

Exploration of the material distribution of complex components in waste electrical and electronic equipment

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Abstract

Technological development combined with a rapid and global market penetration has led to high volumes of Waste Electrical and Electronic Equipment (WEEE). Simultaneously, the use-phase has become shorter resulting in an annual growth rate of WEEE between 3-5%, which makes WEEE one of the fastest growing waste streams. The high metal content of WEEE has been a driving force for behind the expansion of recycling industry. However, during the de-pollution process, a certain type of components is sorted out, which due to their diversity in shape, size, and material composition, cannot be assigned to any homogenous material. These components can generally be classified as complex components and include Printed Circuit Boards (PCB), Hard Disk Drives, Power Supply Units, etc.

The aim of the present research is to provide an assessment of the material composition of complex components exemplified in more detail on PCBs. A set of minimal requirements has been developed in order to increase comparability of available data sets. Furthermore, a novel classification system has been designed for PCBs with according to the current recycling practices in EU. Finally, the paper provides a mapping of complex components with a particularly high content of precious metals and critical raw materials.

Keywords: PCB, precious metals, critical raw materials, trace metals, WEEE characterization.

1. Introduction

Intensive technological development of electrical and electronic devices combined with a rapid and global market penetration has led to high volumes of these products in the markets. At the same time, the use phase of many devices has become shorter, both leading to growing amount of end-of-life appliances including discarded materials and components from electronic equipment, here addressed as Waste Electrical and Electronic Equipment (WEEE). The amount of WEEE generated globally in 2014 was 48.1 Mt with a growth rate of 3-5%

annually, for 2018 this amount will increase to 50 Mt (Baldé *et al.*, 2015).

WEEE is one of the fastest growing waste streams, containing both toxic and high market value materials. Driven by economic interests, informal recycler recovers valuable metals like copper, gold, and silver without concern on consequences from processes e.g. leaching (Wei and Liu, 2012). From these practices, WEEE has become one of the largest sources of heavy metals and organic pollutants in developing countries e.g. China, India and Nigeria, where this waste is being handled and disposed of in a non-environmental-friendly way (Chi *et al.*, 2011).

Electrical and electronic equipment (EEE) contains an assortment of different metals, which have been a driving force for the development of both formal and informal recycling of WEEE. Base metals are providing elementary functions in EEE, e.g. mechanical stability as part of a device housing, component holders, screws, and similar. Output flows of pre-treatment process of high-grade WEEE consist of in general 30-40% of iron, 2-4% of aluminium, and 13-17% of copper and precious metals (Bigum *et al.*, 2012; Unger *et al.*, 2017). These metals can be identified and quantified by simple material tests, i.e. magnet test, swim-sink process, etc., according to their characteristic physical properties. However, EEE contains significant concentrations of precious metals, rare earth metals, and other highly valuable elements in comparably low concentrations in the order of several hundred ppm (İşildar *et al.*, 2016). Furthermore, besides their low concentrations, these elements are usually bound in exceptionally complex components such as Printed Circuit Boards (PCBs), connectors, batteries, capacitors, which makes their identification and quantification particularly challenging.

For approx. three decades, high metal content and consequent high recycling potential have been a driving force behind the interest to analyse complex components from WEEE. An epitome of complex components are PCBs due to the multitude of available types, a convoluted material composition containing over 20 different

intended to perform complex functions. In general, the increasing complexity of a device is directly proportional to an increasing complexity of material composition. Components containing the highest concentration of CRM are integrated circuits (ICs) and semi-conductors from PCBs, Hard Disk Drives (HDDs), LCD and LED displays, fluorescent lamps and other.

3. Complex components in WEEE

In the following section, the term complex components will be defined and subsequently a classification system for PCB will be proposed which should decrease the intricacy of chemical analyses of complex components from WEEE by providing a clear definition of the sample and categorizing them into classes with expected similar material compositions.

3.1. Definition of complex components and their analytical challenges

During the in-depth manual or mechanical disassembly as part of the pre-treatment process of WEEE, emerges a material stream, which due to the complex construction cannot be attributed to any homogenous output stream. Components containing this material stream can be classified as “complex components” (see Figure 2). The complex components represent assemblies of different parts and materials. They are highly versatile in their shape, size, and material composition and include components such as PCBs, HDDs, Power Supply Units, Optical Disc Drives, and other. Since they are usually made of many different elements, the determination of their material composition requires advanced analytical techniques.

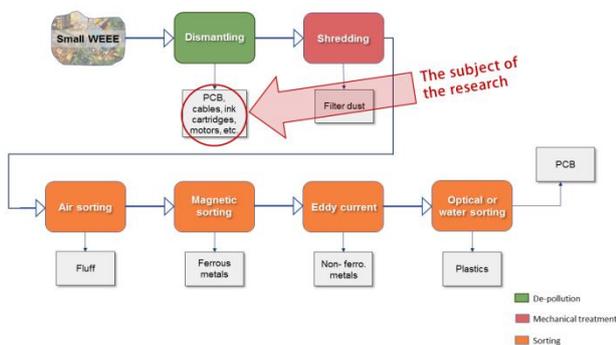


Figure 2. A general overview of pre-processing of WEEE (Jandric, 2017)

On account of high versatility, it is important to find a lowest common denominator for each type of complex components in order to increase for repeatability and reproducibility of the subsequent individual analyses. A process of defining a sample containing complex component is exemplified in the further text on PCBs.

There is no single generally applicable material composition of the PCBs. In this sense, PCBs should be understood as an “umbrella term” for a variety of different component types, which perform a range of different functions and consequently are made of different materials. Therefore, PCBs from different WEEE should not

be combined into a mixed sample. In addition, it is advised to refrain from stripping components from the PCB, since this procedure may vary in its efficiency and thereby have a significant influence on the outcome of the analysis. Also, the year of manufacture and any additional information about the analysed sample, e.g. size of the initial sample, whether the IC, capacitors, and other components have been stripped from the PCBs, significantly increases the value and the integrity of analysis. So far, the most frequently analysed types of PCBs, due to relatively high precious metal concentration, were PCBs from personal computers (PC) and the main PCB from mobile phones.

A further important aspect causing scattered results of material composition analyses is the fact that the analytical procedure has not been standardised with exception of elements defined by the European RoHS Directive, such as Cd, Cr VI, Hg, Pb. So far, the prevailing analytical methods for the analysis of the material composition of PCBs are either based on a spectro-analytical procedure, i.e. inductively coupled plasma mass spectroscopy (ICP-MS) and optical emission spectrometry (ICP-OES), or on X-ray fluorescence (XRF). However, in many cases, the authors did not even indicate the method of analysis, which has been used for determining of the material composition, nor the type of sample preparation. Consequently, the evaluation of conducted analyses or establishing any trends in the material composition is near impossible and hence the scattered results in the scientific literature.

3.2. Classification system for PCBs

Based on the construction procedure, PCBs can be classified into three major groups: single-sided, double-sided and multi-layered. The single-sided boards have a conductive (copper) layer only on one side of the board, whereas double-sided have the conductive layers on both sides of the board. The multi-layered boards have two or more conductive layers separated by the non-conductive material (Ford and Cavette, 1996; Ono *et al.*, 2010; Yamane *et al.*, 2011; Kasper *et al.*, 2011). More layers enable a denser population of the PCB with ICs, capacitors, diodes, and other components.

Another common classification of PCBs is based on the flame retardants applied in the non-metallic fraction (NMF), namely the “Flame Resistant 2” (FR-2) type and “Flame Resistant 4” (FR-4) type of PCBs. The FR-2 denotes a type of non-conductive substrate made of cellulose paper reinforced by phenol formaldehyde (Guo *et al.*, 2009). The FR-2 substrates have a worldwide market share of approx. 12% (EPA, 2014). The FR-4 is a type of non-conductive substrate made of high-pressure flame-retardant woven glass reinforced by epoxy resin. Its main characteristics include near-zero water absorption, electrical insulation and resistance to heat, mechanical shock, and solvents (EPA, 2014). Because of these notable characteristics, the FR-4 substrates have a worldwide market share up to 70% of all types of laminates. The residual market share make composite substrates (5%) and various other substrates (13%) (cf. (Jing-ying *et al.*, 2012; EPA, 2014). A classification of PCBs based on the substrate material is inadequate from

the recycling point of view since the differentiation of laminates would be exceedingly difficult without employing additional analytical equipment and yet the differences in the metal content of PCBs would still stay unaddressed.

In the present research, the *de facto* classification of PCBs has been assessed from more than a dozen recycling companies from Austria, Germany, Spain, and Switzerland. Based on the retail prices of scrap PCBs, a classification system has been developed, which is both practical in terms of assignment of particular PCB to a corresponding category and also outlines the metal composition (GeldfuhrAbfall, 2017; Beinhart, 2017; Computerplatten.de, 2017). The categorisation and price ranges available are based on the nominal prices for PCBs available at the various home pages of e-waste dealing companies. However, the *de facto* prices of PCB may differ from these advertised at the corresponding homepage. An overview of the proposed classification of PCBs can be seen in Figure 3.

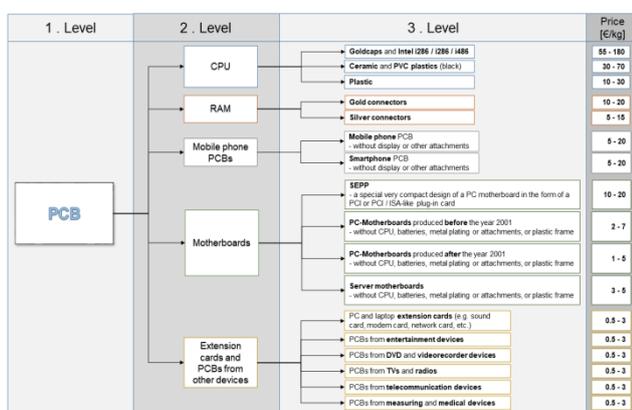


Figure 3. A classification of PCBs based on their price [€/kg] on the scrap market in EU

The proposed classification of PCB, as shown in Figure 3, should be considered as a basis for future analytical procedures since it defines not only the subcategory of PCB but also defines the term PCBs by providing a precise description which components should be included in the analysis.

After analysing the prices on the scrap market, it is apparent that PCBs from PCs and mobile phones (and smartphones) have the highest market value. Although mobile phones and PCs also one of the fastest replacement cycles in relation to other WEEE, their market price is determined by the concentration of Cu, Au and to a lesser extent of other metals. For these PCBs, the scrap market in the EU possesses highly developed categorisation as it differentiates between motherboards, random-access memory (RAM) with gold and silver connectors, and different types of central processing units (CPU) which are subsequently ranked also by varying prices. Less relevant types of PCBs include those from consumer electronics, such as TVs, radios, etc., which lack a subtle categorisation as it is the case with PCBs from Personal Computers (PCs) and mobile phones. Furthermore, this large group

constituted of PCBs of various sizes and functions have very similar market prices. Rather than a signal for similar material compositions, this is much more indicative for the lack of information on their material composition.

4. Material composition of PCBs and other complex components and qualitative mapping of trace metals from WEEE

As determined in the previous chapter, the capacity to accurately determine material composition of PCBs is highly challenging. Nevertheless, the material composition of PCBs significantly influences the market price of this waste stream and thereby shapes the treatment procedures along the whole recycling process.

This section provides results of a comprehensive literature review. The first part of this section focuses on the quantification of metals in PCBs from mobile phones and PCs, whereas the second part strives to pinpoint trace metals to components, i.e. capacitors, connectors, LCD displays etc. However, due to the high scattering of the data, at the present moment, it is not possible to determine precisely and accurately the material composition of individual components. For this reason, these data have been organised qualitatively rather than quantitatively.

4.1. Evaluation of the literature regarding material composition of PCBs

In this research, results have been evaluated from multi-element analytical procedures regarding the material composition of PCBs published in SCI ranked journals analysing PCBs manufactured from the 1980s onwards. Besides SCI ranking, a set of minimal requirements has been established for the results of material composition to be considered for further assessment. The focus is set on the PCB types from PCs and mobile phones. The PCBs from other devices, i.e. PCBs from printers, laptops, DVD players, etc., have not been included in the evaluation due to the data scarcity, which thereby inhibits further statistical analysis. Furthermore, material compositions of mixed samples, i.e. samples containing several different types of PCBs, and material analyses of stripped PCBs have not been included in the assessment. The results of these analyses do not meet minimum requirements for repeatability and reproducibility of the analysis. Figure 4 gives an overview of published scientific papers on the subject of material composition of PCBs with particular focus on types of PCBs, analytical methods, and year of manufacture.

Approx. 40% of analyses carried out regarding the material composition of PCBs have been conducted on either on the mixed samples of PCBs or without any indication what type of PCBs have been analysed. These analyses are impossible to repeat or validate. Also, approx. 70% of available data do not have any information about the production year of analysed samples and additional 12% of data indicate only whether the PCBs have been produced before or after the year 2000. Out of an abundance of scientific literature on the material composition of PCBs, this leaves only approx. 15% of available data to try to determine any trends in change of material composition over time. Based on the

currently available data, it is impossible to determine any trends in change of material composition of PCBs over time.

There are handful different analytical techniques applied for the determination of the material composition of PCBs, e.g. ICP based techniques (i.e. ICP-OES and ICP-MS), XRF, atomic absorption spectroscopy (AAS), thermogravimetric analysis (TGA). By comprehensive literature assessment, it

can be concluded that the prevailing analytical technique covering approx. 60% of available data sets are the ICP techniques. The ICP is followed by XRF based analytical techniques covering approx. 10% of available data sets. Any other analytical approaches for the analysis of the material composition of PCBs are hitherto highly exceptional and cover less than 1% of available data sets and therefore have not been included in the analysis.

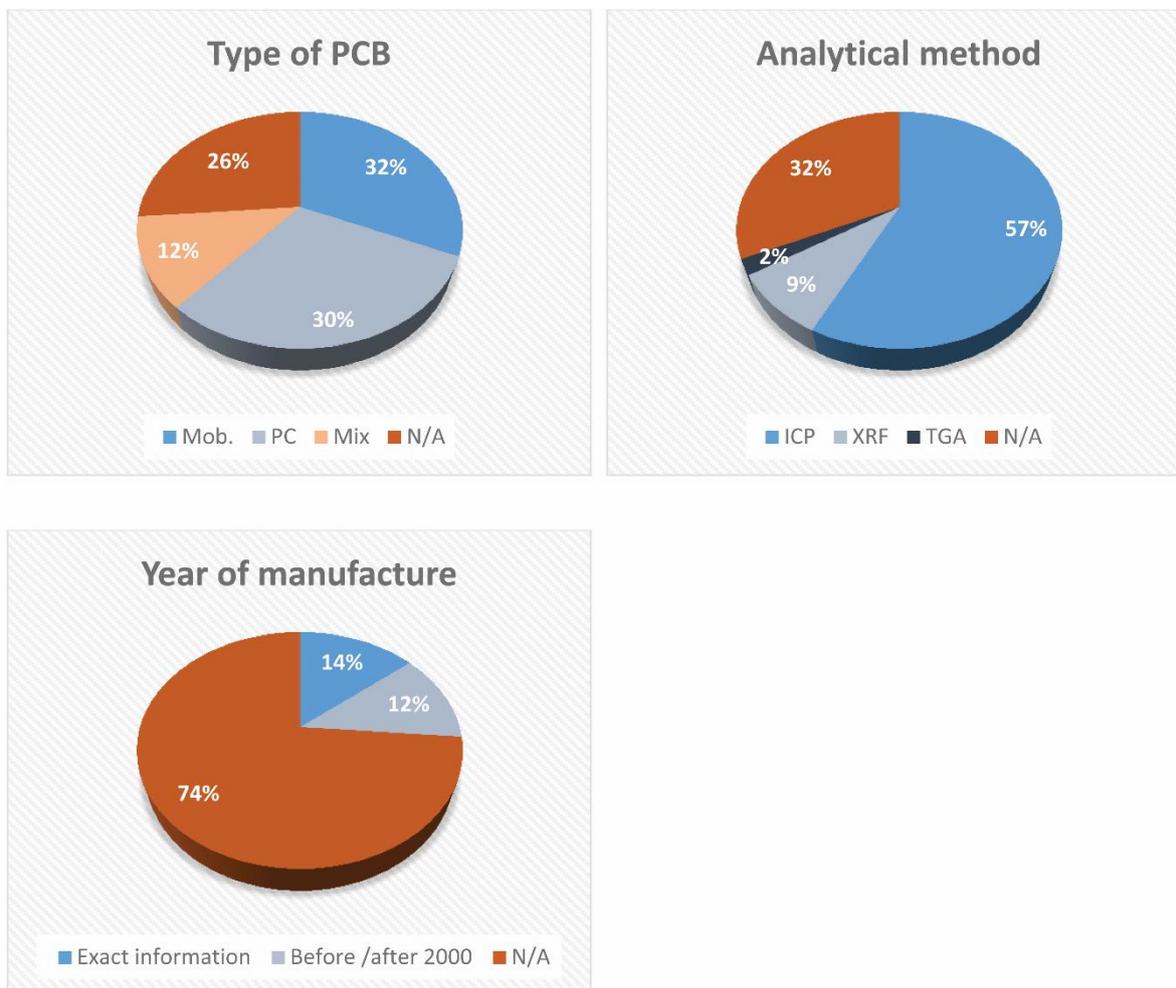


Figure 4. Overview of the scientific literature regarding material composition of PCBs (n= 57)

After considering all of the restraining factors, from initial 57 scientific papers, only remaining 43 could have been used for further research.

4.2. Material composition of PCBs

In general, PCBs are made of three groups of materials: metals, plastics, and inorganic materials, such as glass fibres, ceramics, etc. Based on the availability of data, this paper focuses on metals. This group of materials has the highest recycling potential due to its economic value and poses the highest environmental threat if not treated properly. Metals in PCBs can be generally subdivided into base metals, with concentrations in the “[%] range”, and trace and precious metals, which are present in significantly smaller concentrations in the “[ppm] range”.

Economically the most significant base metal contained in PCBs is copper, ranging between 6-40% of the total recycling revenues of PCB (c.f. Cui and Zhang, 2008). Furthermore, the concentrations of individual metal fractions fluctuate depending on both type of PCB and on the analytical method (see Figure 5). For example, the Cu concentration in PCBs from mobile phones (ICP) with a mean value of 34 wt.% is significantly higher than concentration in PCBs from PCs (ICP), with a mean value of 23%. Simultaneously, PCBs from PCs showed higher Cu concentrations if measured by XRF rather than with ICP. However, due to the insufficient data describing the conducted analyses, it is impossible to conclude whether the analytical method, year of manufacture or some other factor caused the difference in the results.

In Figure 6 Au concentrations for samples containing different types of PCBs are shown. Very similar as for Cu concentrations, the samples made of mobile phones PCBs have significantly higher concentrations than samples made of PCBs from PCs. The data variability is also the

highest for samples containing mobile phones, which can partially be explained by the high diversification of products available in the market. However, the data insufficiency makes any conclusive outcome near impossible.

Table 1. Concentration of trace metals in PCBs [ppm]

[ppm]	Mob				PC			
	ICP (11/33)	Std. dev.	N/A (6/33)	Std. dev.	ICP (12/33)	Std. dev.	XRF (3/33)	Std. dev.
Ba	15000	3266	19333	2687	2523	1054		
Bi	695	599	539	356	160			
Cr	1655	1163						
Co	915	552	298	161	10	0		
Mn					810	810		
Sb	472	72			1000			
Pd	301	326	603	216	176	156	27	
Au	898	581	1450	206	371	322	246	98
Ag	1996	1209	13467	8486	577	384	694	7

Table 2. Mapping of trace metals in comparatively high concentrations in complex components

	Ceramic capacitors	Connectors	LCD displays	Li-ion batteris	Ni-metal hydride batt.	Magnets
	(Prabaharan <i>et al.</i> , 2016)	(Ueberschaar <i>et al.</i> , 2017)	(Zhang <i>et al.</i> , 2017)	(Sommer <i>et al.</i> , 2015)	(Meshram <i>et al.</i> , 2017)	(München and Veit, 2017)
	[ppm]					
Chrome(Cr)	3.000	-	4.600	-	-	10.000
Cobalt (Co)	-	-	-	25.000-140.000	49.000	-
Gallium (Ga)	-	15.000-30.000	-	-	-	-
Germanium (Ge)	-	1.000	-	-	-	-
Gold (Au)	10	7.000-30.000	-	-	-	-
Indium (In)	-	-	80.000	-	-	-
Magnesium (Mg)	-	-	-	-	-	-
Palladium (Pd)	50	-	-	-	-	-
Platinum (Pt)	-	-	-	-	-	-
REE	-	-	-	-	180.000	210.000
Silicon (Si)	-	-	-	-	-	-
Silver (Ag)	130	1.000-3.000	-	-	-	-
Tin (Sb)	-	-	-	-	-	-

Table 1 illustrates trace metals which are contained in low concentrations and their values are expressed in ppm. Since their absolute quantity in PCBs is small, there are several factors influencing the results of a material analysis, such as type/model of analysed PCB, method, and equipment used for the analysis, a focus of the analysis and size of the particle size pre-treated PCBs.

Furthermore, it becomes clear that precious metals, similarly to Cu fraction, have very large dispersion. However, from the material analyses conducted and published, it is possible to determine a reasonable material concentration range present in the PCBs. This in mind, gold fraction ranges between 100 and 500 ppm with the mean value of approx. 370 ppm for the PCB from PCs, whereas the gold concentration in PCBs from mobile phone range between 400 and 1400 ppm with a mean value of approx.

900 ppm. Besides higher concentration, the gold fraction from a mobile phone shows also the very high rate of scattering. Besides differences in analytical method and samples size, an additional cause for the data variability of Au fraction in mobile phone samples can be explained by extraordinary technological development resulting in higher differences between different models and between different manufacturers.

4.3. Complex components with high concentrations of precious metals and critical raw materials

Beside PCBs, there is number of different complex components originating from WEEE, which are also prone to the significant influence of technological development. However, due to their extremely high variety of the shapes, sizes, and functions, the available data in the scientific literature regarding their material composition is even

more inconclusive than it is the case with PCBs. Even though based on the currently available data it is not possible to obtain a reliable total material composition of complex component, by focusing on specific parts and materials it is possible to single out certain parts of complex components, i.e. capacitors, magnets, batteries, etc., with comparatively high concentrations of precious metals and CRM (see Table 2).

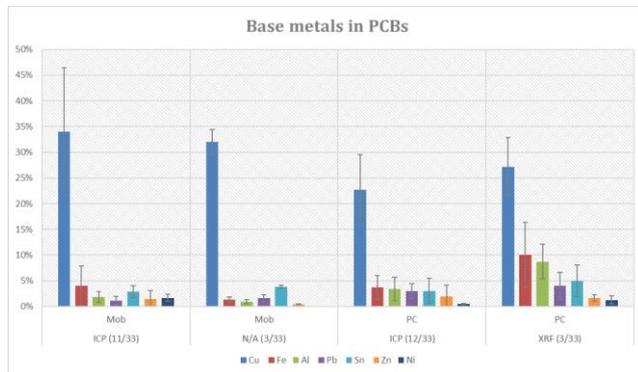


Figure 5. Concentrations of base metals in PCBs

However, due to the inconclusiveness of the research, the listed concentrations should be understood as a binary matrix – it provides information whether the complex component contains or does not contain a particular metal.

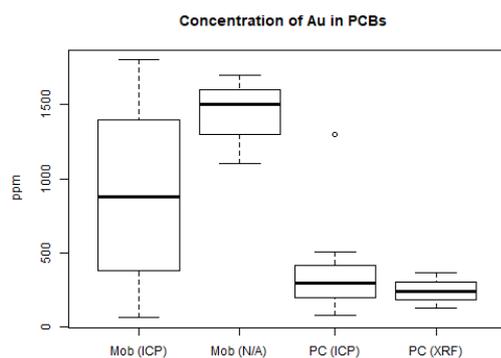


Figure 6. Concentrations of Au in PCBs

5. Conclusion

Despite an evident plenitude of scientific papers regarding the material composition of complex components from WEEE, a majority of these datasets have been rejected for not fulfilling even minimal scientific requirements. In the past, many papers have been published offering different, even opposing results without an appropriate description of the sample or applied analytical procedure.

Although the material composition of complex components has been in the focus of multi-elemental chemical analyses since 1980-is, no standardized analytical procedure for complex components or for any type of WEEE has been developed so far. Up to this day, as guidelines for the analysis of WEEE are used standards for soil samples analyses or standardization for waste samples in general, usually containing also biological materials.

Based on the results obtained from the literature assessment, the PCBs from mobile phones have a concentration of Cu exceeding the 30 wt.% on average which is significantly higher than 22-26 wt.% Cu concentration in the PCBs from PCs. In addition, regardless of the analytical procedure, Au concentration in the PCBs from mobile phones is higher than Au concentration in the PCBs from PCs, ranging between 900 ppm and 400 ppm on average respectively.

Over time a need for a fundamental change in approach to analytics of WEEE became apparent. In a time period where electronic equipment experience rapid technological development and increasing complexity, a demand for critical raw materials require identification, quantification, and finally recycling of elements in exceedingly small quantities from convoluted sample matrices. This puts a heavy strain on the current analytical practice of waste electronics. The needs of the recycling industry have outgrown simple quantification of Au in PCBs and challenge the waste analytics for a robust, easily validated, and reliable analytical approach for the analysis material composition.

Improvement in the analytics of waste electronics would have a significant influence on the recycling landscape enabling the higher efficiency of scrap and secondary material markets, but also allowing more decentralised recycling of waste electronics. Furthermore, it can be expected that a robust data basis would significantly increase the potential for development of new recycling technologies.

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Annex I

Source	Cu	Fe	Al	Pb	Sn	Zn	Ni	Ba	Bi	Cr	Co	Mn	Sb	Ti	Pd	Au	Ag	Sample preparation	Method	Year	Type of PCB
(Sum, 1991)	20.0%	8.0%	2.0%	2.0%	4.0%	1.0%	2.0%	*	*	*	*	*	4,000	*	100	1,000	2,000	N/A	N/A	1991	N/A
(Zhang and Forssberg, 1997)	10.0%	*	7.0%	1.2%	*	1.6%	0.9%	*	*	*	*	*	*	*	*	300	100	Thiourea	ICP	1997	PCB - PC
(Guo <i>et al.</i> , 2009)	26.8%	5.3%	4.7%	*	1.0%	1.5%	0.5%	200	*	500	*	4,700	*	34,000	*	100	3,300	N/A	N/A	1998	N/A
(Veit <i>et al.</i> , 2002)	23.5%	0.1%	1.6%	1.0%	2.5%	0.1%	0.2%	*	*	*	*	*	*	*	*	*	300	Tetra-bromoethane	*	2002	PCB - PC
(Ernst <i>et al.</i> , 2003)	17.2%	*	*	3.5%	*	*	1.1%	*	*	1,040	*	*	2,690	*	95	191	1,420	Aqua regia	AAS	2003	PCB - m. phone
(Kim <i>et al.</i> , 2004)	15.6%	1.4%	*	1.4%	3.2%	0.2%	0.3%	*	*	*	*	*	*	*	100	420	1,240	Pyrolysis	*	2004	PCB - mix
(Park and Fray, 2009)	20.0%	0.8%	*	2.0%	4.0%	4.5%	2.0%	*	*	*	*	*	*	*	100	1,000	2,000	Aqua regia	ICP-MS	2005	PCB - mix
(Ogunniyi <i>et al.</i> , 2009)	17.9%	0.2%	4.8%	4.2%	5.3%	2.2%	1.6%	*	*	*	*	*	*	*	300	400	13	N/A	N/A	2006	N/A
(Hadi <i>et al.</i> , 2015)	7.0%	17.0%	7.0%	0.3%	0.3%	3.0%	2.3%	*	50	20	*	*	*	*	*	300	3,000	N/A	N/A	2006	PCB - mix
(Hadi <i>et al.</i> , 2015)	27.0%	2.0%	1.0%	3.0%	3.0%	0.5%	0.2%	*	500	1,000	*	*	*	*	*	1,000	400	N/A	N/A	2006	PCB - mix
(Oishi <i>et al.</i> , 2007)	26.0%	3.4%	3.2%	3.0%	4.9%	2.6%	1.5%	*	30	*	580	1,100	1,600	*	*	*	630	Aqua regia	ICP-OES	2007	N/A
(Huisman <i>et al.</i> , 2008)	14.8%	15.2%	7.1%	1.5%	1.4%	1.4%	0.4%	*	24	576	*	*	662	*	38	94	586	N/A	N/A	2007	PCB - mix
(Cucchiella <i>et al.</i> , 2016)	18.8%	0.2%	0.0%	0.7%	1.8%	*	0.7%	*	*	*	*	*	*	*	*	4,200	900	N/A	N/A	2007	N/A
(Gongming <i>et al.</i> , 2007)	24.7%	0.2%	1.6%	0.6%	2.3%	0.1%	0.1%	1,600	*	250	*	120	19,700	900	27	76	242	N/A	N/A	27	N/A
(de Marco <i>et al.</i> , 2008)	36.4%	3.9%	8.7%	3.8%	4.6%	3.5%	0.5%	*	*	*	*	*	*	*	100	300	1,600	pyrolysis	ICP	2008	PCB - mix

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(Ogunniyi <i>et al.</i> , 2009)	23.5%	1.2%	1.3%	1.0%	1.5%	1.5%	2.4%	*	*	*	*	*	*	*	294	570	3,301	Aqua regia	ICP-OES	2009	PCB - m. phone
(Park and Fray, 2009)	16.0%	5.0%	5.0%	2.0%	3.0%	1.0%	1.0%	*	*	*	*	*	*	*	100	250	1,000	Aqua regia	ICP	2009	PCB - mix
(Holgersson <i>et al.</i> , 2017)	34.3%	0.7%	1.9%	0.4%	1.9%	0.5%	1.2%	*	40	865	*	*	543	*	119	1,051	2,640	Aqua regia	ICP-SFS	2010	PCB - m. phone
(Williams, 2010)	16.7%	1.1%	2.2%	2.2%	*	0.1%	0.1%	*	*	270	*	*	*	*	*	200	800	Pyrolysis	ICP	2010	PCB - mix
(Williams, 2010)	26.0%	16.0%	10.5%	7.7%	*	1.5%	2.4%	*	*	120	*	*	*	*	*	*	15,020	Pyrolysis	ICP	2010	PCB - PC
(Williams, 2010)	32.3%	0.5%	1.8%	0.3%	*	0.1%	0.7%	*	*	140	*	*	*	*	*	30	4,120	Pyrolysis	ICP	2010	PCB - m. phone
Source	Cu	Fe	Al	Pb	Sn	Zn	Ni	Ba	Bi	Cr	Co	Mn	Sb	Ti	Pd	Au	Ag	Sample preparation	Method	Year	Type of PCB
(Oguchi <i>et al.</i> , 2011)	20.0%	1.3%	1.8%	2.3%	1.8%	0.3%	*	1,900	50	*	48	*	*	*	150	240	570	Aqua regia	ICP-OES / MS	2011	PCB - PC
(Oguchi <i>et al.</i> , 2011)	33.0%	1.8%	1.5%	1.3%	3.5%	0.5%	*	19,000	440	*	280	*	*	*	300	1,500	3,800	Aqua regia	ICP-OES / MS	2011	PCB - m. phone
(Yamane <i>et al.</i> , 2011)	20.2%	7.3%	5.7%	5.5%	8.8%	4.5%	0.4%	*	*	*	*	*	*	*	*	1,300	1,600	Aqua regia	ICP-OES	2011	PCB - PC
(Yang <i>et al.</i> , 2011)	25.3%	0.2%	*	0.1%	0.3%	*	0.0%	*	*	24	*	*	*	*	BDI	105	107	Aqua regia	ICP	2011	PCB - mix
(Birloaga <i>et al.</i> , 2013)	31.8%	13.8%	10.5%	4.9%	7.0%	2.2%	2.0%	*	*	*	*	*	*	*	*	369	689	Aqua regia	XRF	2013	PCB - mix
(Le <i>et al.</i> , 2013)	38.9%	10.8%	1.0%	1.7%	2.5%	0.3%	1.7%	*	*	*	1,700	*	400	*	142	1,645	3,985	N/A	N/A	2013	PCB - mix
(Ortuño <i>et al.</i> , 2013)	24.2%	0.2%	3.3%	0.9%	1.4%	0.1%	0.3%	*	*	*	*	*	*	*	*	600	1,000	Aqua regia	XRF	2013	PCB - m. phone
(Behnamfard <i>et al.</i> , 2013)	19.2%	1.1%	4.0%	0.4%	0.7%	0.8%	0.2%	0.361	*	0.118	*	0.035	*	0.176	27	130	704	N/A	XRF/ICP	2013	PCB - PC
(Yazici and Deveci, 2013)	18.5%	2.1%	1.3%	2.7%	4.9%	*	0.4%	*	*	*	*	*	*	*	97	86	694	Aqua regia	ICP	2013	PCB - PC
(Evangelopoulos <i>et al.</i> , 2015)	30.6%	15.2%	11.7%	6.7%	7.4%	1.9%	1.6%	*	*	*	*	*	*	*	*	238	688	Thiourea	XRF	2014	PCB - mix (stripped)

(Yang <i>et al.</i> , 2014)	25.5%	3.2%	6.3%	2.3%	3.3%	6.2%	0.5%	4,540	*	*	*	1,620	*	*	*	*	*	Aqua regia	ICP-OES	2014	PCB - PC
(Fujita <i>et al.</i> , 2014)	15.0%	2.5%	4.0%	2.0%	*	*	0.5%	*	*	760	62	614	*	1,000	90	320	1,200	N/A	*	2014	PCB - mix
(Camelino <i>et al.</i> , 2015)	65.7%	1.5%	*	1.1%	5.2%	0.2%	2.0%	*	*	*	*	*	*	*	110	168	285	Aqua regia	ICP	2015	PCB - mix
(Birloaga <i>et al.</i> , 2013)	33.9%	1.0%	2.6%	5.0%	*	0.9%	0.1%	1,645		327	3	78	40.8	1,372	12	7	398	Pyrolysis	ICP	2015	PCB - mix (stripped)
(Xiu <i>et al.</i> , 2015)	40.8%	0.3%	*	1.4%	1.6%	0.4%	0.4%	*	*	*	*	*	*	*	50	65	1,060	N/A	ICP-OES	2015	PCB - mix (stripped)
(Chen <i>et al.</i> , 2015)	24.8%	0.2%	2.5%	0.6%	*	*	*	*	*	*	*	*	*	*	*	*	*	Aqua regia	ICP-OES	2015	PCB - mix
(Zhang <i>et al.</i> , 2016b)	30.9%	4.1%	*	2.1%	*	0.4%	0.4%	*	*	*	*	1	*	*	435	385	754	Thiourea	ICP	2016	PCB - PC (stripped)
(Zhang <i>et al.</i> , 2016a)	29.9%	7.8%	12.2%	3.9%	5.3%	0.3%	*	8,100	*	*	*	12,100	15,000	12,100	*	*	*	Pyrolysis	XRF	2016	PCB - mix
(Evangelopoulos <i>et al.</i> , 2017)	17.7%	5.2%	3.6%	0.9%	*	0.5%	0.3%	*	*	290	*	*	*	*	*	21	*	Aqua regia	AAS	2016	PCB-PC
(Evangelopoulos <i>et al.</i> , 2017)	23.0%	3.8%	1.0%	0.1%	*	0.3%	1.2%	*	*	2,000	*	*	*	*	*	320	*	Aqua regia	AAS	2016	PCB - m. phone
(Neto <i>et al.</i> , 2016)	14.7%	3.3%	5.9%	2.4%	0.8%	0.3%	0.5%	*	*	*	*	*	*	*	*	510	440	N/A	*	2016	PCB - mix
(İşıldar <i>et al.</i> , 2016)	33.9%	1.0%	2.6%	5.0%	0.2%	0.9%	0.1%	1,645	*	237	*	*	41	1,372	12	7	398	*	TGA	2017	PCB - PC