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Pre-treatment of Printed Circuit Boards using eco-environmentally friendly techniques to concentrate metals prior their hydrometallurgical recovery and purification.

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Abstract

Printed circuit boards (PCBs) from dismantled WEEE contain various materials such as polymers, ceramics, wood, and metals. Metal recovery is the main objective of effective and appropriate recycling of PCB waste. In addition to precious metals (Ag, Au, Pd, etc.), this waste contains other valuable metals (Cu, Sn, Fe, Al, etc.). A crucial step in the recovery process is the concentration of metal particles. This study aims to determine an effective process for enriching metal particles, using simple methods suitable for developing countries, in order to recover metals, particularly precious metals, contained in PCBs. Two types of crushed PCBs, from RAM memory and mobile phone waste, were studied. Two concentration methods were used: a magnetic separation method using a neodymium magnet and a gravimetric separation method using a vibrating table. The results showed that magnetic separation, although not very effective, reduced the amount of magnetic metals. Gravimetric separation showed that the [0.355-0.09] mm particle size was more suitable for separation by vibrating table than the other particle sizes tested in this study (< 0.09 mm, [0.71-0.355] mm, and [1.5-0.71] mm). The precious metal yields for this particle size range between 73% and 87%.

Keywords: WEEE; PCBs; Metals; Physical separation

1. Introduction

The mean lifetime of electric and electronic equipment has been considerably reduced, causing an important production of waste, called waste of electric and electronic equipment or WEEE. Their production is increasing exponentially with time [1] and they are a global emergent problem, particularly in many developing countries. In addition to the WEEE produced by these countries, a significant flow of used electrical and electronic equipment with limited lifespans, originating from developed countries and sent as donations, adds to the quantities of WEEE that need to be managed [2]. Unlike industrialized countries that set systems of management of WEEE economically practicable for all the categories of equipment, the recycling system in the African countries is widely dominated by the informal sector [3]. For example, Burkina Faso disposes of a basic management of WEEE, that consist of their collection and their dismantling, and of the sorting of the different main components. The accessible and large parts, composed of pure metals - essentially iron, aluminum, copper and of plastics are sold locally. Components such as screens, batteries, chargers, printed circuit boards (PCBs) are either landfilled or exported toward the developed countries for an efficient management [4]. The difficulty of valorization of PCBs lies in their heterogeneity and their very complex composition.

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Moreover, they contain toxic substances such are chromium, lead, mercury, cadmium, tetra-bromo-bisphenol A, polychlorinated biphenyls, hexabromocyclododecane, polybrominated diphenyl-ether, and so on [5], [6], [7]. Despite these characteristics, those components constitute the most important part in the value added of the recycling of WEEE, essentially through the recovery of the precious metals – Ag, Au, Pt, Pd [8], but also of other metals (Al, Cu, Nb, Ni, Sn, Ti, Ta, Zn). As WEEE represent a potential economic resource [9], [10], [11], their recycling through an efficient, economic and environmentally friendly process participates to the relatively new trend called Urban mining [12], [13], [14] and to the preservation of the environment and health. In developed countries, pyrometallurgical/hydrometallurgical route is used, taken advantage of smelters developed in the production of base metals from natural ores and raw metals. Because they consume less energy and yield to a good recovery of metals, hydrometallurgical routes were developed. Nevertheless, they use acids or cyanides that are not environmentally friendly. New developments in hydrometallurgy, using green chemistry, consider the respect of the environment and of the health of people. However, to be economically viable and respectful of the environment (reducing of final waste and pollutions), hydrometallurgy needs pre-treatment stages to concentrate metals in a bulk product prior the hydrometallurgical treatments. This pre-treatment consists of crushing and grinding the PCBs to release metals from other materials such as plastics, ceramics and resins [15], followed by physical processes of separation of the constituents based on their different specific properties [16]. For example, to produce concentrates of metals and other materials contained in end-of-life PCBs, previous studies used magnetic separations [17], [18], gravimetric separations [19], [20], electrostatic and Eddy currents separations [21]. Other authors studied the effect of the particle size fraction of materials on the performances of gravimetric separations [16], [21], [22]. Printed circuit boards (PCBs) contain large amounts of precious metals [23], [24], [25], the aim of our research is to develop a simple route, respectful of the environment, necessitating low costs of use and maintenance and appropriated by developing countries, for the recovery of metals, especially precious metals, but also base metals. This study would be to produce a concentrate of metals by the mean of physical separations. The concentrate of metals will be further treated by hydrometallurgy to separate and purify the metals contained in our future work. The objective of this pretreatment is to remove as much as possible plastics, ceramics and resins and fiberglass, as well as ferrous metals. So, we will obtain a concentrate of non-ferrous metals. Il means that hydrometallurgical route to recover and purify non-ferrous metals, especially precious metals, will be made on a smallest amount of matter i.e. more economically to achieve (less chemicals, smallest reactors), more easily to perform (no or simplest filtration required after the leaching of metals) and with a more environment friendly management of residues of the waste (plastics). Of course, this step on beneficiation of the DEEE need to be performed efficiently: concentrate of non-ferrous metals must be as pure as possible and a as high as possible recovery of non-ferrous metals in the concentrate compared to the feed must be obtained.

2. Material and methods

2.1. Experimental material

Two types of the printed circuit boards (PCBs) are used in this study, the mobile phone boards and Random-Access Memory (RAM) boards, were provided by a local WEEE dismantling unit in Ouagadougou (Burkina Faso, West Africa), "Association Burkinabé pour la Promotion des Emplois Verts (ABPEV)". Some of the components under study are shown in Figure 1. These parts of WEEE were selected to have a relatively homogeneous materials, compared to main printed circuit boards of PC that vary widely with technology and purpose.

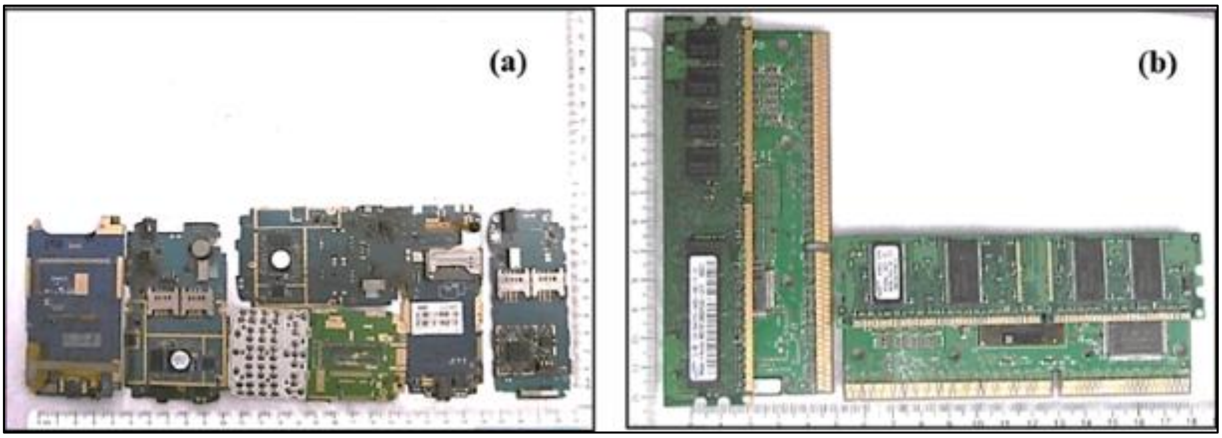


Figure 1 The various types of PCBs: (a) the cards of mobile phone boards and (b) the Random-Access Memory boards

2.2. Techniques of treatment investigated

A granulometric reduction of PCBs below 1.5 mm has been achieved with the successive use of a shredder and a hammer crusher. Its aim is to release the different components of the PCBs and to bring materials to appropriate dimensions for further processing steps.

A magnetic separation, to remove the magnetic metals, essentially Iron, Cobalt, and Nickel, has been realized on the dried crushed PCBs particles. It has been achieved by a manual scanning of a REE permanent magnet above particles spread on a table. Two fractions were obtained, one that is magnetic and another non-magnetic.

A gravimetric separation with a shaking table was used to remove the light particles of PCBs, that are essentially polymers, fiberglass, and ceramic. Shaking table (fig.2) is one of the wet gravity separators widely used in the mineral processing industry to recover valuable minerals from ores. It consists in a rectangular-shaped inclined plane with riffles (deck) animated by asymmetrical shakings (slow forward and rapid return strokes) acting along the longitudinal axis of the table. Separation is based on a combination of sedimentation and of entrainment forces acting on the particles. Crushed material to be treated is fed in a slurry which spread on the deck as a quick moving thin film. As the pulp flows down the incline, the particles settle according to their mass, which is a combination of their size and specific gravity. Light particles, carried by the film of water, pass over the riffles and are discharged along the long edge of the deck (Tailing). Heavy particles, trapped behind the riffles, are transported by the shakings towards the end of the table where they are discharged (Concentrate). Particles with intermediate behaviour are recovered between these two points (Middling).

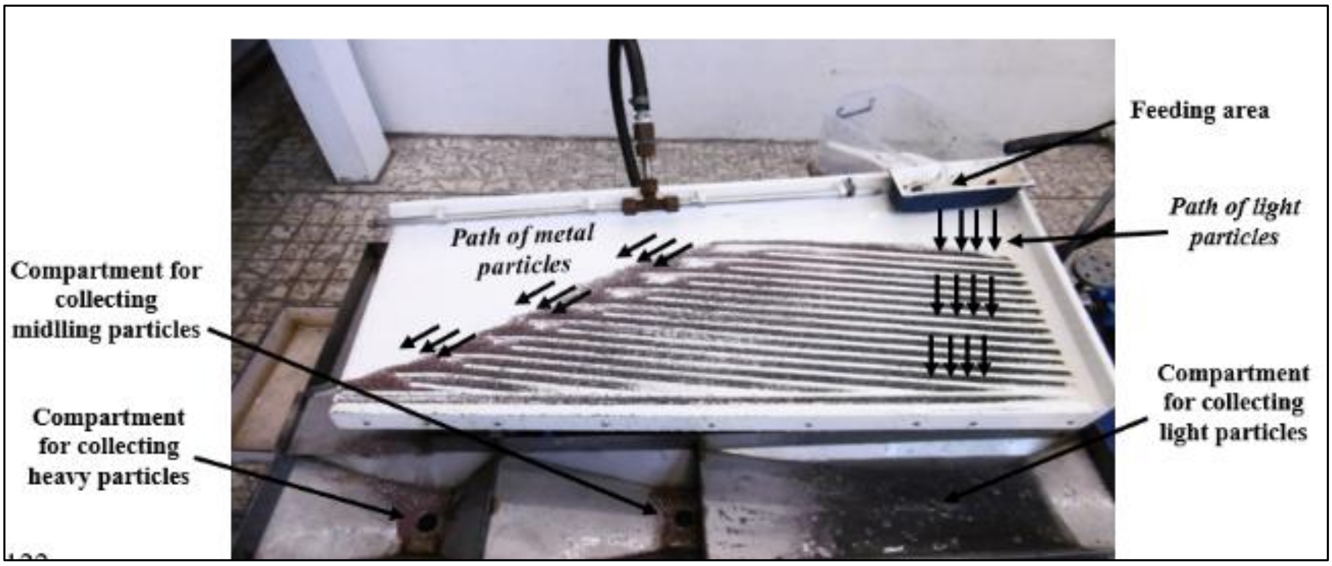


Figure 2 The shaking table used for our tests getting three (03) fractions from feed portion. The heavy fraction (fraction 1) is the concentrate of metals, the light fraction (fraction 3) contains polymers and fiberglass constituting the drain, and the middling fraction (fraction 2) is composed of particles of intermediate mass with not completely released components

Shaking table is an accessible equipment, easy to use and maintain, and may be suitable and effective for the separation of constituents in crushed PCBs. The study of [26], specifying the limits of use of unit operations in gravimetry, indicates that the shaking table would be the appropriate method for separating for particles in a size range from 0.01 to 1.5 mm. Its efficiency rests of different physical parameters of the particles such as size and granulometric distribution, difference of density of the constituents, etc.). Two approaches of gravimetric separation are tested. A first approach realized by means of separation of the particles, and a second approach by separation according to the level of release after a granulometric sort. For this, four particle size portions < 0.09 mm, [0.355 - 0.09] mm, [0.71 - 0.355] mm, et [1.5 - 0.71 mm were collected and enriched with the shaking table. This activity is carried out to study the influence of particle size distribution on the efficiency of gravimetric separation. Previous work has been carried out on the levels of metal particle release from PCB particles crushed into several particle size fractions [23].

2.3. Characterization and Evaluation of metals concentration in fractions

After separation with a shaking table, the obtained fractions were dried, weighted and analyzed. For chemical analysis, samples were leached by aqua regia solution (1:3 molar proportion of HNO_3 and HCl) according the method developed by Konaté et al., (2022). Analytical grade nitric acid (65%) and hydrochloric acid (37%) reagents for metal digestion, and standard solutions for instrument calibration were provided by VWR. Reading instrumental was carried out by ICP-AES Thermo Electron IRIS Intrepid II XSP instrument.

Evaluation of the efficiency of the separation has been made both in terms of the content of metals in the concentrate (the higher is the better) and of the recovery of metals in the concentrate (idem). The metal distribution in the different fractions is obtained from the following formula:

$$\chi_i(\%) = \frac{C_i \times m_i}{\sum C_i m_i} \times 100$$

Where:
Ci (w/w): concentration of the metal determined in the fraction.
mi: Weight of the fraction

Characterization tests were performed using the Hitachi SU8020 scanning electron microscope (SEM) at the Materia Nova research center in Mons, Belgium. The Bruker Titan S1 portable X-ray fluorescence spectrometer was used to determine the concentration in some samples. For this analysis, samples were taken from the obtained fractions, dried, and ground to a particle size < 65 µm before processing.

3. Results and discussion

3.1. Magnetic separation

Magnetic separation gave two fractions, a magnetic fraction which normally should contain ferromagnetic and paramagnetic components (metals), and a non-magnetic fraction constituted of non-magnetic constituents (metals and no-metals). The test was carried out on the whole mix, of crushed PCB particles with a particle size of <1.5 mm. The distribution of the two fractions obtained for the two types of PCBs is given in Table 1. The magnetic fractions constitute around 6-7% of the feed.

Table 1 Distribution of the fractions from the magnetic separation for the two types of PCBs

Fraction	Random Access Memory		Mobile phone PCBs	
	weigh (g)	(%wt)	weigh (g)	(%wt)
Magnetic fraction	60	6.9	55	6.0
Non Magnetic fraction	812	93.1	867	94.0
Feed	872	100	922	100

The magnetic fractions obtained in our study are lower than the quantities obtained in the literature, which are reported to be around 20% by weight of the total mass of the components [17], [27], [28]. This is due to the performance of the magnet used for our study, Neodymium N45, which is less powerful than the magnets used in the literature. Indeed, Yamane et al. (2011) used a cross-belt separator on particles with a grain size of < 2 mm, obtaining yields of 19% for the magnetic fractions of mobile phone cards. Observation of particles in magnetic fractions collected, showed in the Figure 3 carried out that the magnetic fraction contains magnetic particles materialized by dark particles, and non-magnetic materials. Some pure non-magnetic particles as the fiberglass, the plastics, ... were probably mechanically entrained with the magnetic particles and other materials. Also, some magnetic particles are contain both magnetic non-magnetic metals. This may be due to the fact that the release of the different components is not complete regardless of particle size.

Figure 3 Digital optical microscope image of the fraction of magnetic particles containing non-magnetic metals

Tables 2 and 3 present the data calculated on the magnetic metallic fraction obtained after the enrichment phase by magnetic separation for crushed particles of PCB waste from RAM cards and mobile phone cards.

The tables show that the concentrations of magnetic metals (Fe, Ni, and Co) are higher in the magnetic fractions compared to the non-magnetic fraction for both types of PCB waste. The concentration of Fe > Ni > Co in both types of PCB waste studied. However, when considering the weight contents (mg) of magnetic metals (Fe, Ni, and Co) are higher in the magnetic fraction for RAM waste than in the non-magnetic fraction, while for mobile phone card waste, the amount of Fe is higher in the non-magnetic fraction compared to the magnetic fraction. It is the same for Ni. This could be explained by the use of nickel in alloy form, particularly with palladium [29] the resulting alloy therefore having weaker magnetic properties.

It has also been observed that certain particles, due to their fine particle size, react little to magnetic attraction, as particle size influences their attraction by magnets, i.e., their magnetic susceptibility.

Other unreleased particles containing metals with magnetic properties and non-magnetic metals could not be extracted because the non-magnetic part exerts a stronger action on these particles, thereby reducing their reaction to magnetic forces.

It is also noted that some non-magnetic metals were carried over into the magnetic fraction. This would be due to several factors: on the one hand these metals are not completely released in the form of mono-metallic particles as shown in Figure 3, on the other hand these metals form alloys with magnetic properties [30].

Precious metals carried away in the magnetic fraction represents less than 10%, except for the Pd in the Random-Access Memory which is 38% in the magnetic fraction. This can be explained by the paramagnetic properties of Pd [31], and that some alloys from Pd and other metals would have magnetic properties [30], [32]. The larger part of base metals such as Al, Cu, Sn, Pb, … is very concentrated in the non-magnetic fraction. Only Mn is moderately carried away in the magnetic fraction for the two types of PCBs.

Although the separation was not as efficient as expected due to the low magnetic power of the magnet used, in this study it had the advantage of limiting the entrainment of other non-magnetic metals due to alloys and metals bonded to magnetic particles.

Table 2 Results and assessment of magnetic separation on crushed RAM

The type of fraction	Iron				Nickel				Cobalt			
	Content (kg/t)	Weight (g)	Distribution (%)	Distribution in fraction (%)	Content (kg/t)	Weight (g)	Distribution (%)	Distribution in fraction (%)	Content (g/t)	Weight (mg)	Distribution (%)	Distribution in fraction (%)
Magnetic fraction	$3.2\ 10^2$	19	71	32	$1.8\ 10^2$	11	54	17	$1.2\ 10^4$	749	83	1.2
Non-magnetic fraction	5.8	7.7	29	1	11	8.9	46	1	185	150	17	0.03
Feed	31	27	100		22	20	100		1 497	899	100	

Table 3 Results and assessment of magnetic separation on crushed mobile phone cards

The type of fraction	Iron				Nickel				Cobalt			
	Content (kg/t)	Weight (g)	Distribution (%)	Distribution in fraction (%)	Content (kg/t)	Weight (g)	Distribution (%)	Distribution in fraction (%)	Content (g/t)	Weight (mg)	Distribution (%)	Distribution in fraction (%)
Magnetic fraction	$4.7\ 10^2$	26	47	47	36	2.0	12	4	2 215	123	61	0.22
Non-magnetic fraction	34	29	53	3	16	14	88	2	92	79	39	0.01
Feed	61	56	100		18	16	100		219	202	100	

The behaviour of precious metals (gold, silver, and palladium) and certain base metals during the magnetic enrichment phase was also studied. Figures 4 and 5 show the distribution (%) of some metals of interest in the magnetic and non-magnetic fractions.

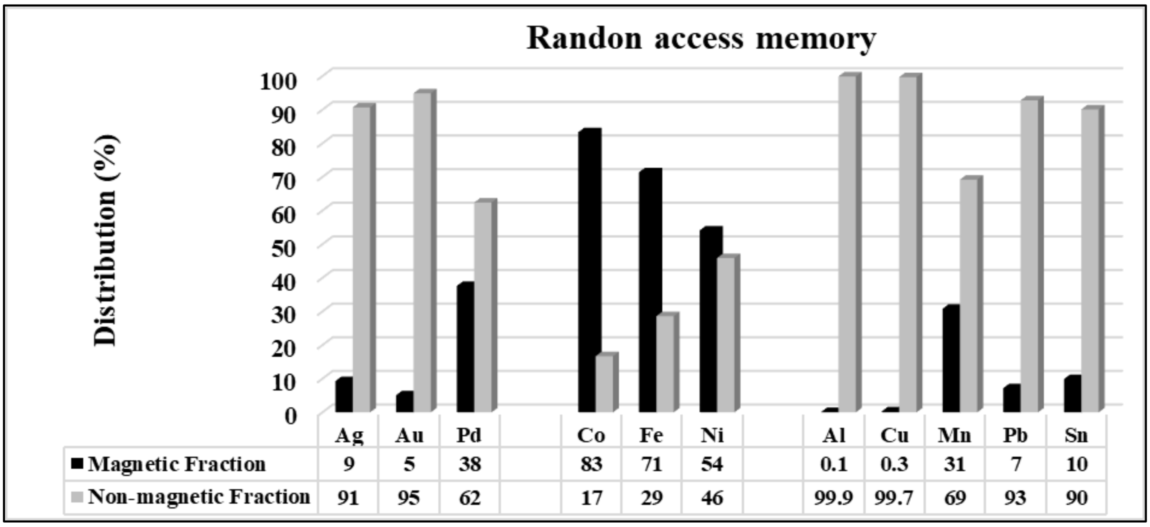


Figure 4 Distribution of metals between the two fractions of the RAM crushed particles

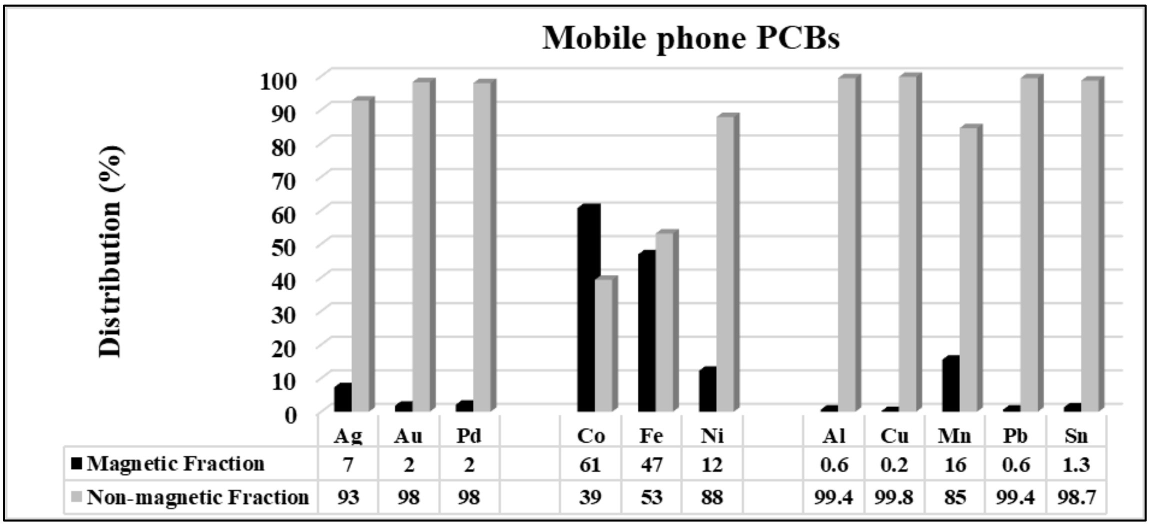


Figure 5 Distribution of metals between the two fractions of the mobile phone PCBs crushed particles

3.2. Gravimetric separation

Gravimetric separation was performed on the non-magnetic fraction resulting from the magnetic separation phase. After various separation tests using a shaking table, the samples were recovered, dried, and weighed. The purpose of this step is to concentrate the metals of interest, mainly precious metals and base metals, in one fraction.

The efficiency report of this concentrate step was carried out on the three fractions obtained, namely the "metal concentrate fraction", the "middling fraction", and the "drain fraction". The samples were crushed using a disc mill before being digested with aqua regia and analyzed by ICP-AES.

3.2.1. Separation of crushed PCBs

For this step, the enrichment test was performed on all of the non-magnetic material from crushed PCB particles. The results obtained for gravimetric separation using the shaking table are presented in the tables 4 and 5. It can be seen that the weights of the "drain fraction" are greater than those of the "metal-concentrated" and "middling" fractions for both types of PCBs. Also, the distribution (%) of precious metals obtained in the "metal-concentrated" fractions is significantly higher than that found in the other two fractions. It should be noted that the mixed fraction is considered to be an intermediate fraction and which must be reintroduced into the material and still subjected to separation. Indeed, large particle sizes show a low release rate, which can influence the properties common to the two types of fractions (reject and metals) to be separated. In an industrial process, the middling's will be recycled (may be crushed) in close a loop on the table.

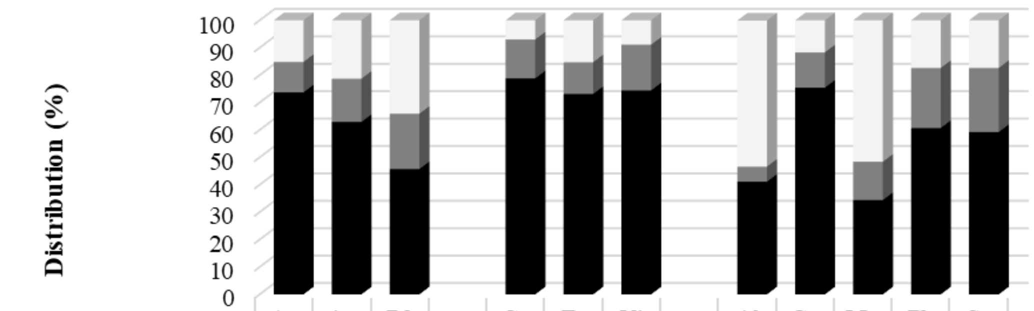
Table 4 Results and assessment of gravimetric separation on the shaking table of the non-magnetic RAM particles crushed

Fractions	Weight (g)	Distribution (%)	Gold (Au)			Siver (Ag)			Palladium (Pd)		
			Weight (mg)	Distribution (%)	Concentration (g/t)	Weight (mg)	Distribution (%)	Concentration (g/t)	Weight (mg)	Distribution (%)	Concentration (g/t)
Concentrated in metals	300.3	37.0	377	62.8	1257	174	74.3	579	92	45.8	307
Middling	122.8	15.1	95	15.8	772	25	10.7	204	41	20.2	330
Drain	389.2	47.9	129	21.4	331	35	15.1	91	68	34.1	176
Feed	812.3	100	601	100	740	234	100	288	201	100	248

Table 5 Results and assessment of gravimetric separation on the shaking table of the non-magnetic mobile phone PCBs particles crushed

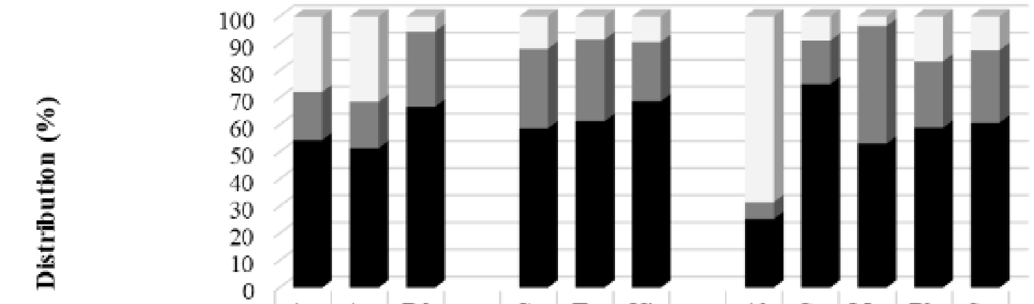
Fractions	Weight (g)	Distribution (%)	Gold (Au)			Siver (Ag)			Palladium (Pd)		
			Weight (mg)	Distribution (%)	Concentration (g/t)	Weight (mg)	Distribution (%)	Concentration (g/t)	Weight (mg)	Distribution (%)	Concentration (g/t)
Concentrated in metals	322.0	37.2	148	50.5	460	182	54.4	565	1429	66.7	4438
Middling	179.9	20.8	50	17.0	278	59	17.7	328	595	27.7	3307
Drain	364.4	42.1	95	32.4	261	92	27.8	252	117	5.5	321
Feed	866.3	100	293	100	339	333	100	396	2142	100	2877

Although separation using the shaking table concentrated most of the metals in one fraction, the yields did not show any remarkable distribution. They varied between 45 and 75%, but these values were not optimal. The concentrations and distribution of base metals and magnetic metals were also determined during this concentration step using a shaking table. Figures 6 and 7 show that Cu exhibits the highest concentration yield of 75% in the "metal-concentrated" fraction. Al and Mn are more concentrated in the "drain fraction" due to their lower density. Other metals, such as Sn, Pb, and the magnetic metals, are more concentrated in the "metal-concentrated fraction" but with yields between 50 and 60%.



	Ag	Au	Pd		Co	Fe	Ni		Al	Cu	Mn	Pb	Sn
Drain	15	21	34		7	15	9		53	12	52	17	17
Middling	11	16	20		14	12	17		6	13	14	22	23
Concentrated in metals	74	63	46		79	73	74		41	75	34	61	59

Figure 6 Distribution of metals between the three fractions of the RAM crushed particles



	Ag	Au	Pd		Co	Fe	Ni		Al	Cu	Mn	Pb	Sn
Drain	28	32	6		12	9	9		69	9	4	17	12
Middling	18	17	28		29	30	22		6	16	43	25	27
Concentrated in metals	54	51	67		59	61	69		25	75	53	59	61

Figure 7 Distribution of metals between the three fractions of the mobile-phones PCBs

After particle size sorting and observation of particles of the concentrate metals fraction under a digital microscope, numerous glass fiber and metal particles were present in the <0.063 mm particle size class, and to a lesser extent in the [0.09 - 0.063] class, as shown in Figure 8. This demonstrates the influence of particle size on gravimetric separation yield. We can also deduce that the shaking table separation technique may not be suitable for concentrating crushed PCB particles with a particle size of < 0.090 mm. Our previous work has shown that the level of efficient metal release is for particle sizes < 0.71 mm (65% release of metal particles) and even better for those < 0.355 (70% release of metal particles) [23].

Therefore, in order to evaluate the influence of particle size on the efficiency of gravimetric separation, tests were conducted on two types of crushed PCBs: mobile phone card waste and RAM strips. The following particle size fractions were used: < 0.09 mm, [0.355 - 0.09] mm, [0.71 - 0.355] mm, and [1.5 - 0.71] mm.

Figure 8 Particles from the metal-concentrated fraction resulting from the gravimetric separation of crushed PCBs observed at a digital microscope according to different particle sizes: a- < 0.063 mm; b- [0.09 - 0.063]; c - [0.125 - 0.09]; d - [0.18 - 0.125]; e- [0.25 - 0.18]; f- [0.355 - 0.25]; g- [0.71 - 0.355]; h- [1.0 - 0.71]; i- [1.5 - 1.0]

3.2.2. Gravimetric separation based on particle size

After separation on the shaking table, the samples were recovered, dried, and weighed. Samples taken from each batch were then analyzed to determine the concentration of the various metals in each fraction for the four (04) different particle size fractions.

The results of precious metal concentrations for the different particle size fractions are presented in Tables 6 and 7. It can be seen that the weights of the ‟drain fraction″ are generally the highest, except in a few cases. Also, the metals are more concentrated in the metal-concentrated fraction than in the other two fractions. It can be seen that the smaller the particle size fractions, the better the separation efficiency, with the notable exception of the finest particle size class (< 0.09 mm). These results are consistent with the fact that the level of metal particle release is better for the finest particle size fractions [33], and with the low efficiency of the shaking table for very small particles (< 0.09 mm). Even though the < 0.09 mm grain size fraction is characterized by a lower metal concentration yield than the [0.355 - 0.09] mm fraction, this yield remains higher than those obtained for the larger grain size fractions ([0.71 - 0.355] mm and [1.5 - 0.71] mm). We conclude that the optimal grain size fraction for effective gravimetric separation using a shaking table and metal concentration is the [0.355 - 0.09] mm fraction.

At this particle size, it was noted that an intermediate fraction between the medium fraction and the metal-concentrated fraction formed a fairly dark-colored fraction, shown in Figure 9.b.

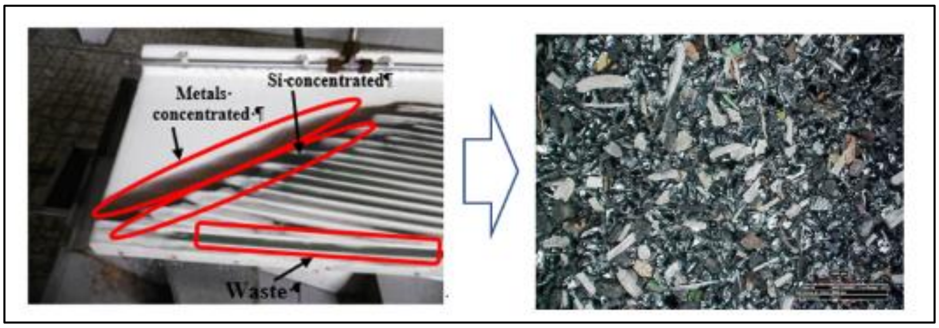


Figure 9 Images of: (a) the shaking table during the separation phase of particles in the [0.355-0.09] mm particle size fraction of RAM PCBs, (b) and the intermediate fraction obtained

Table 6 Gravimetric separation yields as a function of particle size classes on ground mobile phone PCBs

Particle size fraction (mm)	Fraction	Weight of fractions (g)	Ag			Au			Pd		
			Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)	Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)	Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)
< 0.009	Concentrated in metals	182.5	88.2	483.2	64.4	204.1	1118.2	67.8	46.4	254.2	64.8
	Drain	237.3	28.9	121.9	21.1	53.6	225.7	17.8	14.7	61.9	20.5
	Middling	77.5	19.9	256.5	14.5	43.2	556.9	14.3	10.5	135.3	14.7
[0.355 - 0.009]	Concentrated in metals	285.7	325.8	1140.3	82.3	394.5	1380.7	80.0	107.7	377.1	72.9
	Drain	280.5	39.8	142.0	10.1	53.2	189.7	10.8	27.4	97.8	18.6
	Middling	81.3	30.3	373.0	7.7	45.6	560.8	9.2	12.6	155.2	8.5
[0.710 - 0.355]	Concentrated in metals	252.7	161.2	637.9	60.8	94.3	373.2	42.7	24.9	98.5	47.5
	Drain	351.5	84.1	239.4	31.7	86.5	246.0	39.2	25.3	72.0	48.3
	Middling	93.9	19.8	211.3	7.5	39.9	424.9	18.1	2.2	23.8	4.3
[1.5 - 0.71]	Concentrated in metals	362.6	78.9	217.7	44.7	111.1	306.5	39.5	117.6	324.4	65.8
	Drain	225.7	63.4	280.8	35.8	138.0	611.3	49.1	23.0	102.0	12.9
	Middling	115.6	34.5	298.2	19.5	31.9	276.3	11.4	38.2	330.8	21.4

Table 1 Gravimetric separation yields as a function of particle size classes on ground mobile phone PCBs

Particle size fraction (mm)	Fraction	Weight of fractions (g)	Ag			Au			Pd		
			Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)	Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)	Weight (mg)	Concentration (mg/kg)	Distribution in fraction (%)
< 0.09	Concentrated in metals	89.0	66.5	746.8	55.2	130.0	1460.6	70.9	66.4	746.0	77.3
	Drain	178.1	34.5	193.8	28.7	23.5	131.8	12.8	8.5	47.9	9.9
	Middling	49.1	19.4	395.7	16.1	29.9	608.1	16.3	11.0	223.3	12.8
[0.355 - 0.09]	Concentrated in metals	281.4	321.3	1141.7	79.6	482.3	1714.0	86.8	136.8	486.2	85.6
	Drain	322.4	54.8	169.9	13.6	36.6	113.6	6.6	13.2	41.0	8.3
	Middling	74.9	27.5	367.5	6.8	36.6	489.3	6.6	9.9	131.7	6.2
[0.71 - 0.355]	Concentrated in metals	268.7	172.6	642.2	61.6	403.9	1503.1	65.0	110.9	412.7	52.6
	Drain	291.2	68.7	235.8	24.5	122.7	421.5	19.8	50.9	174.7	24.1
	Middling	94.5	38.8	410.1	13.8	94.4	999.4	15.2	49.1	519.8	23.3
[1.5 - 0.71]	Concentrated in metals	397.4	167.8	422.3	39.5	486.8	1224.9	41.2	241.8	608.5	46.4
	Drain	443.6	177.0	399.0	41.7	367.2	827.7	31.1	139.5	314.4	26.8
	Middling	259.4	80.0	308.5	18.8	327.8	1263.5	27.7	139.5	537.6	26.8

An X-ray fluorescence analysis was performed on a sample of this fraction, and the results are presented in Table 8. It shows that this fraction is majorly composed by Silica (Si), but it also contains some metals in fairly low concentrations. Its density valor is between metals and waste which are composed of polymer, wood, ceramic, etc.

Table 8 Elements content (%) in the residue fraction obtained for the particle size portion [0.355 - 0.009] from the separation with the shaking table, analysis by X fluorescence, mainly composed of Si

Chemical elements	Si	Al	As	Cu	Ti	Fe	Pb	W	Sn	Zr
Distribution (%)	**92.5**	**2.7**	**2.8**	**1.2**	**0.3**	**0.1**	**0.1**	**0.1**	**0.04**	**0.02**
Uncertainty (%)	**0.5**	**0.2**	**0.1**	**0.03**	**0.1**	**0.02**	**0.01**	**0.01**	**0.01**	**-**

The distribution (%) of other metals of interest, major metals, and remaining magnetic metals was also examined. The results are presented in Figures 10 and 11. It can be seen that most metals are more concentrated in the concentrated metals fraction″, except for aluminum, which is more concentrated in the ‟drain fraction″. This can be explained by the low density of Al, which behaves like the particles that make up the drain fraction [34]. It can be seen that the [0.355 - 0.09] mm particle size fraction has better separation yields for both PCB components. However, unlike precious metals, the [1.5 - 0.71] mm particle size fraction is followed by the [0.71 - 0.355] mm fraction. The < 0.09 mm particle size fraction has the lowest yields for base metals except for Pb.

These data confirm the previous statements. The most suitable particle size for separation with the shaking table is [0.355 - 0.09] mm.

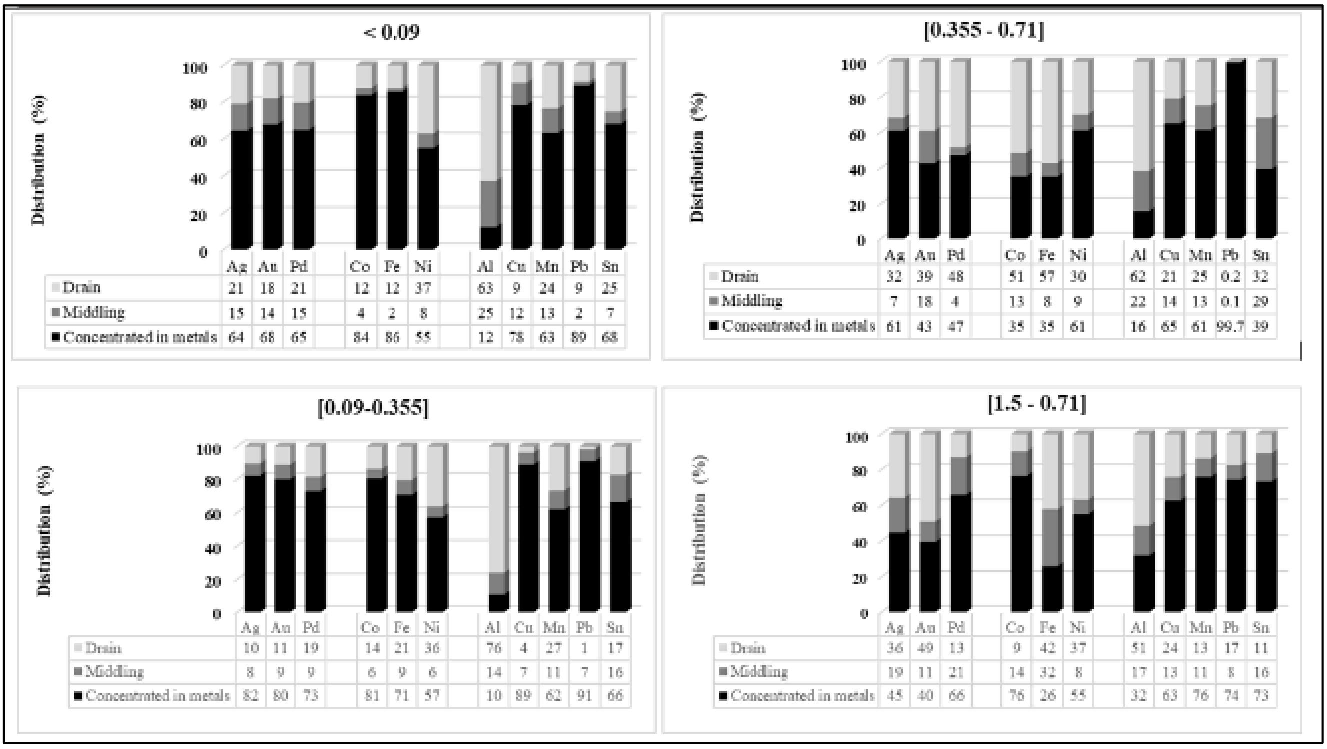


Figure 10 Distribution of metals between the three fractions of Random Memory Access based on particle size

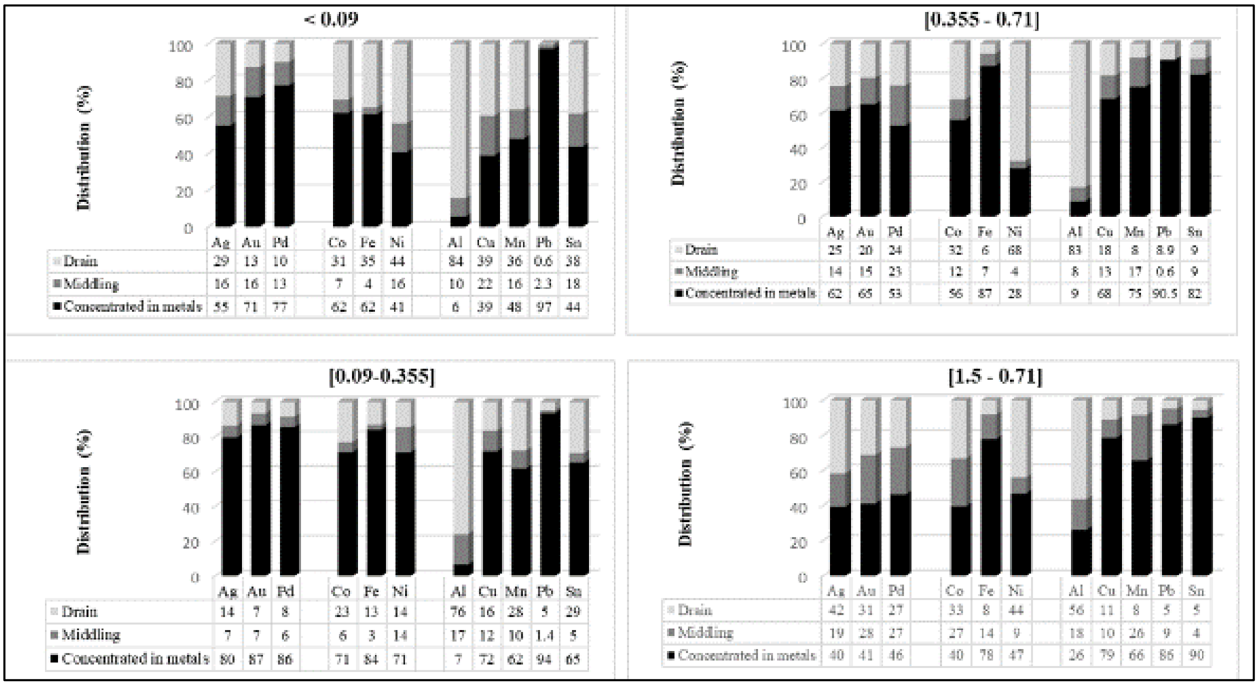


Figure 11 Distribution of metals between the three fractions of mobile phone PCBs based on particle size

A map of the distribution of metals for the [0.09 - 0.355] mm grain size fraction was obtained by SEM-EDX (Figure 12).

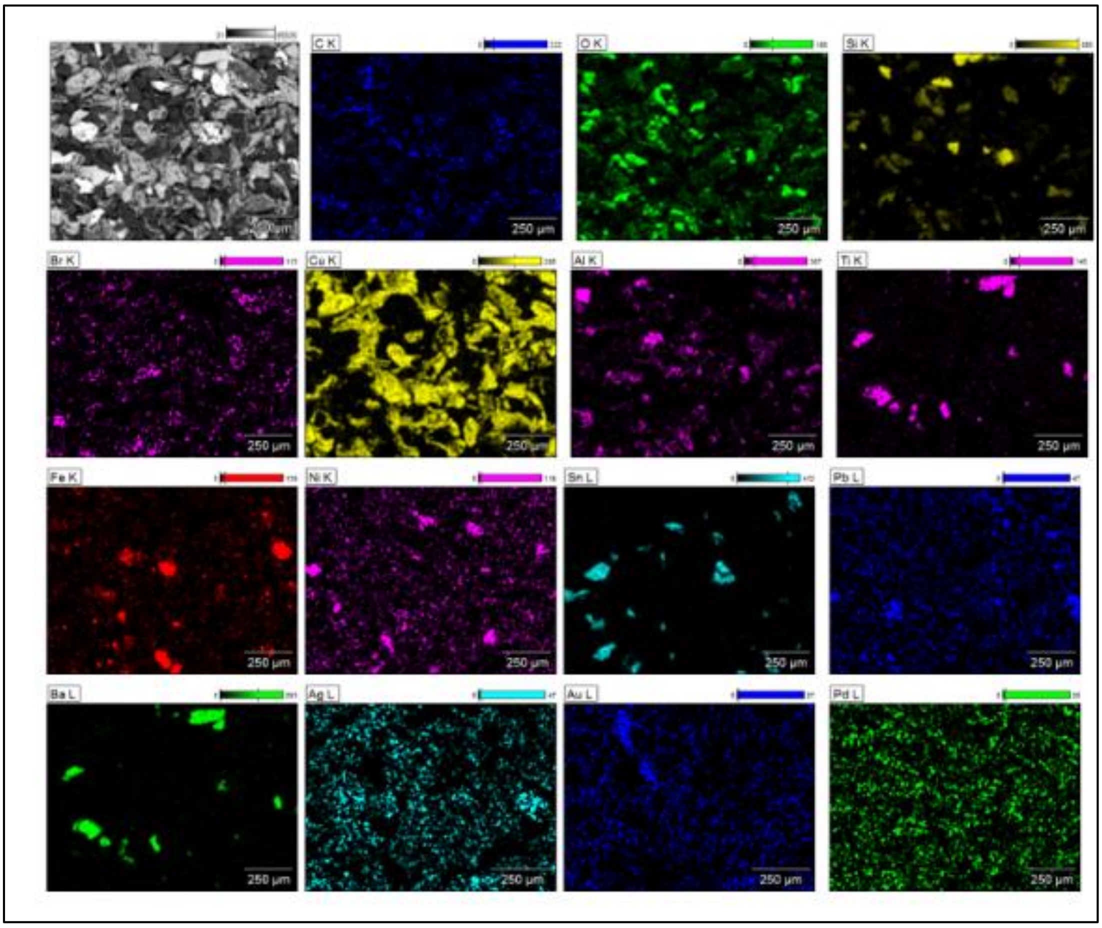


Figure 12 Mineralogical mapping performed using SEM-EDX for the [0.355–0.09] mm particle size fraction concentrated in metals from crushed PCBs

As expected, copper is the most abundant element. The following metals have been identified: Al, Ti, Fe, Ni, Sn, Pb, Ba, in addition to precious metals (Ag, Au, and Pd). Polymers were also identified, with the presence of carbon (C) and oxygen (O), as well as bromine (Br) and silicon (Si), albeit in small quantities. SEM imaging identified elementary metal particles

4. Conclusion

The metal enrichment process was carried out in two stages: magnetic separation followed by gravimetric separation. Magnetic separation generally proved effective for magnetic metals (iron, nickel, and cobalt). More than half of the magnetic metals were extracted into the "magnetic metal concentrate fraction" for RAM. Ni and Fe concentration was less effective for cell phone particles. The amounts of precious metals (silver, gold) lost in the magnetic metal concentrate were less than 20%. Palladium was present in higher proportions in the magnetic fraction due to its alloying with magnetic metals. Small amounts of major metals (<10%) such as copper, aluminum, lead, tin, and zinc were also present in the magnetic fractions. Gravimetric separation, performed on a vibrating table, was carried out on particles with size fractions of [1.5–0.71], [0.71–0.355], [0.355–0.09], and < 0.09 mm. The results showed that metal concentration is optimal in the [0.355–0.009] mm particle size fraction. In general, precious metals were concentrated at yields between 87% and 73%, unlike the other fractions where the best yields were between 68% and 40%. The particle size fraction < 0.09 mm exhibited the highest yields after the [0.355–0.009] mm fraction for precious metals. So, the best method for enriching metallic particles in printed circuit board waste involves magnetic separation of particles smaller than 0.355 mm using a low-intensity magnet to recover the most magnetic particles and avoid the removal of Pd. Separation with a rare-earth magnet may be necessary to remove less magnetic particles and fine particles. Gravimetric separation requires two different particle size ranges: [0.355 - 0.09 mm] and < 0.09 mm to perform this concentration step.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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