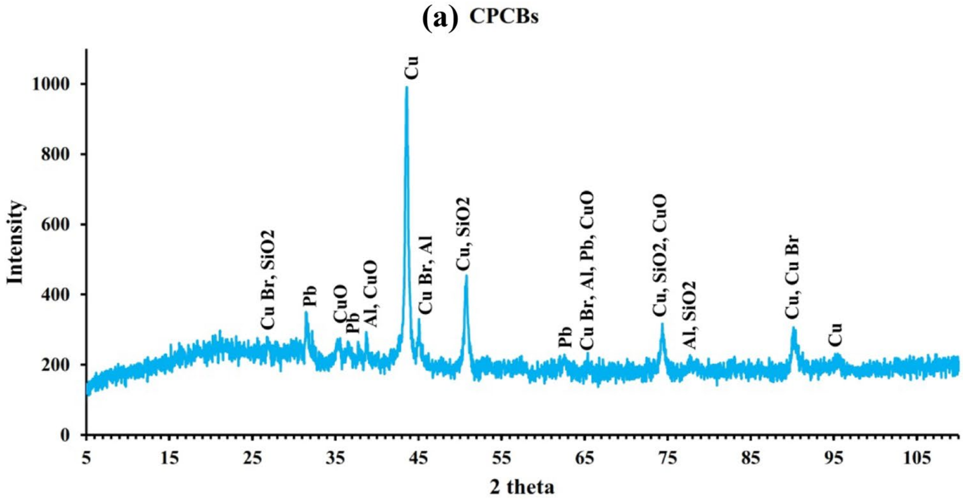
Figure 3 exhibits XRD patterns of all samples; elemental Cu has the highest peak area, which confirms the high concentration of Cu in the E-waste.

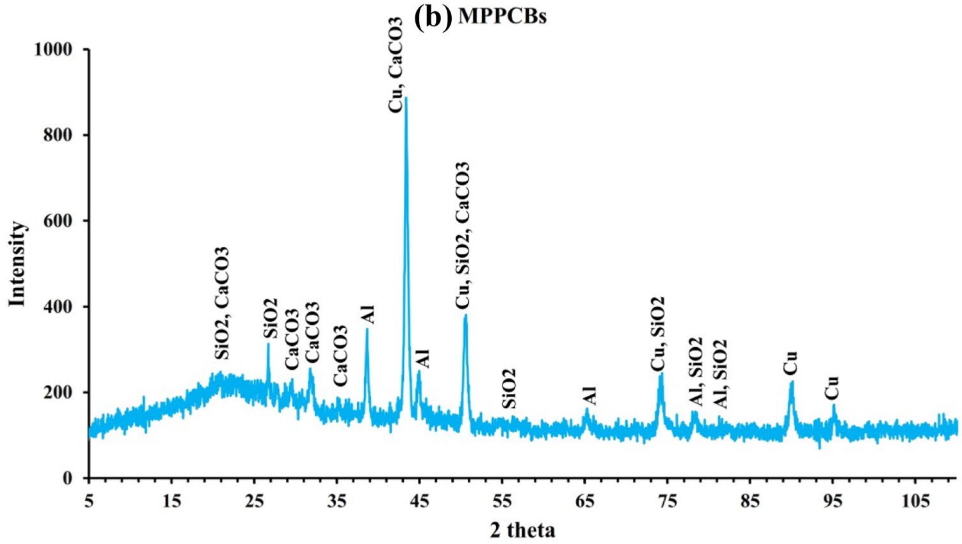
Cu element is present in the form of Cu, copper (II) oxide (CuO), copper (I) bromide (CuBr), and Cu137Sn. CPCBs, COPCBs, and FPCBs contain Cu, CuO, and CuBr. MPPCBs and CPU only consist of elemental Cu. TVPCBs include Cu and $Cu_{137}Sn$. Al and Pb exist in the PCBs in their elemental forms. The dominant phase of Si is silicon dioxide (SiO_2), and just in CPU Si is identified as FeSi. Calcium carbonate ($CaCO_3$) is one of the main phases of MPPCBs.

Conclusion

In this study, three fraction sizes of CPCBs, MPPCBs, TVPCBs, FPCBs, COPCBs, and CPU, including $F1 < 1$ mm, $1 < F_2 < 3$ mm, and $3 < F_3 < 8$ mm were provided. Dissolving the E-waste sample in aqua regia, H_2O_2, and HF in the ration (1:1:3 ratio) was suggested as the standard acid digestion method. The results proved waste of PCBs is an economical metal resource. Recycling of E-waste is necessary to save natural ores. Findings implied that the smaller parts of the crushed E-waste contain significant amounts of Au while the bigger particles contain more Pd. F_1 is more precious and $\sum W_{ti} \mathrm{Pr}_{ti}$ values of all PCBs are higher for the first fraction size. The average Au content of different types of PCBs is about 32 times higher than the average Au content of the world's top ten Au mines. The average values distribution of precious metals (Au and Pd) and all of the metals of different types of PCBs are about 19 and 21 times higher than the average value of the world's top ten mines in the world. It was concluded that Au and Pd are, respectively, the most economical metals that have to be recycled. The average value distribution of all other metals (without Au and Pd) for different types of PCBs is about 15%. The total price of precious metals of the examined E-waste with/out plastic separation is as follows: CPU > MPPCBs > COPCBs > FPCBs > CPCBs > TVPCBs. CPUs, FPCBs, and COPCBs are important e-wastes that have not been considered for precious metal recovery.

Fig. 3 XRD patterns of **a** CPCBs, **b** MPPCBs, **c** TVPCBs, **d** COPCBs, **e** FPCBs, and **f** CPU





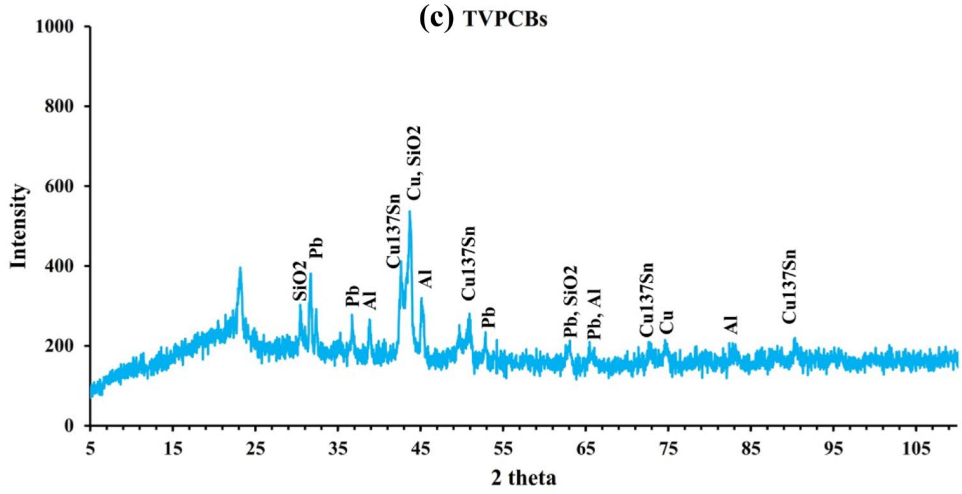
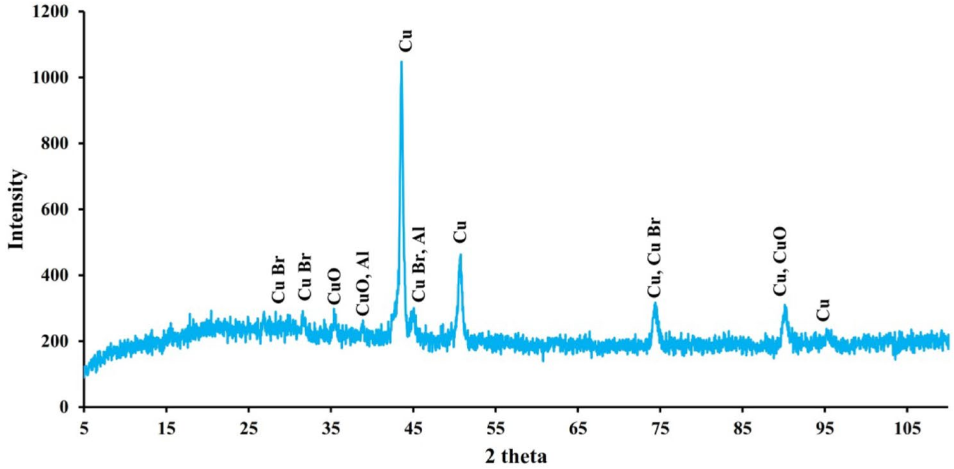
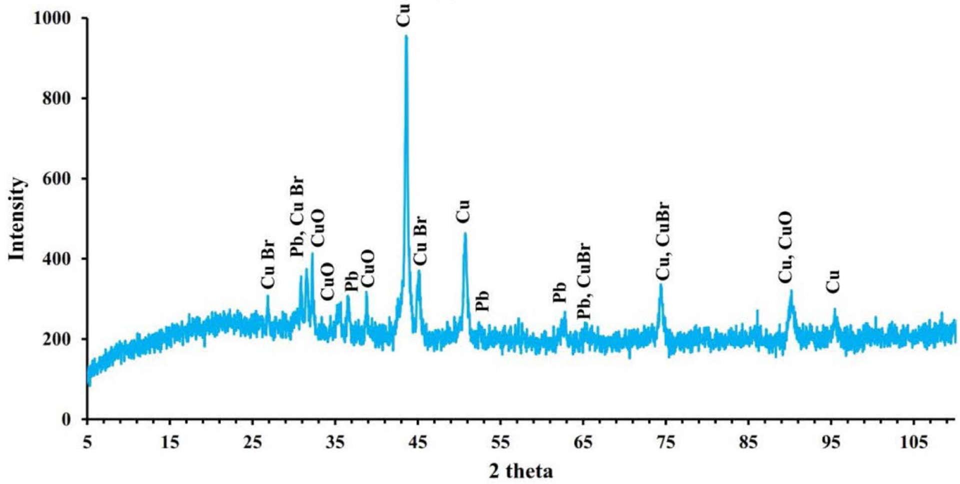


Fig. 3 (continued)

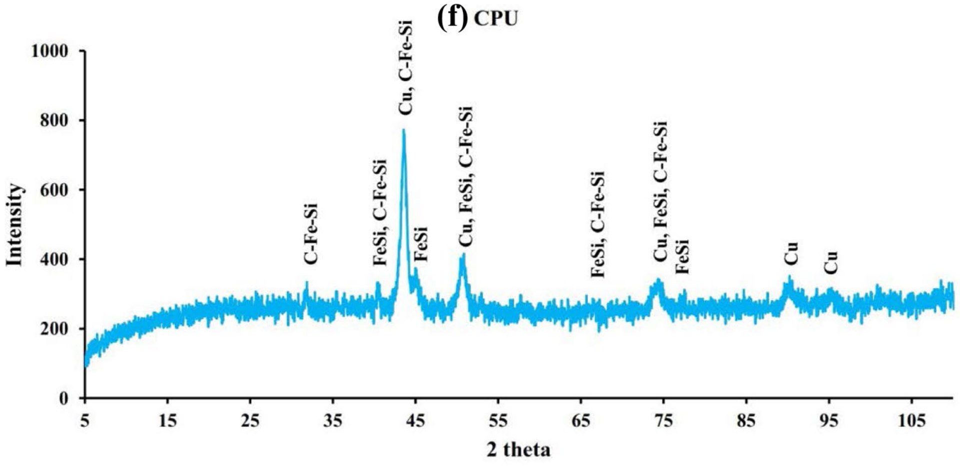
(d) COPCBs



(e) FPCBs



(f) CPU



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References

1. Pariatamby A, Victor D (2013) Policy trends of e-waste management in Asia. J Mater Cycles Waste 15(4):411–419
2. Habuer NJ, Moriguchi Y (2017) Resource-availability scenario analysis for formal and informal recycling of end-of-life electrical and electronic equipment in China. J Mater Cycles Waste 19(2):599–611
3. Ghodrat M, Rhamdani MA, Khaliq A, Brroks G, Samali B (2018) Thermodynamic analysis of metals recycling out of waste printed circuit board through secondary copper smelting. J Mater Cycles Waste 20(1):386–401
4. Rudnik E, Pierzynka M, Handzlik P (2016) Ammoniacal leaching and recovery of copper from alloyed low-grade e-waste. J Mater Cycles Waste 18(2):318–328
5. EPA (United States Environmental Protection Agency) (2004). The life cycle of a mobile phone, Solid waste and emergency response. (accessed 20 March 2010)
6. Holgersson S, Steenari BM, Bjorkman M, Cullbrand K (2018) Analysis of the metal content of small-size Waste Electric and Electronic Equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resour Conserv Recy 133:300–308
7. Garlapati VK (2016) E-waste in India and developed countries: Management, recycling, business and biotechnological initiatives. Renew Sust Energ Rev 54:874–881
8. Singh M, Thind PS, John S (2018) An analysis on e-waste generation in Chandigarh: quantification, disposal pattern and future predictions. J Mater Cycles Waste 20(3):1625–1637
9. Tanskanen P (2013) Management and recycling of electronic waste. Acta Mater 61(3):1001–1011
10. Jiang P, Song YX, Chen BQ, Harney M, Korzenski MB (2014) Environmentally benign solution for recycling electronic waste using the principles of green chemistry. Adv Mat Res 878:406–412
11. Korte F, Spiteller M, Coulston F (2000) The cyanide leaching gold recovery process is a nonsustainable technology with unacceptable impacts on ecosystems and humans: The disaster in Romania. Ecotox Environ Safe 46(3):241–245
12. Zhu P, Yang YZ, Chen Y, Qian GR, Liu Q (2018) Influence factors of determining optimal organic solvents for swelling cured brominated epoxy resins to delaminate waste printed circuit boards. J Mater Cycles Waste 20(1):245–253
13. Adie GU, Sun L, Zeng X, Zheng L, Osibanjo O, Li J (2017) Examining the evolution of metals utilized in printed circuit boards. Environ Technol 38(13–14):1696–1701
14. Dangton J, Leepowpanth Q (2014) A study of gold recovery from E-waste by bioleaching using Chromobacterium violaceum. Appl Mech Mater 548–549:280–283
15. Fogarasi S, Imre-Lucaci F, Egedy A, Imre-Lucaci A, Ilea P (2015) Eco-friendly copper recovery process from waste printed circuit boards using Fe3+/Fe2+ redox system. Waste Manage 40:136–143
16. Natarajan G, Ting YP (2014) Pretreatment of e-waste and mutation of alkali-tolerant cyanogenic bacteria promote gold biorecovery. Bioresource Technol 152:80–85
17. Xiang Y, Wu P, Zhu N, Zhang T, Liu W, Wu J, Li P (2010) Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. J Hazard Mater 184(1):812–818
18. Arshadi M, Mousavi SM, Rasoulnia P (2016) Enhancement of simultaneous gold and copper recovery from discarded mobile phone PCBs using Bacillus megaterium: RSM based optimization of effective factors and evaluation of their interactions. Waste Manage 57:158–167
19. Arshadi M, Mousavi SM (2015) Enhancement of simultaneous gold and copper extraction from computer printed circuit boards using Bacillus megaterium. Bioresource Technol 175:315–324
20. Kavitha AV (2014) Extraction of preious metals from E-waste. Int J Chem Pharm Sci 147–150
21. Yamane LH, Moraes VTD, Epinosa DCR, Tenorio AS (2011) Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. Waste Manage 31(12):2553–2558
22. Ilyas S, Lee JC, Kim BS (2014) Bioremoval of heavy metals from recycling industry electronic waste by a consortium of moderate thermophiles: process development and optimization. J Clean Prod 70:194–202
23. Yang Y, Chen S, Li S, Chen M, Chen H, Liu B (2014) Bioleaching waste printed circuit boards by Acidithiobacillus ferrooxidans and its kinetics aspect. J Biotechnol 173:24–30
24. Shah MB, Tipre DR, Purohit MS, Dave SR (2015) Development of two-step process for enhanced biorecovery of Cu-Zn-Ni from computer printed circuit boards. J Biosci Bioeng 120(2):167–73
25. Bazargan A, Bwegendaho D, Baford J, Mckay G (2014) Printed circuit board waste as a source for high purity porous silica. Sep Purif Technol 136:88–93
26. Das AK, Chakraborty R, Mde G, Cervera ML, Goswami D (2001) ICP-MS multielement determination in fly ash after microwave-assisted digestion of samples. Talanta 54(5):975–981
27. Imre-Lucaci F, Fogarasi S, Ilea P, Tamasan M (2012) Copper recovery from real samples of WPCBs by anodic dissolution. Environ Eng Manag J 11:1439–1444
28. Das S, Ting YP (2017) Evaluation of wet digestion methods for quantification of metal content in electronic scrap material. Resources 6(4):64
29. Arshadi M, Yaghmaei S, Mousavi SM (2018) Content evaluation of different waste PCBs to enhance basic metals recycling. Resour Conserv Recy 139:298–306
30. Lee H, Mishra B (2018) Selective recovery and separation of copper and iron from fine materials of electronic waste processing. Miner Eng 123:1–7
31. Ghosh B, Ghosh MK, Parhi P, Mukherjee PS, Mishra BK (2015) Waste Printed Circuit Boards recycling: an extensive assessment of current status. J Clean Prod 94(Suupplement C):5–19
32. Robinson BH (2009) E-waste: An assessment of global production and environmental impacts. Sci Total Environ 408(2):183–191
33. Basov V (2015) The world's highest grade gold mines. www.Mining.com
34. Tuncuk A, Stazi V, Ackil A, Yazici EY, Deveci H (2012) Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. Miner Eng 25(1):28–37
35. Metalary (*15 January* 2020). www.Metalary.com.
36. www.wikipedia.com
37. Basov V (2017) These 10 mines have the world's most valuable ore
38. Van Schaik A (2010) Reuter MA (2010) Dynamic modelling of E-waste recycling system performance based on product design. Miner Eng 23(3):192–210
39. Inc S (1999) Chapter 7: Basic of X-ray Diffraction: www.scintag.com. p: 1–25