Waste Management 139 (2022) 17–24

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Waste electrical and electronic equipments as urban mines in Burkina Faso: Characterization and release of metal particles

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A R T I C L E I N F O

Keywords:
WEEE
PCBs
Metals release
Chemical elements characterization
Metals distribution

A B S T R A C T

Like other developing countries, Burkina Faso is one of the preferential destinations for second-hand electrical and electronic equipments (EEE). At the end of their life, these EEEs are classified as waste electrical and electronic equipment (WEEE) including Printed Circuit Boards (PCB). A particle size reduction is realized for the release of metals by shredding and grinding to obtain particles smaller 1.5 mm. A granulometric sorting was realized and nine granulometric portions were obtained. Particles were characterized by optical microscopy and Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (EDS). The experiments confirmed that the fractions contained polymers, glass fibers and metals under the form of single metals or alloys. The release of metal was efficient for particles with a size smaller than 0.71 mm. Three digestion procedures were experimented on four components to assess the impact on metals leaching. Microwave-assisted digestion method was the best procedure, compared to the analysis methods ISO 11466: 1995, and method 3050B, adapted. The characterization by Inductively coupled plasma atomic emission spectroscopy (ICP-AES) of these PCBs exhibited important amounts of precious metals (Ag, Au, Pd) and other metals in greater quantities (Cu, Pb, Ni, Co, etc.), leading to their qualification as "Urban Mines" calling for their recovery. The characterization of metals in each granulometric portion is realized. Precious and others metals were distributed in all granulometric size portions. So granulometric size reduction was not efficient for metal separation and recovery from PCBs and alternative methods should be investigated for selective precious metal recovery.

1. Introduction

The global amount of waste electrical and electronic equipments (WEEE) is increasing dramatically, causing important health and environmental concerns (Ghosh et al., 2015). Electronic waste (e-waste) consists of several types of materials: plastics (polyethylene, polypropylene, polyesters, and polycarbonates), recoverable metals (Ag, Al, Au, Br, Ca, Co, Cu, Fe, Mn, Nb, Ni, Pd, Pt, Si, Sn, Ti, Ta, Zn), toxic metals (Cr, Pb, Hg, Cd, etc.) and organic compounds (tetrabromo-bisphenol A, polychlorinated biphenyls, hexabromocyclododecane, polybrominated diphenyl ether used as flame retardants in Printed Circuit Boards (PCBs), etc. (Cesaro et al., 2018; Tian et al., 2018; Guo et al., 2011; Hadi et al., 2015; Souza et al., 2017). Because of toxic substances in e-waste with significant risk levels for human health and the environment, responsible management of end-of-life WEEE has to be promoted (Achillas et al., 2013). Current e-waste management strategies recommend recycling for better control of toxic metals such as Pb, Hg, Cd, Be, etc., when WEEE are landfilled or incinerated. An additional good e-waste management strategy is the recovery of precious and special metals (Au, Ag, Pd, Cu, Pt, etc.) for the generation of economic income. In addition to locally generated WEEE, African and Asian countries are the main destinations for many second-hand EEE from the rest of the world (Bimir, 2020; Li et al., 2013; Ongondo et al., 2011). The widespread recycling techniques for electronic waste in Africa are basic and the lack of

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https://doi.org/10.1016/j.wasman.2021.12.014
Received 12 April 2021; Received in revised form 5 December 2021; Accepted 7 December 2021
Available online 16 December 2021

technical facilities and skills make a challenge of the handling and recycling of hazardous materials (Rajarao et al., 2014). The typical e-waste management strategies consist of the collection and manual dismantling of WEEE, and uncontrolled incineration for the recovery of metals, emitting hazardous components in the atmosphere (Rajarao et al., 2014). Besides countries with poor WEEE management practices, some African countries as Ghana, Nigeria, Kenya, Egypt, etc., (Bimir, 2020; Maphosa et al., 2020) have well-organized sectors for WEEEs recycling, generating important amounts of recovered materials mainly Fe, steel, Al, and Cu (Rachid, 2018). In Burkina Faso, both formal and informal sectors are in charge of the collection, dismantling, and sorting of WEEE. Available metals from dismantling (Fe, Al, and Cu) are recovered manually and sold to local artisans. Plastics, screens, and printed circuit boards are most of the time exported to developed countries for recycling. Printed circuit boards (PCBs) contain large fractions of metals deposited on substrates (Alzate et al., 2016; Jadhav and Hocheng, 2015). PCBs represent up to 4 or 7% of the total mass of WEEE (Li et al., 2018) and are essentially composed by three types of materials: organic materials, ceramics, and metals (Hubau et al., 2019; Khaliq et al., 2014; Shittu et al., 2021). Precious metals constitute the largest share in terms of the added value of recycling WEEE (Zhang et al., 2017), hence their name “urban mines” (Arora et al., 2017). This category of WEEE in sub-Saharan Africa is partly intended for export to developed countries for more efficient and effective treatment (Kaya, 2016). Therefore, it is suitable to design and implement in developing countries appropriated facilities for precious metals recovering to optimize income generation from urban mines.

Four PCBs types were concerned by the present study: cell phone printed circuit boards, computer printed circuit boards, Random Access Memory (RAM), and Processors. These four types of PCBs are representative of the collected and exported PCBs from Burkina Faso (Rachid, 2018).

Pretreatment is the first step in the recovery process. It consists of metal release from other materials by particle size reduction. Mechanical processes are recommended compared to pyrolysis which is less protective for the environment because of harmful gas emissions (Buekens and Yang, 2014). The key role of pretreatment techniques on the release of metals from plastics, cardboard, and other materials is well established. For characterization of chemicals elements in PCBs, grinding methods is also appropriate for samples preparation, for a best leaching of the metals. And it is more interesting to realize a fine grinding. Ogunniyi et al. (2009) and Kitane et al., (2015) reported respectively studies about fine grinding and shredding followed by pyrolysis as techniques promoting metal particles liberation.

For an efficient metal release from supporting materials, a two-step particle size reduction process was reported (Lee et al., 2017; Wang et al., 2018). The first step consisted of shredding and the second one of finer grinding. Sarvar et al. (2015) reported a complete release of metals from plastic, ceramic and cardboard respectively for the following particle size portions (in millimeters): [1.68 – 2.38], [0.21–0.42] and $<$ 0.21.

Dissolution of resulting particle portions in wet solutions was also carried out by two digestion methods: open environment digestion by heating on a hotplate (Petter et al., 2014) and microwave-assisted digestion in closed environment. According to literature, many leaching solutions are available for metal digestion: HNO_3-HCl, HF, H_2SO_4-H_2O_2, HCl, HNO_3, fusion with Na_2O_2 or $LiBO_2$ followed by dissolution in dilute HCl solution. Ogunniyi et al. (2009) compared some digestion procedures and showed that dissolution in aqua regia was better than microwave digestion with a mixture of HNO_3 and HF, and then fusion with Na_2O_2followed by dissolution in HCl solution. Some other authors (Mičková et al., 2018; Subhabrata and Yen-Peng, 2017; Tunali et al., 2020) showed that H_2O_2 added to acid solutions (HCl and HNO_3) was more effective and less harmful than aqua regia, but this digestion procedure has been only the subject of few recent publications.

The present study aims to, assess the method for particle size reduction to ensure efficient metal release from PCBs, determine the most suitable digestion procedure to ensure accurate quantitation of metals in PCBs, and to establish the relation between particle size and metal content.

2. Materials and methods

The four components of printed circuit boards (PCBs) that are the motherboard PCBs, mobile phones PCBs, processors, random access memory were provided by a local WEEE dismantling unit in Ouagadougou (Burkina Faso, West Africa), “Association Burkinabé pour la Promotion des Emplois Verts (ABPEV)”. Analytical grade HNO_3 (65%) and HCl (37%) reagents for metal digestion, and standard solutions for instrument calibration were provided by VWR. Analytical grade H_2O_2 (30%) was provided by MERCK.

2.1. *Particle size reduction for metal liberation*

To achieve efficient metal release, two steps of particle size reduction were realized. The first step consisted of shredding PCBs with a knife grinder, manufactured locally with initial particle sizes from 6 cm to 35 cm. The second step consisted of cascade grinding by a hammer grinder Retsch SK 300 with grids of 5, 3, and 1.5 mm. During this step, the temperature of the grinder chamber was about 113 °C ± 1.5 °C. A particle size sorting was then carried out with a sieve shaker Retsch AS 300 control. Basing on literature data (Sarvar et al., 2015) to release the maximum metal particles from the polymer, the biggest sieve size was 1.5 mm. Therefore, ten particle size portions were collected and analyzed ([1.5–1.4]; [1.4–1.0]; [1.0–0.71]; [0.71–0.355]; [0.355–0.250]; [0.250–0.180]; [0.180–0.125]; [0.125–0.090]; [0.090–0.063]; $<$0.063) mm. Scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX) experiments were carried out for microstructural characterization of sorted particles with a Hitachi SU8020 microscope at Materia Nova Research Center in Mons (Belgium).

2.2. *Elemental characterization of particle portions*

Fine grinding was carried out with a RETSCH grinder disc for two minutes to obtain particles size inferior to 125 μm. The particles were then dried at 50 °C for 24 h in an oven. Three digestion procedures were used to determine the most efficient for metal characterization in the PCBs. The first method consisted of leaching 1 g of the ground particles in a beaker with 20 mL of aqua regia solution (1:3 M proportion of HNO_3 and HCl), adapted of the analysis method ISO 11466:1995. The solution was stirred at 105 °C in a watch-glass-covered beaker until a volume of approximately 5 mL was obtained after evaporation. The leachate was then filtered and diluted with a HNO_3 solution. The second digestion method is adapted of the analysis method 3050B. It has consisted of mixing 10 mL of HNO_3 with 1 g of ground particles; the mixture was stirred at 95 °C for 30 min. Then 5 mL of H_2O_2 were added for the oxidation of the organic material. The solution was completed with 15 mL of HCl, and after 30 min the remaining solution was recovered with a diluted HNO_3 solution. The third procedure consisted of acid digestion by an Ethos Milestone microwave power 220 V/50–60 Hz, 2.4 kW. The HPR-ME-10 digestion program suitable for single metals and Ag, Au, Pd, and Pt alloys samples was applied. The whole digestion is carried out at a pressure of 45 bar. The program is starts by an increase of temperature to reach 220 °C in 20 min followed by a dwelling time of 15 min before the decrease. 0.1 g of ground particles, 2 mL of HNO_3, 6 mL of HCl, and 0.5 mL of H_2O_2 were mixed in a teflon vessel for this digestion program.

Metal concentrations were determined by ICP-AES with a Thermo Electron IRIS Intrepid II XSP instrument.

2.3. Determination of metal percentages in granulometric portions

Particles were grinded for to get samples of size < 125 µm, and they were dried. After drying and grinding, particles were digested according to the procedure described for aqua regia and the metal content determined by ICP-AES. The metal proportion for each granulometric portion was calculated from Gámez et al. (2019) relation (1).

$$P_x(\%) = (W*100)/W_t \quad (1)$$

where:

P_x = Metal proportion (%) content in the particle size portion
W = Metal mass in granulometric portion
W_t = Total metal mass in all granulometric portions.

3. Results and discussion

3.1. Influence of granulometric reduction on metal particles liberation

It is well known that smaller the particles are better metal elements can be released from polymer supporting material of PCBs. The desired final particle size had to be inferior to 1.5 mm for efficient metal release (Sarvar et al., 2015). From initial dimensions ranging from approximately 35 cm to 6 cm, the particles obtained after shredding were smaller than 20 mm. Some were inferior to 1.4 mm. The weight fraction of particles size inferior to 1.4 mm after shredding were respectively 33%, 25%, 16%, and 51% for Mobile phone printed circuit boards, Computer printed circuit boards, Random Access Memory (RAM), and Processors. These particles were removed before performing the second size reduction. From grinding the obtained particle size were inferior to 1.5 mm. The particles obtained after mechanical size reduction are composed of several types of material as specified by several authors (polymers, fiberglass, and metals) (Bachér et al., 2015; Hadi et al., 2015).

The particles obtained after grinding were subjected to a size sorting to produce the logarithmic curves representative of the cumulative weights in % of the ground particles as presented in Fig. 1.

The curves showed a constant evolution of the slope between the class portions −0.063 mm to [0.71–0.355] meaning that the quantities were fairly constant for these portions. But the proportions of the biggest particles were more important, as attested by the sudden sharpening of the curve. In general, all curves had the same shape, showing that the type of component had no significant influence on the results of grinding. The hammer mill was effective for secondary particle size reduction. The most important portions in weight were [0.71–0.355], [1.0–0.71] and [1.4–1.0] mm fractions. In each portion, different types of materials were observed: metals presented with a bright appearance and many morphologies, fiberglass presenting tapered morphology, and polymers with a green color.

EDX analyses were performed to estimate the mean elemental composition in some specific areas of the surface samples. The EDX results can be used to estimate the concentration of some chemical elements, but more importantly, used to assess the liberation level of the metals particles (Gonçalves and Otsuki, 2019; Otsuki et al., 2020). The data that were obtained for analysis of the different granulometric portions showed that the particles with dimensions inferior to 0.71 mm exhibited a better release of metals. Some metals were superimposed while other formed alloys, meaning that the size reduction techniques did not allow efficient separation leading to single metal release.

Polymer particles were attested by the presence of C and O in high content, as presented in Table 1 (particles portions 2, 3, and 6). The portions consisting mainly of metals were particle portions 1, 4, and 5 (Table 1). The major metals were encountered in large particle size portions while precious metals were predominant in small particle size portions.

The release of metals was improved when the particle size decreased. Some of the particles of the finest fraction were analyzed by MEB-EDX and the results were presented in Table 2. The metals particles analyzed (shiny particles) showed that they are constituted also of polymers and glass fibers and traces of silica. Some metal particles were constituted by a single metal while others were alloys. Particle 5 and 6 in Table 2 constituted by Fe, Cr and Ni could be identified as a stainless-steel alloy. Particle portion 1 containing Sn and Pb originated probably from soldering alloy.

3.2. Influence of digestion procedure on the elemental characterization of PCBs

The concentration of twenty-one (21) metals occurring in PCBs is presented in Table 3. Precious metals (Au, Pd, Ag, etc.), magnetic metals (Co, Fe, Ni), potentially toxic metals (Cr, Pb, As, Hg, etc.), and some major metallic elements were identified in the granulometric portions.

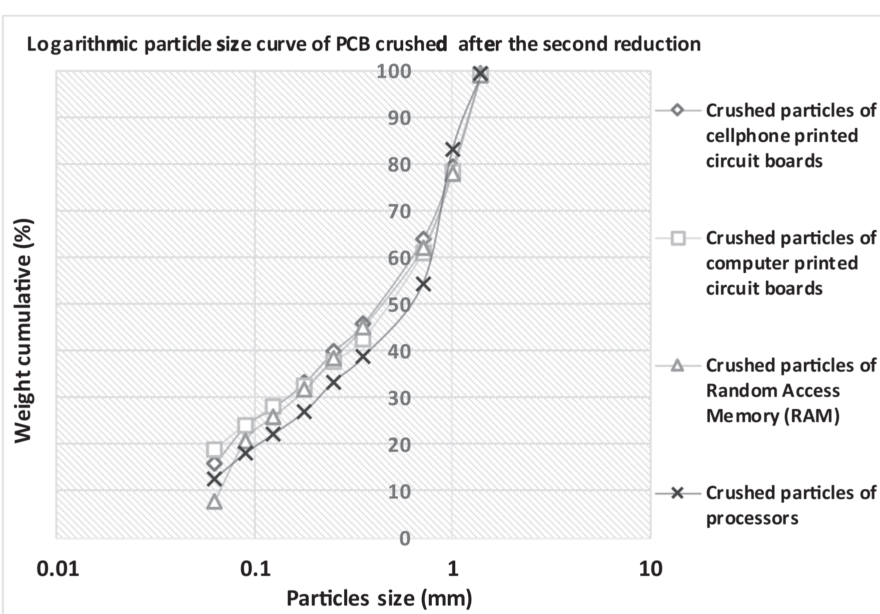

Fig. 1. Logarithmic particle size curve of PCBs crushed after the second reduction.

Table 1
Composition of crushed PCBs particles for [0.71–0.355] mm granulometric fraction analyzed by SEM-EDX.

Chemical elements	Wt. %					
	Particle 1	Particle 2	Particle 3	Particle 4	Particle 5	Particle 6
C	8.2 ± 0.3	**33.3 ± 0.5**	**45.6 ± 0.6**	15.9 ± 0.7	9.0 ± 0.3	**48.3 ± 0.6**
O	19.7 ± 1.4	**30.5 ± 0.9**	**35.9 ± 0.9**	4.9 ± 0.3	13.0 ± 0.3	**36.0 ± 0.6**
Mg	–	0.2 ± 0.1				0.1 ± 0.1
Al	1.5 ± 0.2	5.6 ± 0.1	–	0.8 ± 0.2	1.9 ± 0.2	5.9 ± 0.5
Si	2.9 ± 0.2	5.8 ± 0.1	3.8 ± 0.1	0.8 ± 0.1	–	5.9 ± 0.1
S	0.2 ± 0.1	–	0.2	–	0.3 ± 0.1	–
Ca	–	1.6 ± 0.1	0.5 ± 0.1	0.1	–	0.2
Fe	–	0.2 ± 0.1	0.3 ± 0.1	–	0.7 ± 0.2	0.5 ± 0.1
Ni	0.6 ± 0.3	–	–	1.8 ± 0.4	–	–
Cu	4.9 ± 0.9	22.5 ± 0.7	5.3 ± 0.5	**75.8 ± 2.2**	2.3 ± 0.4	1.9 ± 0.3
Br	–	–	8.1 ± 0.2	–	–	6.6 ± 1.1
Sn	**61.9 ± 1.4**	–	–	–	**70.1 ± 14**	–
Ba	–	0.3 ± 0.1	0.3 ± 0.1	–	2.8 ± 0.3	–

Table 2
Composition of crushed PCBs particles of − 0.063 mm granulometric portion as analyzed by SEM-EDX.

Chemical elements	Wt. %					
	Particle 1	Particle 2	Particle 3	Particle 4	Particle 5	Particle 6
C	8.8 ± 0.3	**11.2 ± 0.4**	**8.6 ± 0.4**	18.3 ± 0.5	4.3 ± 0.2	**8.7 ± 0.4**
O	5.0 ± 0.4	**3.7 ± 0.5**	**7.2 ± 0.4**	8.4 ± 0.5	1.4 ± 0.7	**6.0 ± 0.7**
Al	1.4 ± 0.1	1.8 ± 0.2	2.3 ± 0.1	1.4 ± 0.2	0.6 ± 0.1	1.0 ± 0.1
Si	–	1.7 ± 0.2	0.7 ± 0.1	1.2 ± 0.2	1.4 ± 0.1	1.2 ± 0.1
Ca	0.1	0.6 ± 0.2	0.2 ± 0.1	0.3 ± 0.1	–	–
Cr	–	–	–	–	16.0 ± 0.5	14.7 ± 0.3
Mn	–	–	–	–	1.4 ± 0.3	0.9 ± 0.3
Fe	–	–	–	1.4 ± 0.2	67.7 ± 1.1	57.0 ± 1.0
Ni	–	–	–	–	7.2 ± 0.8	6.5 ± 0.8
Cu	–	81.0 ± 1.6	81.1 ± 1.6	69.0 ± 1.5	–	1.2 ± 0.4
Sn	2.6 ± 0.3	–	–	–	–	–
Ba	–	–	–	–	–	1.9 ± 0.5
Pb	81.8 ± 6.7					

Table 3
Metal content (ppm) and (%) for the four types of PCBs according to digestion methods on particles of < 0.125 mm in (1) Computer printed circuit boards, (2) Mobile phone printed circuit boards; (3) Processors; (4) Random Access Memory (RAM).

Digestion Methods		$HCl + HNO_3 + H_2O_2$				Aqua regia				Microwave digestion			
Composants		(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Precious metals (mg/kg)	**Ag**	**750**	**861**	**128**	**537**	**543**	**478**	**109**	**520**	**718**	**1189**	**119**	**1507**
	Au	**234**	**234**	**897**	**585**	**278**	**260**	**917**	**480**	**366**	**469**	**1381**	**940**
	Pd	**251**	**2447**	**277**	**353**	**262**	**2345**	**246**	**942**	**245**	**2171**	**225**	**829**
	Pt	4.6	5.2	6.0	2.9	5.7	5.2	6.2	3.9	6	2.3	3.2	3.6
	Rh	–	–	–	–	4.8	6.2	2.3	7.3	–	–	–	2.4
	Ru	10	185	–	11	357	3609	107	1286	386	3974	212	1259
	Ir	4.3	15	54	20	2.9	11	48	3613	–	8	31	8
Toxic metals (mg/kg)	**Cd**	9	15	12	6	9	15	11	9	11	15	8	9
	Cr	733	11 010	259	855	6161	6517	628	848	702	7345	411	2359
	Hg	–	–	–	–	–	–	1,26	–	–	–	–	–
	As	12	48	18	23	19	46	21	32	21	40	36	32
	Pb	14 254	7149	5895	7944	13 530	7222	10 684	9229	14 912	8358	7802	8796
Other metals (%)	**Al**	2.0	0.7	0.2	0.5	2.6	1.6	2.3	1.9	3.1	2.1	1.6	1.8
	Co	0.2	0.05	2.4	0.08	0.3	1.4	1.7	0.08	0.2	0.03	1.4	0.05
	Cu	21.1	28.9	27.0	20.3	26.2	28.1	27.0	20.6	20.0	22.3	22.6	16.0
	Fe	3.7	8.8	9.8	3.9	6.4	9.0	7.4	4.3	4.5	6.6	4.9	4.6
	Mn	0.06	0.2	0.05	0.07	0.1	0.2	0.06	0.1	0.06	0.1	35.9	0.08
	Ni	0.9	1.8	6.7	2.6	1.5	4.1	5.8	2.8	1.1	1.7	3.9	3.1
	Sn	3.1	2.0	2.5	1.8	3.1	2.8	3.5	2.1	3.8	2.7	3.8	2.2
	Zn	1.5	1.0	0.1	0.2	1.4	0.5	1.0	0.2	2.2	0.8	16.3	0.2

Collected data revealed that Cu was the major metallic element for the four types of WEEEs, with an average content higher than 20 wt% as reported by previous studies (Hubau et al., 2019; Tunali et al., 2020). Al, Co, Fe, Ni, Sn, and Zn also occurred in relatively higher concentrations. Compared to natural mines contents in precious metals (Ag, Au, Pd) which are generally not higher than 20 ppm (Butler, 2011; Zuzolo et al., 2018), the recovery of these metals from WEEEs exhibited very interesting yields (from 200 to over 2000 ppm) confirming the status of urban mines of that e-wastes (Ilankoon et al., 2019).

The proportions for the different metallic elements depended on the type of electronic waste. Despite changes in digestion procedures the differences in metal contents for the four types of electronic waste remained the same.

Thus, Pd was more abundant in Mobile phone printed circuit boards (2) than in other types of e-wastes. Pd release was not affected by the digestion procedure. Au was more abundant in Processors (3). Ag seemed more abundant in Mobile phone printed circuit boards (2), but the release of that metal was not very effective with aqua regia digestion. The observed variations in metal content depending on the digestion procedure could be due to sampling variability for each experience: indeed, even after effective mixing of the initial sample portion before sampling, the obtained samples for digestion remained heterogeneous (Sarvar et al., 2015).

Microwave digestion with the mixture acids HCl and HNO_3 associated with H_2SO_4 has shown better results for the dissolution in general of the contents of precious metals compared to other methods of digestion method ISO 11466: 1995, and method 3050B adapted. Experiments generally highlighted that microwave digestion, leading to a complete dissolution in closed environment, presented the best results compared to the other digestion methods (association of HNO_3, HCl, H_2O_2, and aqua regia) (Jacques et al., 2014; Subhabrata and Yen-Peng, 2017). Au, Ag, and Ru were better leached by the microwave digestion. However, Rh was leached by the aqua regia digestion method for all types of WEEEs, and only for Random-access memory (RAM) after microwave digestion.

Nevertheless, mercury (Hg) was not released by microwave digestion but with aqua regia digestion in the case of Processors (3). Interferences must have intervened in the digestion of the other metals due to the heterogeneity of the particles. Literature available data confirm the influence of sampling on the variability of metal content from WEEEs (Laubertova et al., 2019; Mählitz et al., 2020).

It is noticeable that the metal content in PCBs from the present study was significantly different from those of previous studies except the one of Oguchi et al. (2013). For precious metals, the concentrations of Au and Ag were in the same range for Oguchi et al. (2013). However, Pd concentrations were significantly higher in mobile phones than in all previous studies. Cu was the main element from all studies with about more than 20 wt% of the total metal content, excepted in data presented by Ogunniyi et al. (2009) who reported much lower Cu content for PCBs. The assessment of Hg appeared challenging for all studies. Pb was abundant in all studies. Cd, another toxic metal was in much lower concentrations. The present study reported higher content of toxic Cr than previous papers. For all studies, the main metals were Al, Cu, Fe, Ni, Sn, and Pb (Gámez et al., 2019; Hall and Williams, 2007; Stellan et al., 2016). However, it must be noted that, the disc grinding having been carried out on a sampled fraction of the particles < 1.5 mm obtained after the secondary grinding (hammer grinding); the metal contents obtained is related to this fraction. Sampling of a different amount could have an influence on the representativeness of initial metal content, because to the heterogeneity of the particles of the starting fraction.

In their study, (Mičková et al., 2018) have found that microwave digestion with HCl-HNO_3-H_2O_2 was more efficient than the digestions realised with aqua regia, and HCl - HNO_3 - H_2O_2 mixtures. (Tunali et al., 2020) have obtained the same conclusions, mainly for the precious metal recovery, in their study that addresses the same comparison of the three analysed methods. Our conclusions are in adequation with those of the literature: a total microwave digestion method using the mixture of the acid solutions HCl-HNO_3 with H_2O_2 appears to be the best digestion method for the treatment of precious metals.

In addition, several other studies on digestion methods have figured out that the heterogeneity of the samples has an impact on the results interpretation (Remeteiová et al., 2020; Subhabrata and Yen-Peng, 2017).

3.3. Metals characterization for the different granulometric portions

After shredding and grinding different types of WEEEs it was important to characterize the metal content for each portion. This helps determine the best granulometric portion for the optimal concentration of metals of interest. Experiments were carried out for the four classes of WEEEs (computer PCBs, Mobile phone PCBs, Processors, and RAMs). Metal contents were determined by ICP-AES after aqua regia digestion.

3.3.1. Distribution of metals in the granulometric fractions of crushed computers PCBs

Precious metals content in computer PCBs as reported in Fig. 2 showed that Au and Ag were homogeneously spread in all portions with a predominance in < 0.063 and [1.4–1.0] mm portions. However, Pd was very concentrated in the [1.4–1.0] mm class with up to 70 % for this metal. Oliveira et al. (2010) showed that gold (Au) distribution in granulometric fractions of ground PCBs did not depend on the size portions while silver (Ag) concentration increased when the size of particle portions decreased.

Major metals were also distributed in all classes as presented in Fig. 2. These elements were predominant in the [1.0–0.71] and [1.4–1.0] mm fractions and lower in [0.71–0.355] mm portion. Only Al and Fe were significantly concentrated in the smallest portion ($<$0.063 mm).

3.3.2. Distribution of metals in the granulometric fractions of crushed mobile phones PCBs

The distribution of metal content for different granulometric portions is presented in Fig. 3. From this figure, it appeared that Ag and Au were distributed in all class portions with a preference for < 0.063 and [1.4–1.0] mm fractions. As for computer PCBs, Pd was very concentrated in [1.4–1.0] and [1.0–0.71] mm portions with respectively 66 % and 14 % of total Pd in those fractions. Fig. 3 exhibited that the major metals were distributed in all the class portions. However, Cr, Fe, and Mn were specifically concentrated in [1.4–1.0] class portion, representing respectively 65, 68, and 65% of the total metal content. Al, Cu, Pb, and Sn were more or less present in all class portions.

Ani et al. (2020) showed that both major and precious metals are more important in the fractions with the largest particle sizes. Palladium (Pd) was exclusively concentrated in intermediate particle size ([1–0.5] mm). The larger particle size for these authors was 4 mm while it was 1.5 mm for the present study. It can be assumed that for the [4–1] mm particle portion Pd is not released from the supporting material. And under 0.5 mm particle size, there is no more Pd in the portion.

3.3.3. Distribution of metals in the granulometric fractions of crushed processors

The distribution of precious metals according to granulometric portions (Fig. 4) showed that silver (Ag) was well distributed in all portions with a preference for the smaller ones. On the contrary gold (Au) and palladium (Pd) were respectively highly concentrated in [1.4–1.0] and [1.0–0.71] mm fractions; these portions represented respectively 52% and 62% of the total content for Au and Pd.

From Fig. 4 it appeared that the major magnetic metals (Co, Fe, and Ni) were highly concentrated in the [1.4–1.0] and [1.0–0.71] portions (respectively 95%, 85%, and 90% of the total metal amount). However, for other major metals (Cr, Cu, Pb, Sn, and Zn), significant amounts were present in all portions. About 50% of aluminum (Al) were in the finer fraction.

3.3.4. Distribution of metals in the granulometric fractions of crushed random-access memory (RAM)

Data reported in Fig. 5 showed that silver (Ag) and palladium (Pd) were present in significant quantities in the [1.4–1.0] and [1.0–0.71] mm fractions, representing more than 70% of the total precious metal content. Pd preferentially occurred in [1.4–1.0] and [1.0–0.71] fractions but was well distributed in the other particle size portions. Magnetic metals (Co, Fe, and Ni) and Zn, as shown in Fig. 5 were abundant in [1.4–1.0] and [1.0–0.71] mm portions with more than 75% of the total amount of major metal content. The other major metals (Al, Cr, Cu, Mn,

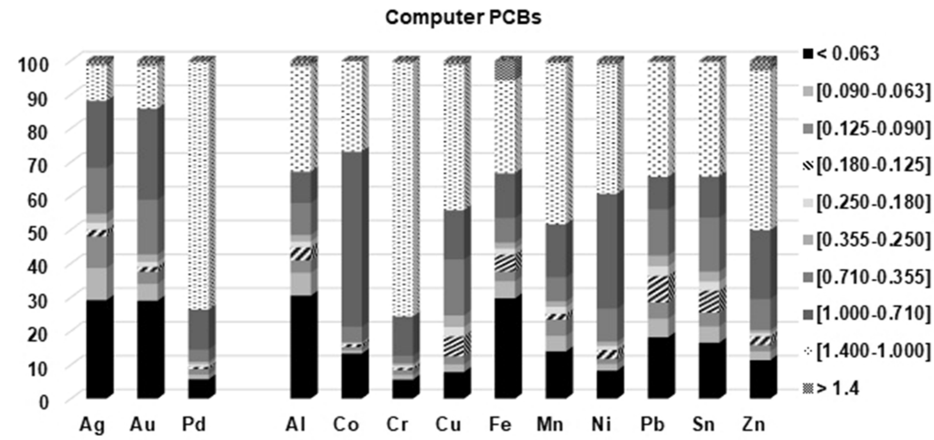

Fig. 2. Precious metals and Major metals distribution in the particle size portion for computer PCB (% w/w).

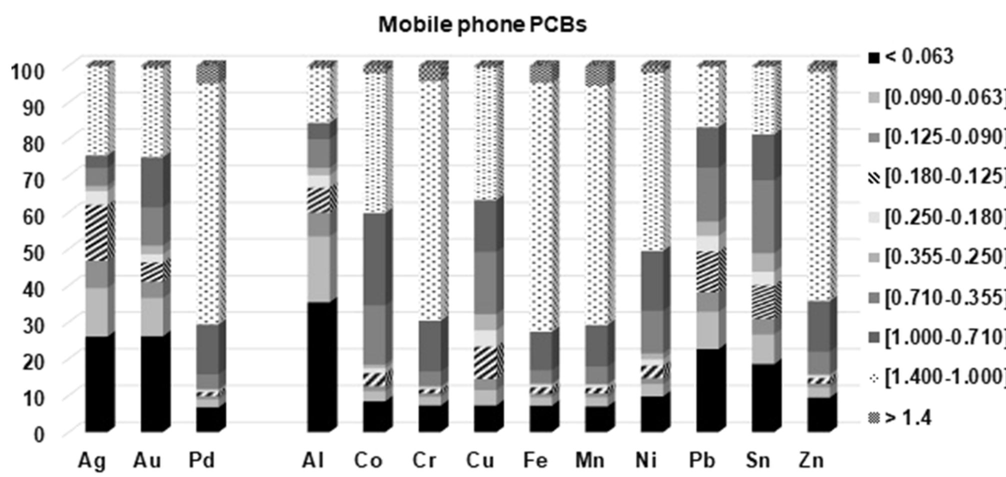

Fig. 3. Precious metals and Major metals distribution in particle size portions for mobile phone PCB (% w/w).

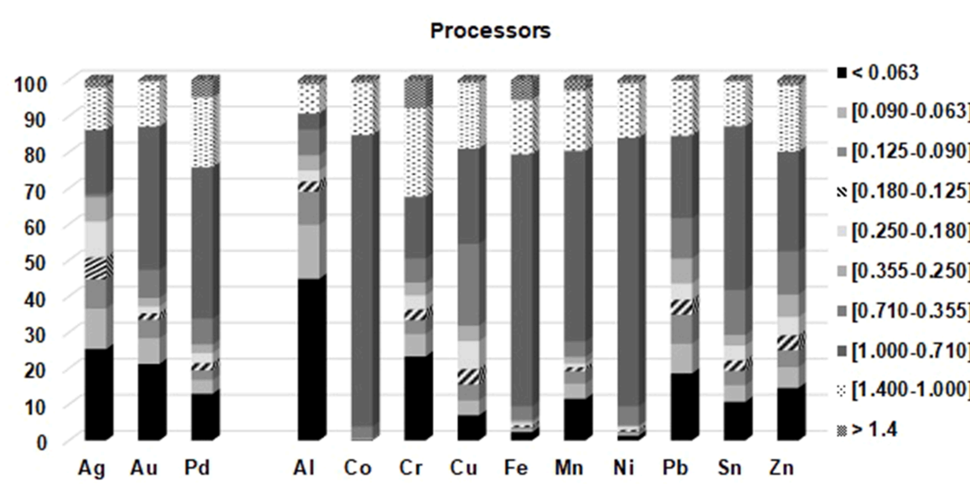

Fig. 4. Precious metals and Major metals distribution in particle size portions for processors (% w/w).

Pb, Sn) were distributed in all portions with a preference for the [1.4–1.0] and [1.0–0.71] mm fractions.

4. Conclusion

The granulometric size reduction process by shredding and grinding showed an effective release of the particles from the studied PCBs, for a granulometric smaller than 0.71 mm. The SEM analysis showed that free metal particles, whatever their size, were most of the time associated with other metals or non-metallic materials. Therefore, it was hard to achieve a total release of specific metal by grinding. Chemical analysis showed that the metal content depended on both PCBs type and

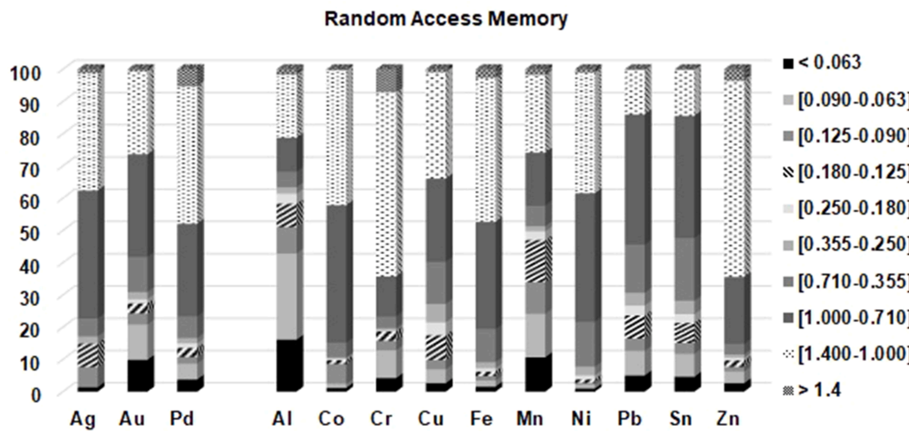

Fig. 5. Precious metals and Major metals distribution in particle size portions for RAM (% w/w).

digestion procedure. Microwave-assisted digestion led to better metal leaching than other open environment hotplate digestion methods. The concentrations of precious metals were quite high and confirmed the interest in developing procedures for environmental-friendly metal recovery in WEEE collected in Burkina Faso. It appeared from metal distribution in granulometric portions data that metals were distributed most of the time in all size classes. Therefore, granulometric separation could not be seriously implemented for efficient recovery of metals from WEEE. It would be more suitable to envisage a strategy for the concentration of metals, specifically precious metals (Ag, Au, Pd) to recover metals whatever the granulometric size fraction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by ARES-CCD and the authors would like to thank Materia Nova Research Center in Mons (Belgium) for SEM-EDS analysis.

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