EVALUATION OF RECOVERY POTENTIAL FOR PRECIOUS AND RARE EARTH METALS FROM E-WASTE

by

MERVE ŞAHAN

BS. in Env. E., Marmara University, 2013

Submitted to the Institute of Environmental Sciences in partial fulfillment of

the requirements for the degree of

Master of Science

in

Environmental Technology

Boğaziçi University

2016

ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my thesis supervisor Assoc. Prof. Dr. Burak Demirel for his continuous guidance, kind support and encouragement during this study and also my master education. It was an honor and privilege to work with him.

I am also grateful to Boğaziçi University Research Fund for financial support by project number 8741 and the Scientific and Technological Research Council of Turkey (TUBITAK) by project number 113Y011.

I would like to express my sincere gratitude to the jury members; Prof. Dr. Nadim Copty and Prof. Dr. Barış Çallı for their time and valuable suggestions.

In addition, I would like to thank to Gülhan Özkösemen, Mehmet Ali Küçüker and Filiz Ayılmaz for their scientific help and support during the study.

I am also grateful to all my friends from the Institute of Environmental Sciences for their unique friendship, encouragement and support during this study and also my master education.

Finally, I would like to express a deep sense of gratitude to my parents, Birsen Şahan and Hüseyin Şahan and my sister Eda Şahan for their constant love, endless encouragement and blessings.

EVALUATION OF RECOVERY POTENTIAL FOR PRECIOUS AND RARE EARTH METALS FROM E-WASTE

Considering the enormous production of electrical and electronic wastes in recent years, it is obvious that the research of their material composition is essential in order to manage them properly and prevent health and environmental problems resulting from their inappropriate disposal. On the other hand, it is known that the e-wastes contain valuable metals in them and these valuable metals are lost during the current disposal and recycling processes. Therefore, the detection and quantification of these metals in e-waste samples is important for increasing recycling rate of them.

The main objective of this study was to evaluate the recovery potentials of certain precious and rare earth metals from e-waste. The metal characterization of twenty five different e-waste samples collected from various sources was completed as a first step. Selected base, precious and rare earth metals in these e-waste samples were detected and quantified by using ICP-OES. Since the number of printed circuit boards of mobile phone samples and motherboards of computer samples is relatively higher than the number of other samples, their recovery potentials in terms of base, precious and rare earth metals were finally determined.

Results of this study show that, while the recovery of precious metals should be the main goal of the recycling process of printed circuit boards from mobile phones, the recovery of both precious metals and rare earth elements should also be the focus of the recycling process of motherboards of computers.

E-ATIKLARDAKİ DEĞERLİ VE NADİR TOPRAK METALLERİNİN GERİ KAZANIM POTANSİYELİNİN DEĞERLENDİRİLMESİ

Son yıllarda atık elektrikli ve elektronik eşyalarda hızlı bir artış olduğu göz önüne alınacak olursa, bu atıkların uygun şekilde yönetilebilmesi ve aynı zamanda sağlığa ve çevreye verebileceği zararların önlenebilmesi açısından içerisindeki materyal kompozisyonunun araştırılması son derece önemlidir. Ayrıca, e-atıkların ekonomik olarak değerli metaller ihtiva ettiği ve bu metallerin büyük bir kısmının günümüz geri dönüşüm yöntemleri ile geri kazanılamadığı da bilinmektedir. Bu sebeple e-atıkların yapısındaki değerli metallerin tespit edilebilmesi ve miktarlarının belirlenmesi bu metallerin geri dönüşüm oranlarının arttırılabilmesi açısından önem arz etmektedir.

Bu çalışmanın asıl amacı elektronik atıklardan kıymetli metal ve nadir toprak elementlerinin geri kazanım potansiyellerinin araştırılmasıdır. Bu amaçla ilk öncelikle çeşitli kaynaklardan elde edilen birbirinden farklı yirmi beş elektronik atık numunesinin metal karakterizasyonu yapılmıştır. Belirlenen temel, kıymetli ve nadir toprak metallerinin bu numuneler içerisindeki miktarları ICP-OES cihazı kullanılarak ölçülmüştür. Daha sonra ise sayıca diğerlerinden daha fazla olan cep telefonu devre kartlarının ve bilgisayar anakartlarının temel, kıymetli ve nadir toprak metalleri açısından geri dönüşüm potansiyelleri hesaplanmıştır.

Bu çalışmadan elde edilen geri kazanım potansiyeli sonuçlarına göre, cep telefonu devre kartları için kıymetli metallerin geri kazanımı asıl geri dönüşüm hedefi olması gerekiyor iken bilgisayar anakartları için hem kıymetli metallerin hem de nadir toprak elementlerinin geri dönüşümüne odaklanılması gerektiği sonucuna varılmıştır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

Abbreviation	**Explanation**
EEE	Electrical and Electronic Equipment
E-waste	Electrical and Electronic Waste
WEEE	Waste Electrical and Electronic Equipment
REE	Rare Earth Element
PCB	Printed Circuit Board
HDD	Hard Drive Disk

1. INTRODUCTION

All over the world, living standards and requirements of the societies are altering fast. In this process, individuals satisfy their fundamental needs via technology based items. Therefore, electrical and electronic equipments (EEEs) are a significant part of the modern life with various applications in the field of communication, transport, medicine, education, security and environmental protection.

In recent years, the rapid increase in technological developments has caused a considerable reduction in the life span of most electrical and electronic equipments. Short life span of EEEs has led to the generation of huge amounts of electronic waste (e-waste). Based on recent researches, it is evident that the e-waste generation will be growing very fast in near future. Most recent studies indicate that the amount of discarded electronic devices that enter the waste stream is more than 40 million tonnes annually worldwide (Bhat et al., 2012; Xu et al., 2012). Furthermore, it is stated that the amount of e-waste is increasing by 3-5% per year with a speed of three times more than that of the municipal solid waste (MSW) raise (Davis and Herat, 2008).

The toxic chemicals present in e-waste may pose danger to human beings and the environment if not properly managed. In addition, e-waste occupies a large amount of land in nature. Therefore, collection and recovery of e-waste has a significant importance for human health and environmental safety. Moreover, since many precious metals and rare earth elements (REEs) are used in the production of electrical and electronic devices, e-waste has a high potential for recovery of valuable elements that can be a great source of raw materials for industrial activities.

In the European Union (EU), the companies producing electrical and electronic equipment have been put under some obligations based on the WEEE Directive in regard to organize their collection, disposal and recovery activities.

When the situation in Turkey is considered, certain administrative, legal and technical principles on e-waste have been developed in the process of adaptation to the European Union during the last decades. Moreover, the restrictions about the management of e-waste have been specified by a legislation in May 2012. Although there is a regulation about e-waste management in Turkey, legal e-waste collection and recycling ratio is still less than 1% of the total generated e-waste (Republic of Turkey Ministry of Science, Industry and Technology, 2012). In contrast, in USA, approximately 14% of generated e-waste was recycled in 2008 (Saphores et al., 2012). Recycling ratios in European Union and Japan are in the range of 25–40 and 64–84%, respectively (Kell, 2009). Therefore, much more effort is needed to reach the desired e-waste collection and recycling levels in Turkey.

The objective of this study is to collect information about the inventory of e-waste generated in Turkey. In this study, legislations about e-waste management in EU and Turkey have been analyzed and compared to find out whether there is a possibility to propose concrete suggestions in order to improve Turkish legislations about the application of more effective e-waste management strategies. Furthermore, selected e-waste samples have been collected and analyzed in the laboratory in order to determine the amount of base metals, precious metals and rare earth elements that they contain. In parallel with the experimental results, the potential of recovery of precious metals and rare earth elements from e-waste has been evaluated.

2. LITERATURE REVIEW

2.1. Information about Electrical and Electronic Waste

With the digital revolution starting from 1970s, the quality of electrical and electronic products increased incrementally. Therefore, the life span of electronic products shortened simultaneously due to the widespread of internet use and reduced product prices (Widmer et al., 2005; Li et al., 2006; Gullett et al., 2007; Nnorom and Osibanjo, 2008a; Nnorom and Osibanjo, 2008b; Chung et al., 2011; Meng, 2008). This period has eventually led to a rapid growth in the amount of unwanted and out of date electronic devices. Thus, a new type of waste has been generated and it has been called as Waste Electrical and Electronic Equipment (WEEE) or e-waste, both in the literature and practice (Dwivedy and Mittal, 2010). The term e-waste is used to define the obsolete forms of all sorts of devices that have parts, which transmit and process data by the help of electrical current such as computers, phones, large and small household appliances, lighting equipment or medical devices. In other words, e-waste is defined as electronic devices that are out of date and not functional due to breakdown, physical damage or failure (Kohama, 2007). Definitions of e-waste used in different sources are expressed as “any appliance using an electric power supply that has reached its end-of-life’’ or “an electrically powered appliance that no longer satisfies the current owner for its original purpose’’ (Sinha, 2004; OECD, 2001).

E-waste was categorized in Swiss Ordinance on the Return, the Taking Back and the Disposal of Electrical and Electronic Equipment in 1998 as; a) household appliances, b) electronic appliances for entertainment, c) appliances forming part of office, communication and information technology, and d) electronic components of these appliances. In the WEEE Directive of European Union that came into force in 2003, e-waste was classified in ten different categories; 1) Large household appliances, 2) Small household appliances, 3) IT and telecommunications equipment, 4) Consumer equipment, 5) Lighting equipment, 6) Electrical and electronic tools, 7) Toys, leisure and sports equipment, 8) Medical devices, 9) Monitoring and control instruments, and 10) Automatic dispensers (European Commission-WEEE Directive, 2003).

2.1.1. Amount of Global E-waste Generation

Waste electrical and electronic equipment (WEEE) or in other words e-waste is one of the fastest growing waste types in the world (Dreschse, 2006; He et al., 2006; Khetriwal et al., 2009; Pant et al., 2012; Tuncuk et al., 2012). The UNEP (United Nations Environment Programme) estimates that the global production of e-waste reaches up to 50 million tonnes per year (Kaya, 2012). Today, it is known that the amount of e-waste is increasing by 3-5% per year with a speed three times more than that of municipal solid waste (Davis and Herat, 2008). Recent studies demonstrate that e-wastes make up 1–5% of the municipal solid wastes, and especially in rich countries this percentage goes up to 8% (Nnorom and Osibanjo, 2008a; Kang and Schoenung, 2005; Robinson, 2009).

According to most recent studies, e-waste generation in Europe has reached up to about 11 million tons per annum or about 15 kg per inhabitant. The countries with the highest e-waste generation are Germany, United Kingdom, France and Russia with 1.8, 1.5, 1.4 and 1.2 million tonnes per year, respectively. Approximately 9 million tonnes of e-waste has been generated in European Union (EU) annually and the amount of e-waste collected in EU countries in 2013 is displayed in Figure 2.1 (Eurostat, 2015). Although the per-capita waste production in countries of Asia has been lower than that of the other regions, because of high population in certain countries, such as China and India, the annual e-waste generation is about 16 million tonnes. For example in China, e-waste generation is approximately 4.4 kg per capita and 6 million tonnes per year. Generation rates of e-waste in America, Africa and Oceania are around 12 million tonnes, 2 million tonnes and 0.6 million tonnes per year, respectively (Baldé et al., 2015).

E-waste generation rate of countries changes according to their life standards and technological tendency. High technological equipment usage of Turkey due to its young population causes excess e-waste generation. According to data from the Turkish Ministry of Environment and Urban Planning, the amount of e-waste generated in Turkey is about 539,000 tonnes per year. In other words, 7 kg of e-waste is generated per person. The amount of generated e-waste per capita (kg) in Turkey is illustrated in Figure 2.2 (REC Turkey, 2011). Ozturk (2015) stated that 31510 tons of computers and 2257 tonnes of mobile phones were discarded in Turkey in year 2012. However, legal e-waste collection rate in Turkey is quite lower than EU countries. According to the report of the Regional Environmental Center (REC) Turkey, only 1% of generated e-waste was recycled by accredited recycling companies in 2011.

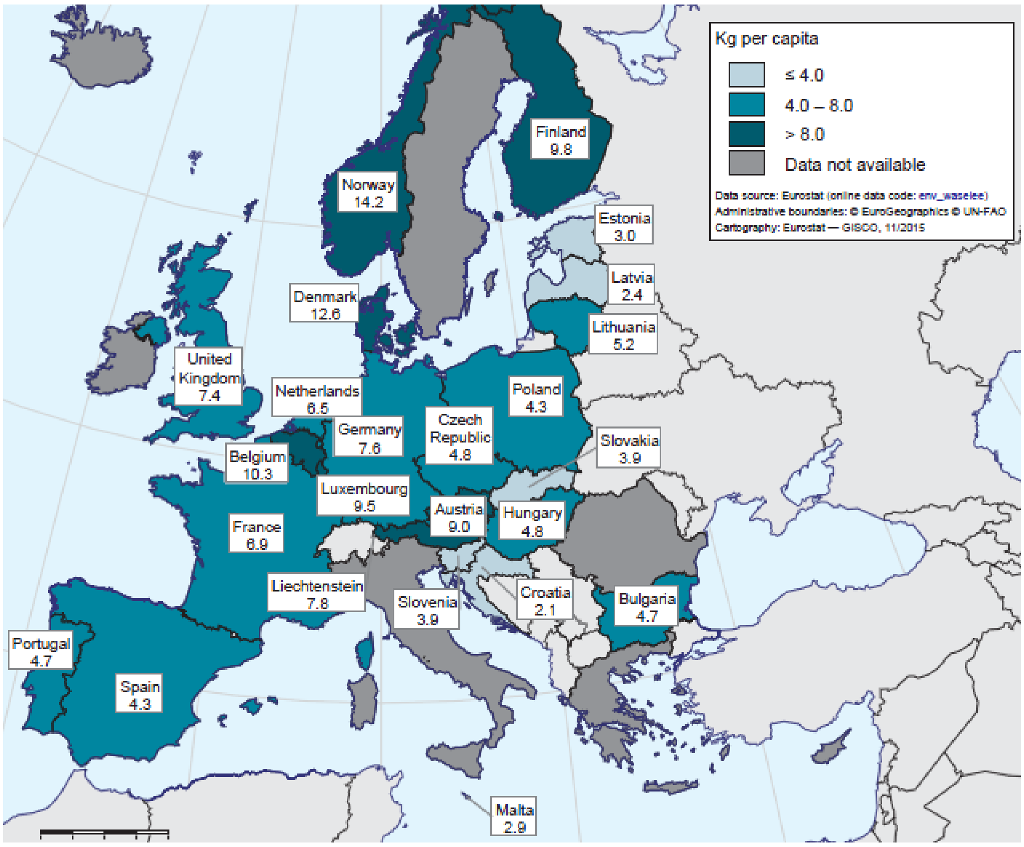

Figure 2.1. The collection rate of WEEE from households in EU Member States (Eurostat, 2015).

The reason of considerable amount of e-waste in some developing countries is due to importation of e-waste from developed countries. Even though transboundary trade of e-waste is restricted by the Basel Convention, e-wastes are still being sent to developing countries, which lack proper regulations regarding public and environmental health (Shinkuma and Huong, 2009). For instance, it has been indicated that e-wastes coming to China increased almost 70% in recent years (Li et al., 2013). Therefore, developing countries are facing serious problems in the e-waste management (Nnorom and Osibanjo, 2008b; Pant et al., 2012). Overcoming these problems is difficult due to the socioeconomic situation of these developing countries (Babu et al., 2007). Today, e-waste management is a global problem and it needs international e-waste management solutions.

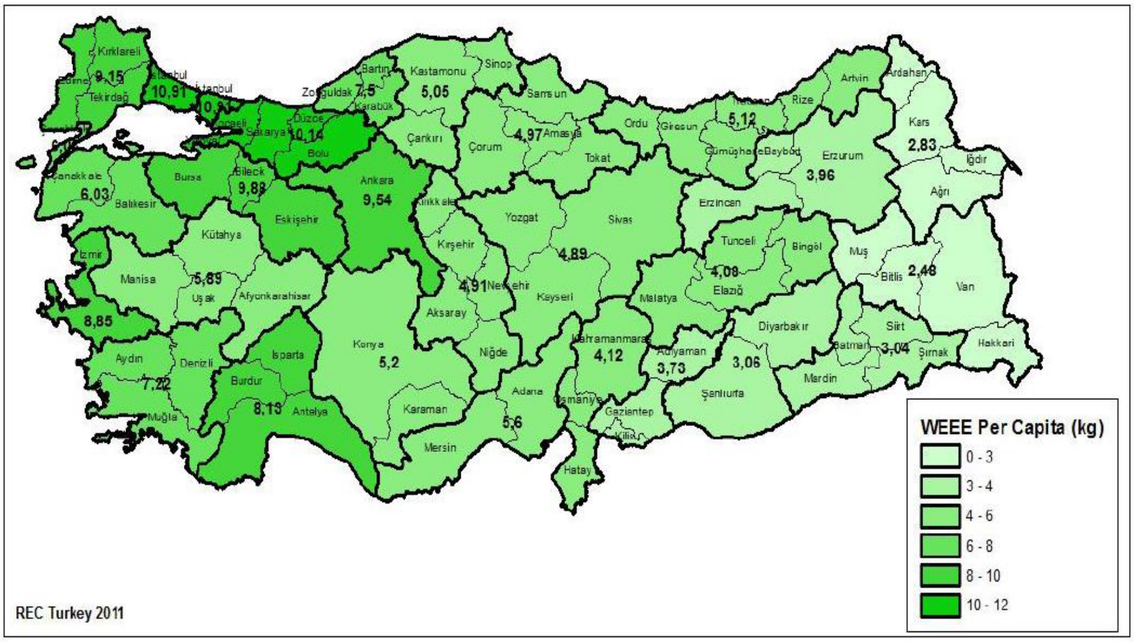

Figure 2.2. The amount of generated WEEE per capita (kg) in Turkey (REC Turkey, 2011).

2.1.2. Material Content of E-waste

E-waste contains different types of appliances ranging from televisions, refrigerators, washing machines to computers, mobile phones and lighting equipments. Because of the diverse range of devices present in e-waste, it is difficult to generalize material composition of the entire waste stream. However, most studies categorize materials found in e-waste as ferrous metals, non-ferrous metals, glass, plastics and other. Nearly 60% of the e-waste stream consists of ferrous and non-ferrous metals such as iron (Fe), copper (Cu), aluminum (Al), lead (Pb), gold (Au), silver (Ag), platinum (Pt) and palladium (Pd). Gramatyka et al. (2007) states that the typical metal scrap comprises of 20% copper (Cu), 8% iron (Fe), 4% tin (Sn), 2% nickel (Ni), 2% lead (Pb), 1% zinc (Zn), 0.02% silver (Ag), 0.1% gold (Au) and 0.005% palladium (Pd) metals. Plastics are the second most common materials in e-waste stream by comprising 15% of the e-waste composition. Metal-plastic mixture, cables, screens, printed circuit boards and pollutants are the other fractions of e-waste streams and the percentages of these materials are shown in Figure 2.3. Studies have proved that there are more than 1000 materials encountered in e-wastes, which are hazardous for human health or can be hazardous after application of specific processes. However, the metal content of e-waste has remained the biggest portion, while the pollutants and hazardous components have steadily declined over time (Widmer et al., 2005).

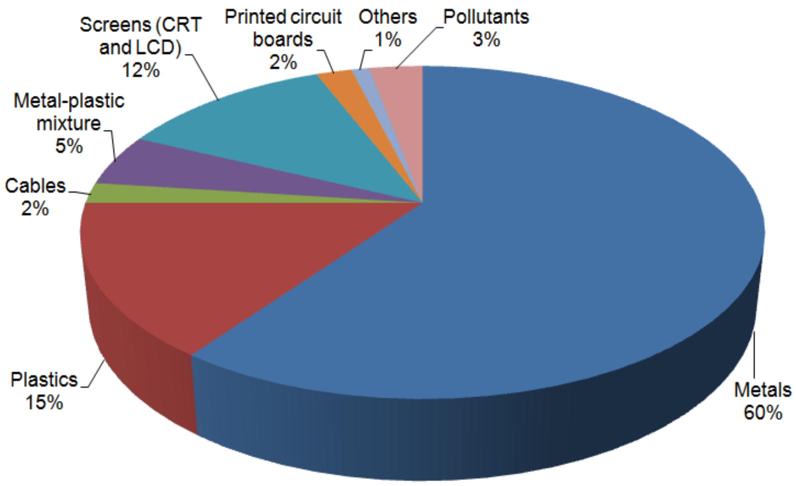

Figure 2.3. Composition of e-waste (F.O. Ongondo et al., 2010).

The weight percentages of materials found in e-waste may differ according to types of products in waste stream. However, studies indicate that iron and steel have the highest portion of e-waste stream and correspond to almost half of the total weight. Copper and aluminum are the other metals that have high percentages by weight with 7 and 4.7%, respectively. Also, plastic materials such as non-flame retarded plastics and flame retarded plastics consist of about 21% of the total weight of e-waste stream. Figure 2.4 displays the composition of the e-waste stream according to weight percentages of the materials in detail (F.O. Ongondo et al., 2010)

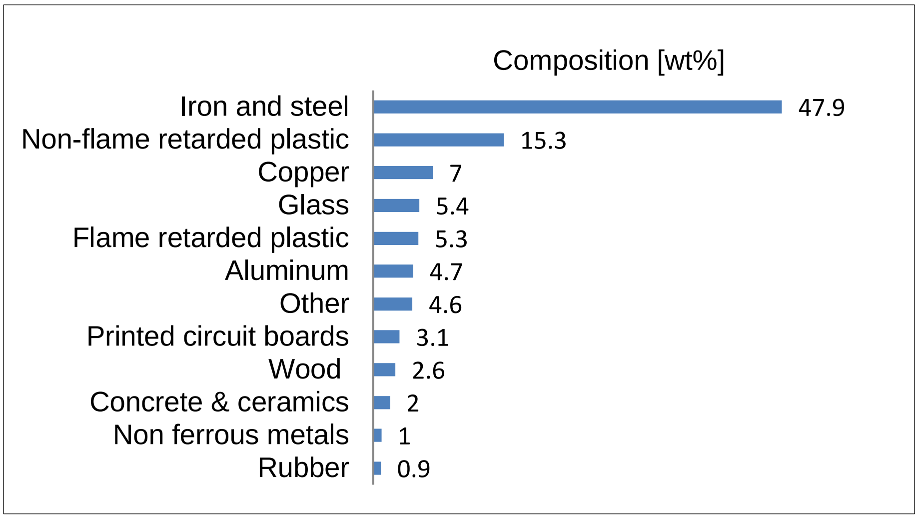

Figure 2.4. WEEE material composition and weight percentages (European Topic Centre on Resource and Waste Management).

The amount of e-waste has been rising each year due to technological innovations and shortening of lifetimes of electronic equipment. By considering the lifetime of a computer as 2–5 years and of a mobile phone as 1-2 years, it is estimated that around 17 million computers and 100 million mobile phones are scraped annually in the world (Rao, 2006; Cui and Forssberg, 2003). Because of their accumulated amounts and material contents, computers and mobile phones are important secondary sources of valuable materials such as base metals, precious metals and rare earth elements (REEs) (Guo et al., 2010; Veit et al., 2006). Table 2.1 shows the metal contents of various types of e-waste (Cui and Zhang, 2008). Since almost 63% of each e-waste contains valuable and precious metals such as gold, silver, copper, iron, lead, aluminum, mercury, platinum, selenium, cadmium, chromium and palladium, which all have an economic value, recycling and recovery of e-waste has become very attractive in the world today (Hagelüken, 2006; Yazici et al., 2010).

Table 2.1. Several types of e-waste and their metal contents (Cui and Zhang, 2008).

E-Waste	Fe (wt%)	Cu (wt%)	Al (wt%)	Pb (wt%)	Ni (wt%)	Ag (ppm)	Au (ppm)	Pd (ppm)
TV board scrap	28	10	10	1	0.3	280	20	10
PC board scrap	7	20	5	1.5	1	1000	250	110
Mobile phone scrap	5	13	1	0.3	0.1	1380	350	210
Portable audio scrap	23	21	1	0.14	0.03	150	10	4
DVD player scrap	62	5	2	0.3	0.05	115	15	4
Calculator scrap	4	3	5	0.1	0.5	260	50	5
PC mainboard scrap	4.5	14.3	2.8	2.2	1.1	639	566	124
Printed circuit boards scrap	12	10	7	1.2	0.85	280	110	-
TV scrap (CRT's removed)	-	3.4	1.2	0.2	0.038	20	<10	<10
Electronic scrap	8.3	8.5	0.71	3.15	2	29	12	-
PC scrap	20	7	14	6	0.85	189	16	3
Typical electronic scrap	8	20	2	2	2	2000	1000	50
E-scrap sample 1	37.4	18.2	19	1.6	-	6	12	-
E-scrap sample 2	27.3	16.4	11	1.4	-	210	150	20
Printed circuit boards	5.3	26.8	1.9	-	0.47	3300	80	-
E-waste mixture	36	4.1	4.9	0.29	1	-	-	-

Printed circuit boards, popularly known as PCBs, are the backbone of most electronics and they are generally composed of metals, ceramics and polymers. Even though they contribute only to 6% of the weight of e-waste, they are the main carriers of valuable metals. According to Cui and Zhang (2008), precious metal content in telephone and PCBs is about 70%, while it is about 40% in TV boards and DVD players. PCBs of computers and mobile phones contain the highest amounts of valuable metals compared to the PCBs of other electronics, such as televisions, refrigirators, DVD players and calculators. Hagelüken (2006) states that a typical computer PCB contains 250 g/ton Au and 20 wt.% Cu, while a mobile phone contains 350 g/ton Au and 13 wt.% Cu (Hagelüken, 2006). In addition, the economic value of Au and Pd recovered from one ton of PCBs was estimated as $15200 and $1850, respectively (Wang and Gaustad, 2012).

FR-2 (Flame Resistant 2) and FR-4 (Flame Resistant 4) are the types of printed circuit boards used in computers and mobile phones. The FR-2 type, which is made of single layer of fiberglass or cellulose paper reinforced with a phenol formaldehyde resin (phenolic resin) and coated with a copper layer, is the most common type of PCB used in computers (William and Williams, 2007; Murugan et al., 2008). The FR-4 type generally used in small devices such as mobile phones is composed of multilayer of fiberglass reinforced with epoxy resin and coated with a copper layer (Ladou, 2006). Metals are the most common materials used in PCBs of computers and mobile phones. The 20–35% of a mobile phone's weight is generated from PCB and the general distribution of materials of a mobile phone's PCB is approximately 30 wt.% of polymers, 30 wt.% of refractory oxides and 40 wt.% of metals (Stutz et al., 2002; Tange and Drohmann, 2005; Kasper et al., 2011). However, a typical PCB of a computer is composed of 27% polymers, 28% ceramics and 45% metals by weight (Yamane et al., 2011).

The base metals found in printed circuit boards are used because of their conductive properties. Generally, copper has the highest percentage in printed circuit boards due to its high conductivity. Recent studies state that copper concentrations of computer PCB and mobile phone PCB are about 20 % and 30 % (by weight), respectively. Since the printed circuit board of mobile phone is multilayer and copper is found between layers of resin, the copper concentration of mobile phone PCB is higher than that of the copper concentration of single layer computer PCB. Also, lead and tin are other base metals used in PCBs during welding of electronic components (Zhang and Forssberg, 1999). Since there are more inserted components in PCB of computers, concentrations of these metals are higher in computer PCBs than mobile phone PCBs (Yamane et al., 2011). However, tin, silver or gold may be used in PCBs as a thin film to protect electrical contacts against oxidation (Veit et al., 2006; Cui and Zhang, 2008). In addition, the solder material, which contains tin, silver, lead and cadmium, is used for the conductive bonds between PCBs surface and components. Furthermore, a mobile phone PCB may also contain elements such as indium, titanium, gallium, silicon, arsenic and germanium, located in chips and semiconductors (Zhang et al., 2004). Table 2.2 displays the several metal concentrations of printed circuit boards of personal computers and mobile phones from different studies.

Table 2.2. Metal concentrations (% weight) of printed circuit boards of personal computers and mobile phones in different works.

[wt.%]	Personal computer PCB		Mobile phone PCB		
	Oguchi et al. (2012a)	Yamane et al. (2011)	Kasper et al. (2011)	Yamane et al. (2011)	Nnorom et al. (2011)
Al	1.8	5.7	0.61	0.26	-
Cr	0.03	-	-	-	-
Fe	1.3	7.33	4.85	10.57	-
Ni	-	0.43	2.54	2.63	-
Cu	20	20.19	37.81	34.49	250 ± 923 g/kg
Zn	0.27	4.48	1.82	5.92	-
Cd	0	-	-	-	2.1 ± 3.3 mg/kg
Sn	1.8	8.83	2.55	3.39	-
Pb	2.3	5.53	1.23	1.87	20.1 ± 8.4 g/kg

PCBs of notebooks consist of various electronic components and connectors which contain precious metals such as gold, silver and palladium. Gold is used in the production of microchips and bonding wires, while silver is used in solder, and palladium may be used in capacitors. Hard disk drives of computers, which are divided into aluminum based drives and glass based drives, also contain gold, silver, palladium, platinum, rhodium and ruthenium in different amounts. Table 2.3 shows the weight and concentrations of precious metals in the components of notebooks (OEKO, 2012).

In addition to the precious metals, there are rare earth elements used in screens and permanent magnets of notebooks. Permanent magnets known as neodymium iron boron (NIB) magnets contain neodymium, praseodymium and dysprosium elements in various percentages and used in spindle motors for the hard disk drives and the optical drives, voice coil accelerators of the hard disk drives and loudspeakers. Moreover, yttrium, europium, lanthanum, cerium, terbium and praseodymium are the rare earth elements used in the production of screens of notebooks. Table 2.4 displays the amount of precious metals and rare earth elements in LCD and LED notebooks in detail (OEKO, 2012).

Table 2.3. Weight and concentrations of precious metals in components of a notebook (OEKO, 2012).

Components	**Weight per unit [g]**	**Ag [mg/kg]**	**Au [mg/kg]**	**Pd [mg/kg]**
Motherboard	310	800	180	80
Memory cards	20	1650	750	180
Small PCBs	28	800	180	80
Hard disk drive PCB	12	2600	400	280
PCB for optical drive	25	2200	200	70
Display PCB	37	1300	490	99
Glass-based HDD platters	4.8	<3	<6	<2.3

According to various studies, a mobile phone, which has an average weight of about 75– 100 g, contains more than 40 elements in its components (Schluep et al., 2009). Hagelüken et al. (2008) states that precious metals such as silver, gold and palladium are used in PCBs of mobile phones and the amounts of these metal per device are 250 mg, 24 mg and 24 mg, respectively. In terms of rare earth elements, neodymium and praseodymium are used in loudspeakers, cobalt is used in batteries, tantalum and gallium are used in the PCBs and also indium is used in the displays of mobile phones. Since the high performance in electronics requires high content of special metals, smart phones contain higher amounts of precious metals and rare earth elements.

Table 2.4. Mean content of raw materials in notebooks (OEKO, 2012).

Metal	Content per notebook (CCFL) [mg]	Content per notebook (LED) [mg]	Occurrence
Cobalt	65000	65000	Lithium-ion batteries (100%)
Neodymium	2100	2100	Spindle motors (37%), voice coil accelerators (34%), loudspeakers (30%)
Tantalum	1700	1700	Capacitors on motherboard (90%), capacitors on other PCBs (10%)
Silver	440	440	Motherboard (57%), other PCBs (43%)
Praseodymium	270	270	Voice coil accelerators (53%), loudspeakers (47%)
Gold	100	100	Motherboard (54%), other PCBs (46%)
Dysprosium	60	60	Voice coil accelerators (100%)
Indium	40	40	Display & background illumination (100%)
Palladium	40	40	Motherboard (64%), other PCBs (36%)
Platinum	4	4	Hard disk drive platters (100%)
Yttrium	1.8	1.6	Background illumination (100%)
Gallium	0	1.6	LED background illumination (100%)
Gadolinium	0.01	0.75	Background illumination (100%)
Cerium	0.08	0.1	Background illumination (100%)
Europium	0.13	0.03	Background illumination (100%)
Lanthanum	0.11	0	CCFL back ground illumination (100%)
Terbium	0.04	0	CCFL back ground illumination (100%)

2.2. Recovery Methods of Metals from E-waste

E-waste contains a variety of hazardous substances such as mercury, lead, arsenic, cadmium, hexavalent chromium and flame retardants, which may cause to serious health and environmental problems. Puckett and Smith (2002) states that about 70% of the heavy metals in the landfills of United States, such as mercury and cadmium, come from e-waste. They also indicate that the consumer electronics are the reason of 40% of the lead found in landfills. Therefore, the proper implementation of successful e-waste recycling and recovery strategies enables the control of health and environmental risks based on toxic materials present in e-waste. However, e-waste is an important secondary metal resource because of its high content of base, precious metals and rare earth elements. Therefore, recycling of e-waste considerably reduces the energy consumption for the metal production and conserves natural resources as long as it is technically and economically feasible.

The amount of e-waste and metal concentrations in it, metal losses, environmental impacts and the scale of operation are the factors that should be considered in the selection of proper recycling processes to be applied for e-waste. Goosey and Kellner (2002) pointed out that the metals could be recycled by conventional mechanical, pyrometallurgical, hydrometallurgical and biometallurgical proceses or a combination of these techniques. Throughout the world, e-wastes recycling processes can be roughly divided into three major steps:

a) Pre-treatment: Different electronic devices are dismantled and separated into various components, such as batteries, PCBs, capacitors, LCDs and into fractions such as metals, plastics, glass, ceramics and wood in pre-treatment process (Antrekowitsch et al., 2006). These separated components could be reused or recycled after certain processes are conducted. Following the dismantling process, size reduction is applied by using shredders and hummer mills in order to prepare materials for further processes.

b) Physical separation: Materials found in e-waste have different physical properties, such as specific gravity, electrical conductivity and magnetic susceptibility. With the help of these properties, metals are separated from non-metals by using mechanical processes such as magnetic, electrostatic and eddy-current separation (Zhang and Forssberg, 1998; Cui and Forssberg, 2003).

c) Metallurgical methods: With the purpose of treatment and purification of desirable materials, pyrometallurgical, hydrometallurgical, biometallurgical and the combination of these methods are used as a last step (Cui and Zhang, 2008; Duan et al., 2009; Ilyas et al., 2010; Tuncuk et al., 2012).

2.2.1. Pyrometallurgical Methods

Pyrometallurgy is a process that requires thermal energy to bring physical and chemical transformations in the materials. Pyrometallurgical processes have been used for the recovery of valuable metals from e-waste during the last decades. Incineration, combustion, smelting in furnaces and pyrolysis are the typical e-waste recycling processes. Pyrometallurgical processes are considered as one of the best available recycling techniques. However, they are high-cost processes due to their intensive energy and high grade feed requirements.

2.2.2. Hydrometallurgical Methods

Since the mid 20th century, research attention has been focused on hydrometallurgical processes for recovery of metals from e-waste. Because of the small concentrations of metals in secondary sources, hydrometallurgical recovery methods have been prefered to pyrometallurgical methods (Cui and Zhang, 2008; Ilyas et al., 2010; Tuncuk et al., 2012). Hydrometallurgical techniques are promising to be more exact, predictable and easily controlled. Hydrometallurgical processes offer higher metal recoveries with low capital cost and environmental impact compared to pyrometallurgical recovery methods (Yazıcı and Deveci, 2009).

Biohydrometallurgy is regarded as one of the most promising and revolutionary technologies of hydrometallurgical processing (Veglio and Beolchini, 1997; Volesky, 2003; Ahluwalia and Goyal, 2007). In recent years, a great number of investigations on biohydrometallurgical process have been conducted in order to develop appropriate recycling techniques. Biohydrometallurgy is a natural process that uses microorganisms to enhance the dissolution of metals from mineral ores by making them more amenable to dissolution in aqueous solutions (Simate and Ndlovu, 2008). This solubilization is the result of lixiviating action of organic and inorganic acids, oxidants or other complexing agents generated by microorganisms on metals/minerals through oxidation, reduction and complexing reactions. Microorganisms can manage the solubilization attaching directly to solid phase and/or, indirectly, generating the lixiviant in the bulk of solution (Barrett et al., 1993; Bosecker, 1997; Sand et al., 2001; Tribustch, 2001). Biohydrometallurgical processes have been used in the industry for the pretreatment of refractory gold ores to improve gold extraction in subsequent cyanide leaching and the recovery of copper from low grade sulphide ores for many years.

2.3. Legislation about E-waste

In many countries of the world, e-wastes are still considered as a part of municipal solid waste because of the uncertainties in the e-waste management system. However, the huge growth in e-waste generation and the disposal problems associated with the increase in production of Electrical and Electronic Equipments (EEEs) require an advanced e-waste management system (Davis and Herat, 2008). The management of e-waste is very important, not only for waste treatment, but also for recovery of valuable materials as well. Electronic wastes include health and environment threatening hazardous materials, such as heavy metals, together with precious and rare earth metals, as explained previously. Waste electrical and electronic equipments must be disposed of properly to reduce the amount of waste, to protect the environment from hazardous materials and to obtain more recoverable and recycling materials (Khetriwal et al., 2005). Therefore, e-waste management is a complex program due to economic values and environmental aspects (Kaya, 2012).

2.3.1. E-waste Legislation in European Union (EU)

The management of e-waste has become an important part of waste management systems of the European Union (EU) in the last two decades. The EU has taken precautions to reduce the generation rate of e-waste and also has promoted reuse, recycling and recovery of such wastes. Two different legislations have been brought into force by the EU for management of e-waste. The first legislation is called ‘The directive on waste electrical and electronic equipment’ (European Commission-WEEE Directive, 2003). The second legislation is called

‘The directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment’ (European Commission-RoHS Directive, 2002). After the WEEE and RoHS directives came into force in the member states, the conventional end-of-pipe management approach to environmental issues changed. More attention has been focused on improving the design of electrical and electronic equipments (EEEs) in order to reduce their potential environmental impacts throughout their life cycle.

2.3.1.1. Waste Electrical and Electronic Equipment (WEEE) Directive. It was decided to establish management programmes for particular types of waste streams with the approval of the European Council resolution about waste policy in May 1990. With respect to this development, e-waste was identified as one of the priority waste stream by the EU in 1991 and a project group was formed to find out solutions for the environmental impacts of e-waste. In June 2000, the European Commission (EC) decided to propose a directive about e-waste management. In April 2001, the Directive on waste electrical and electronic equipment was submitted to the European Parliament and in February 2003, the WEEE Directive (2002/96/EC) came into force in the EU. August 2004 was designated as the deadline for transposition in the member states. In August 2012, the directive was revised to struggle with the rapidly increasing e-waste stream and the new WEEE directive (Directive 2012/19/EU) became effective in February 2014 in the member states.

The priority purpose of the WEEE Directive is to reduce the e-waste generation and to prevent landfilling and incineration of such wastes by promoting reuse, recycle and recovery of them. The directive also aims to increase the responsibility of producers, distributors and consumers in the management of e-waste.

The directive describes ten different categories of WEEE and sets targets for their separate collection and recycling. WEEE categories covered in the directive are indicated in the Table 2.5.

Table 2.5. WEEE categories according to the EU Directive (Directive 2012/19/EU).

No.	WEEE Category	Label
1	Large household appliances	Large HH
2	Small household appliances	Small HH
3	IT and telecommunications equipment	ICT
4	Consumer equipment	CE
5	Lighting equipment	Lighting
6	Electrical and electronic tools[a]	E & E tools
7	Toys, leisure and sports equipments	Toys
8	Medical devices[b]	Medical equipment
9	Monitoring and control instruments	M & C
10	Automatic dispensers	Dispensers

[a] With the exception of large-scale stationary industrial tools
[b] With the exception of all implanted and infected products

The WEEE Directive dwells on certain issues and stipulates the followings about them.

Product design: The design and production of electrical and electronic equipments should enable dismantling and recovery of WEEE with the purpose of later reuse and recycling of their components and materials. In addition, recycled material usage in new equipments should be increased by manufacturers.

Separate collection: Member States should take measures to minimise the disposal of WEEE as unsorted municipal waste. They should attach importance to increasing the level of separate collection of WEEE. Furthermore, effective collection systems and convenient facilities should be set up to collect WEEE from private households at least free of charge.

The first WEEE Directive (2002/96/EC) sets separate collection target as at least 4 kg on average per inhabitant per year from private households. The revised directive (2012/19/EU) indicates minimum collection rates of WEEE as 45% of electronic equipment sold, in the period from 2016 to 2019, and 65% of equipment sold or 85% of WEEE generated, after 2019.

Proper treatment: Proper treatment for WEEE is essential in order to prevent the dispersion of pollutants into environment. Therefore, best available treatment, recovery and recycling techniques must be used to protect the human health and the environment. For this reason, selective treatment techniques for materials and components of WEEE and technical requirements for storage and treatment facilities are specified in the annexes of directive. Also it is indicated that treatment facilities must get a permit from the competent authorities.

Treatment operations may take place outside the Community subject to conformity with Council Regulation on the supervision and control of shipments of waste within, into and out of the European Community. Moreover, exporters must demonstrate that treatment conditions outside the Community are equivalent to the requirements of WEEE Directive.

Recovery: Reuse of WEEE and its components should be preferential if conditions are appropriate. Otherwise, all collected WEEE should be subjected to recycling and recovery at proper facilities. The targets for recovery, recycling and reuse of WEEE had been set by the EU Commission with the first WEEE Directive in 2003 and they had been revised in 2012. Table 2.6 shows the recovery and reuse/recycling targets for producers according to WEEE categories and years.

Informing: The users of electrical and electronic equipment in private households should be informed about the separate collection of WEEE, the potential effects of hazardous substances in EEEs on the human health and the environment, collection systems available to them, their role in the recovery systems and the meaning of the symbol on the packaging of EEEs. In addition, producers must mark EEEs put on the market after 13 August 2005 with the crossed-out wheeled bin symbol in order to inform users about separate collection of WEEE. Figure 2.5 presents the crossed-out wheeled bin symbol.

Table 2.6. Recovery and reuse/recycling targets per WEEE category.

Directive 2002/96/EC (by 31 Dec 2006)			Directive 2012/19/EU (by 15 Aug 2015)		
Category	Recovery[a] (%)	Reuse/recycling[b] (%)	Category	Recovery[a] (%)	Reuse/recycling[b] (%)
1, 10	80	75	1, 10	85	80
3, 4	75	65	3, 4	80	70
2, 5, 6, 7, 9	70	50	2, 5, 6, 7, 8, 9	75	55
(5)[c]	80	80	(5)[c]	80	80

[a] Recovery by weight
[b] Component material and substance reuse and recycle by weight
[c] Gas discharge lamps

Reporting: Member States should record the information of categories and quantities of EEEs put on the market. Besides that, they should keep records on mass and components of recycled WEEE for the purpose of calculating recovery and recycling levels. States also must send every three years a report to the EU Commission on the application of the directive.

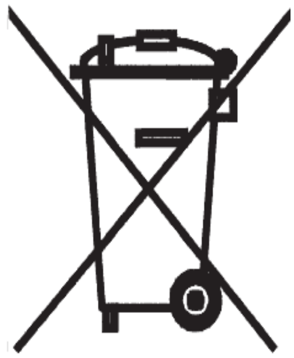

Figure 2.5. Crossed-out wheeled bin symbol.

2.3.1.2. Restriction of Hazardous Substances (ROHS) Directive. The directive restricting the use of hazardous substances in electrical and electronic equipment (Directive 2002/95/EC) came into force in February 2003. The RoHS Directive prohibits the use of six hazardous substances more than agreed levels in the production of certain types of electrical and electronic equipment. The main purpose of this directive is to reduce the environmental impact of EEEs during the disposal and recovery periods. RoHS restricts the use of the following six substances:

1. Lead (Pb)
2. Cadmium (Cd)
3. Mercury (Hg)
4. Hexavalent chromium (Cr^{6+})
5. Polybrominated biphenyls (PBB)
6. Polybrominated diphenyl ether (PBDE)

In July 2011, the RoHS directive was revised and it took effect in January 2013 in the member states. The revised directive handles the same hazardous substances as the first directive while improving legal provisions.

2.3.2. E-waste Legislation in Turkey

The rapid advancement of technology in Turkey has caused not only an increase in the production and consumption of electronic goods, but also to a challenge of the management of e-waste. To overcome of the e-waste management problem, certain legislations were prepared in line with the EU Directives.

The first e-waste regulation of Turkey, ‘‘Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipments’’, was issued on 30.05.2008 in order to regulate and prohibit the use of hazardous substances in electrical and electronic equipments. Two years later, the current EU Directive on WEEE was adapted with several modifications by the Ministry of Environment and Urbanism in Turkey. This revised version of the regulation was published on 22 May 2012. After this regulation became valid, the first regulation was removed and the restriction of the use hazardous substances started to be evaluated under the regulation of “Waste Electrical and Electronic Equipments”.

The objectives of the WEEE legislation are the restriction of the use of hazardous substances in EEEs in order to protect human health and environment, getting under control the import of EEEs and setting targets on reuse, recycling and recovery of e-waste in Turkey. In addition, this legislation specifies the duties and responsibilities of the Ministry of Environment and Urbanism, municipalities, producers and distributors of electrical and electronic equipments, consumers and also operators of recycling plants (Republic of Turkey Ministry of Environment and Urbanism, 2012).

Table 2.7. E-waste collection targets presented in WEEE legislation of Turkey.

Categories	**Collection Targets (kg/person-year)**				
	2013	**2014**	**2015**	**2016**	**2018**
1. Refrigerators/Air conditioners	0.05	0.09	0.17	0.34	0.68
2. Large Households (with the except of category 1)	0.1	0.15	0.32	0.64	1.3
3. TVs and Monitors	0.06	0.1	0.22	0.44	0.86
4. IT and Telecommunication Equipments	0.05	0.08	0.16	0.32	0.64
5. Lighting Equipments	0.01	0.02	0.02	0.04	0.08
6. Small households, Electrical and Electronic Tools, Toys, Leisure and Sports Equipments, Monitoring and Control Instruments	0.03	0.06	0.11	0.22	0.44
Total	**0.3**	**0.5**	**1**	**2**	**4**

Technical specifications of e-waste recycling plants are reported in the WEEE legislation. Therefore, e-waste collection and recycling companies in Turkey have to obtain an operating license from the ministry and they have to use the best available recovery and recycling techniques. However, recycling companies have to submit certain documents related with the collected, recycled and transported e-waste to the ministry on a monthly basis. In addition, companies have to take a hazardous waste transfer license from the ministry for the trasportation of e-waste.

According to the regulation, the producers of electrical and electronic equipments are responsible for collection and recycling of products that complete their useful life. Table 2.7 presents the domestic e-waste collection targets for producers of electrical and electronic equipment set by the Ministry of Environment and Urbanism with the published WEEE legislation. In the legislation, e-wastes have been categorized under six group and projected collection rates have been indicated in kg/person-year in yearly basis. Table 2.8 also shows the e-waste recycling and recovery goals specified according to the types of electronic products and years in the WEEE legislation.

Table 2.8. E-waste recycling and recovery targets presented in WEEE legislation of Turkey.

Categories	**Recycling (weight, %)**		**Recovery (weight, %)**	
	2013	**2018**	**2013**	**2018**
Large Households	65	75	75	80
Small Households	40	50	55	70
IT and Telecommunication Equipments	50	65	60	75
Consumer Equipments	50	65	60	75
Lighting Equipments	20	50	50	70
Electrical and Electronic Tools	40	50	50	70
Toys, Leisure and Sports Equipments	40	50	50	70
Medical Devices	-	-	-	-
Monitoring and Control Instruments	40	50	50	70
Automatic Dispensers	65	75	70	80

In 2011, 8000 tons of e-waste were collected by 21 licenced e-waste facilities. In the current situation, Turkey has a legislation in order to manage e-waste. However, the disposal strategies and management systems do not meet even half of the total e-waste generated today (Exitcom, Personal Communication).

3. STATEMENT OF THE PROBLEM

The production and manufacturing of electric and electronic equipments is one of the fastest growing industries in the world. Consequently, it is expected that the generation of e-waste will increase globally in near future. However, it is also very well known that heavy metals found in e-waste may pose significant threat to human health and the environment. Furthermore, e-waste contains appreciable quantities of base metals, precious metals and REEs with high economic values. Therefore, proper management and recycling strategies for handling e-waste have to be immediately developed and implemented.

Even though there exists current legislation about e-waste management in Turkey and e-waste is collected by some private companies with licence, the information about the potential of precious metals and/or rare earth elements recovery from e-waste for Turkey is scarce. Thus, the main objective of this study is to determine the recovery potential of precious metals and rare earth elements from e-waste. Therefore, firstly information about the inventory of e-waste generated and collected in Turkey was collected as the first step. Then, selected e-waste samples collected from various sources both in Turkey and Germany were analyzed in the laboratory to determine the concentration of base metals, precious metals and rare earth element contents. Finally, recovery potentials for the selected e-waste types and metals (precious metals and rare earth element) were estimated to evaluate the feasibility of recovery of resources from e-waste. The information obtained as a result of this study can suggest revisions/improvements in the e-waste legislation of Turkey in order to make use of our resources in a more efficient and economical manner.

4. MATERIALS AND METHODS

In this chapter, specifications of collected e-waste samples and their preparation methods, analytical methods performed to determine metal content of e-wastes and recovery potential method were explained, respectively.

4.1. Sample Collection and Preparation

At the beginning of the study, twenty five (25) different out of use electronic devices were collected from various sources in order to determine their metal concentrations and to chemically characterize these e-waste samples. Ten (10) of the forementioned electronic devices were collected by a national private company (Ludre Yazılım) for this study. Thirteen (13) e-waste samples were supplied from the Institute of Environmental Technology and Energy Economics of Technical University of Hamburg (TUHH), Germany. The last two (2) of samples were obtained from the Mining Engineering Department of Karadeniz Technical University (KATU). Specifications of e-waste samples used in this study are presented in Table 4.1. However, the properties of these collected e-waste samples and their preparation processes for further metal analyses are explained in the following sections briefly.

4.1.1. Samples taken from TUHH

E-waste samples taken from TUHH consisted of eight (8) printed circuit boards (PCB) of mobile phones, two (2) displays of mobile phones, one laptop mainboard and one hard disk drive. In the first step of sample preparation process, which was performed at the laboratory of TUHH, the e-waste samples were disassembled manually and the desired parts were separated for analyses. Separated parts were cut into about 2 cm x 2 cm pieces using a stainless steel scissor and then crushed into pieces smaller than 2 mm by using a mechanical miller (Retsch SM 300, Germany). The pieces smaller than 250 μm were sorted by a sieve, collected and then sent to the Institute of Environmental Sciences of

Boğaziçi University for further elemental analyses. The prepared e-waste samples were packaged separately and labeled properly to avoid any confusion. The mechanical miller used in the size reduction at TUHH is shown in Figure 4.1.

a) Outer view b) Inside view

Figure 4.1. Mechanical miller (Retsch SM 300, Germany) used in the size reduction at TUHH.

4.1.2. Samples taken from Ludre

Four (4) printed circuit boards (PCB) of mobile phones, two (2) printed circuit boards (PCB) of computer, two (2) printed circuit boards (PCB) of computer monitor and two (2) mainboards of computer were collected by Ludre Yazılım in Istanbul area for this study. These collected e-waste samples were cut into around 1.5 - 2 cm pieces by using a hammer. Due to lack of a powerful cutting machine at the laboratory of the Institute of Environmental Sciences at Boğaziçi University, these e-waste samples were sent to TUHH for further size reduction. During size reduction processes performed at TUHH, a mechanical miller (Retsch SM 300, Germany) was used. The e-waste samples smaller than 250 μm were send back to Boğaziçi University for further elemental analyses.

One for each of dismantled computer and mobile phone samples supplied by Ludre Yazılım are presented in Figure 4.2. In addition, Figure 4.3. shows a) the initial form of PCB of computer b) the form of PCB after cutting and c) the form of PCB after shredding.

4.1.3. Samples taken from KATU

Two (2) different printed circuit boards (PCB) of obsolete computers produced before 2006 were collected by a research group from KATU for this study. After manual separation, the size of the PCB components were reduced to 3.35 mm by using a four-bladed rotary cutting shredder and then to 1 mm, using a laboratory type rotary cutting mill (Thomas Wiley Laboratory Mill Model 4, Thomas Scientific, United States). Finally, the shredded samples were minimized to 250 µm pieces by using an ultra-centrifugal mill (Retsch ZM 200, Germany) at laboratory of KATU and then sent to Boğaziçi University for further chemical analyses.

a) Computer sample b) Mobile phone sample

Figure 4.2. Dismantled computer and mobile phone samples supplied by Ludre Yazılım.

a) PCB of computer

b) PCB of computer after cutting c) PCB of computer after shredding

Figure 4.3. a) The initial form of PCB of computer, b) the form of PCB after cutting and c) the form of PCB after shredding.

Table 4.1. Specifications of e-waste samples used in the study.

Sample No	Category	Model	Source
1	PCB of mobile phone	Nokia 3310	TUHH (Germany)
2	PCB of mobile phone	Nokia 6210	
3	PCB of mobile phone	Nokia 3210	
4	PCB of mobile phone	Siemens C5	
5	PCB of mobile phone	Nokia 6110	
6	PCB of mobile phone	Nokia 3410	
7	PCB of mobile phone	Blackberry smartphone	
8	PCB of mobile phone	Mixture of various models	
9	PCB of mobile phone	Mixture of various models	
10	Display of mobile phone	Blackberry	
11	Display of mobile phone	Nokia	
12	Motherboard of laptop	Mixture of various models	
13	Hard drive disc	Mixture of various models	
14	PCB of mobile phone	Asus Pegasus	LUDRE (Turkey)
15	PCB of mobile phone	General Mobile	
16	PCB of mobile phone	NG 870	
17	PCB of mobile phone	Nokia C5	
18	Motherboard of computer	ASUS A6J	
19	PCB of computer monitor	ASUS A6J	
20	Motherboard of computer	Compaq Armada 7330T	
21	PCB of computer monitor	Compaq Armada 7330T	
22	Motherboard of computer	Gıgabyte	
23	Motherboard of computer	MSI 865	
24	PCB of computer	Mixture of various models	KATU (Turkey)
25	Motherboard of computer	Mixture of various models	

4.2. Digestion Method

After sample preparation processes were completed, chemical analysis step was conducted to characterize the e-waste samples with regard to their precious and rare earth metal contents. Therefore, an acid digestion method was employed in order to completely transfer the solid components of the e-waste samples into a liquid solution, so that they can be introduced into the subsequent metal determination step. Microwave assisted acid digestion method was selected and performed in this study due to its short processing time, low contamination risks and less possibility of volatilization loses. In addition, the microwave assisted digestion method requires lower amount of samples and acids according to conventional digestion procedures (Soylak et al. 2004). The critical parameters of this closed vessel digestion method are the digestion temperature, pressure, time and the type of chemicals used.

The prepared e-waste samples were digested using a Mars 6 Microwave Accelerated Reaction System (CEM Corporation, North Carolina, USA) equipped with 12 high pressure sample digestion vessels including a control vessel. In the first step of the digestion procedure, 100 mg of each e-waste sample was weighed using an analytical balance and transferred into microwave digestion vessels. 10 mL of hydrochloric acid (HCl) (35% m/v) and 3.5 mL of nitric acid (HNO_3) (69% m/v) were added to each vessel (Smita et al., 2013). Then, the vessels were closed, put into a support module and placed inside the microwave instrument as shown in Figure 4.4. The heating program was performed in two stages under high pressure. In the first stage, the temperature was increased to 140°C in 15 minutes and held at 140°C for 5 minutes. In the second stage, the temperature was increased linearly from 140°C to 200°C in 16 minutes and held at 200°C for 15 min. The operational conditions for microwave digestion are summarized in Table 4.2 and presented as a graph in Figure 4.5.

Table 4.2. Operational conditions of microwave digestion system.

Operational Parameters	**1st stage**	**2nd stage**
Power (watts)	800	800
Ramp time (minutes)	15	16
Temperature (°C)	140	200
Hold Time (minutes)	5	15
Pressure (psi)	400	600

After microwave digestion program was completed, the vessels were taken out and left for cooling. Then, the digested samples were transferred to clean tubes, diluted to 50 mL with high purity water and filtered from 0.45 µm Syringe Filter. Five different aliquots of each e-waste sample were digested and chemically analysed during this study.

Figure 4.4. Mars 6 Microwave Accelerated Reaction System.

Between each batch of digestion process, the vessels were cleaned by running a cleaning program of microwave digestion system to avoid contamination. After cleaning program was completed, the vessels were filled with diluted HNO_3 solution and kept until further use. All glassware and polymeric tubes used during the experimental procedure were soaked in a HNO_3 solution (10% v/v) bath for a day, rinsed with high-purity water and then dried in a clean environment before use. HCl (35% m/v) and HNO_3 (69% m/v) used during digestion procedure were of analytical grade and purchased from Merck (Darmstadt, Germany).

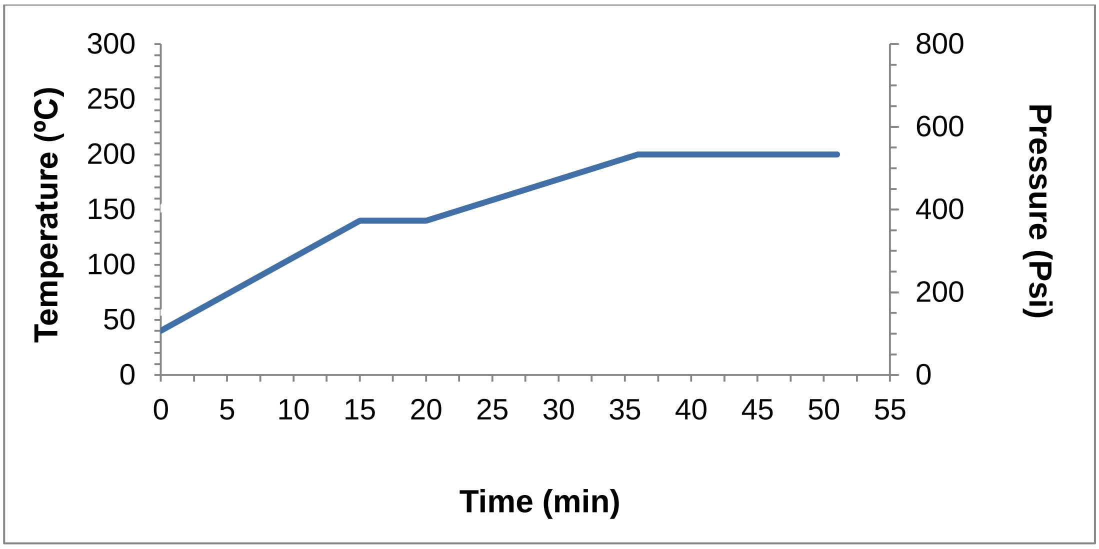

Figure 4.5. Microwave operational conditions.

4.3. Inductively Coupled Plasma Optical Emission Spectrometry

Inductively coupled plasma optical emission spectrometry (ICP-OES) was used as an elemental analysis technique in order to identify and quantify the elements that were present in digested e-waste samples. ICP-OES was employed in the study due to its capability of determining over 70 elements present in the periodic table with low detection limits. ICP-OES is also rapid in simultaneous multi-element analysis and has ability to analyse small sample sizes as well.

A simultaneous inductively coupled plasma optical emission spectrometer (Optima 2100 DV, Perkin Elmer, USA) with an axially viewed configuration was used in the study to detect and quantify the selected elements given in Table 4.3. The ICP-OES instrument was equipped with a solid state detector, cyclonic spray chamber and an extended spectral range. The selected elements for chemical analyses, the operating conditions of ICP-OES and selected wavelengths for each element during ICP-OES analyses are summarized in Table 4.3, Table 4.4 and Table 4.5, respectively. In addition, detection limits of ICP-OES for each of selected elements are presented in Table 4.6.

Table 4.3. Selected elements for chemical analysis of e-waste samples.

Base Metals	**Precious Metals**	**Rare Earth Elements**
Aluminum (Al)	Gold (Au)	Cerium (Ce)
Cadmium (Cd)	Silver (Ag)	Dysprosium (Dy)
Cobalt (Co)	Palladium (Pb)	Lanthanum (La)
Chromium (Cr)	Platinum (Pt)	Neodymium (Nd)
Copper (Cu)		Praseodymium (Pr)
Iron (Fe)		
Lead (Pb)		
Nickel (Ni)		
Zinc (Zn)		
Tin (Sn)		

During ICP-OES analyses, standard solutions were used to construct a multipoint calibration curve involving the range of elemental concentrations anticipated in e-waste samples. Standard solutions were prepared from mono-elemental high-purity grade 1000 mg/L stock solution of each element (Merck, Darmstadt, Germany). They were prepared freshly before analysis by diluting with analytical reagent grade HCl (35% m/v) and HNO_3 (69% m/v) (Merck, Darmstadt, Germany) and deionized (DI) water. High purity grade (99.99 %) argon (Ar) gas was used to create plasma during analyses.

Table 4.4. ICP-OES operating parameters (Koto et al., 2010).

BASE METALS			
Al, Cd, Co, Cr, Cu, Fe, Ni, Pb, Zn		**Sn**	
Parameter	**Value**	**Parameter**	**Value**
Forward Power	1450 W	Forward Power	1450 W
Plasma gas flow	16 L/min	Plasma gas flow	17 L/min
Auxiliary gas flow	0.6 L/min	Auxiliary gas flow	0.3 L/min
Nebulizer gas flow	0.6 L/min	Nebulizer gas flow	0.6 L/min
Sample uptake rate	1.50 mL/min	Sample uptake rate	1.50 mL/min
Plasma viewing	Axial	Plasma viewing	Axial
Peak algorithm	Peak area	Peak algorithm	Peak area
Measurement point	5 points/peak	Measurement point	7 points/peak
PRECIOUS METALS			
Au, Pd, Pt		**Ag**	
Parameter	**Value**	**Parameter**	**Value**
Forward Power	1300 W	Forward Power	1300 W
Plasma gas flow	16 L/min	Plasma gas flow	15 L/min
Auxiliary gas flow	0.6 L/min	Auxiliary gas flow	0.2 L/min
Nebulizer gas flow	0.8 L/min	Nebulizer gas flow	0.8 L/min
Sample uptake rate	2.00 mL/min	Sample uptake rate	1.50 mL/min
Plasma viewing	Axial	Plasma viewing	Axial
Peak algorithm	Peak area	Peak algorithm	Peak area
Measurement point	7 points/peak	Measurement point	5 points/peak
RARE EARTH ELEMENTS			
Ce, Dy, La, Nd, Pr			
Parameter	**Value**		
Forward Power	1400 W		
Plasma gas flow	15 L/min		
Auxiliary gas flow	1.2 L/min		
Nebulizer gas flow	0.8 L/min		
Sample uptake rate	1.50 mL/min		
Plasma viewing	Axial		
Peak algorithm	Peak area		
Measurement point	7 points/peak		

Table 4.5. The wavelenghts of the measured elements.

Element	Wavelength (nm)
Pd	340.458
Pt	265.945
Au	267.595
La	398.852
Ce	406.109
Nd	413.764
Pr	390.844
Dy	353.170
Zn	206.200
Pb	220.353
Co	228.616
Cd	228.802
Ni	231.604
Fe	238.204
Cr	267.712
Cu	327.393
Al	396.153
Ag	328.068
Sn	189.927

Table 4.6. ICP-OES detection limits of the measured elements.

Element	**Detection Limit (μg/ L)**
Pd	2
Pt	1
Au	1
La	0.4
Ce	1.5
Nd	2
Pr	2
Dy	0.5
Zn	0.2
Pb	1
Co	0.2
Cd	0.1
Ni	0.5
Fe	0.1
Cr	0.2
Cu	0.4
Al	1
Ag	0.6
Sn	2

4.4. Recovery Potential Method

After the elemental characterization of the e-waste samples was completed, recovery potentials of base, precious and rare earth metals were estimated by using equation 4.1. Recovery potentials of metals were determined by combining elemental concentration values obtained from experimental analyses and certain literature values about e-waste.

$$\text{Recovery potential (t)} = \frac{\text{metal}}{\text{component}}\left(\frac{g}{kg}\right) \times \frac{\text{component}}{\text{device}}\left(\frac{g}{g}\right) \times \text{WEEE (t)} \tag{4.1}$$

Due to the lack of an official information about the amount of discarded computer and mobile phone devices in Turkey, estimated amounts of discarded devices by Ozturk (2015) were used to determine recovery potential in this study. Ozturk (2015) stated that 31510 tonnes of computers and 2257 tonnes of mobile phones were discarded in Turkey in year 2012 (Ozturk, 2015).

In this study, recovery potentials of metals from components of computers and mobile phones were separately determined. While weight percentage of PCBs in mobile phones were stated as 25 % generally, the percentage of motherboards in computers were generalized as 15 % according to information from literature (Stutz et al., 2002; OEKO, 2012). Therefore, these percent weight of components in devices were used in the calculations in this work.

$$\frac{\text{metal}}{\text{component}}\left(\frac{g}{kg}\right) = \frac{\text{concentration of metal}\left(\frac{mg}{L}\right) \times \text{volume of sample (L)}}{\text{weight of sample (kg)}}$$

Volume of sample: 50 mL

Weight of sample: 0.1 g (4.2)

The concentrations of metals in the components of electronic devices were determined by using an ICP-OES in unit of mg/L. Therefore, equation 4.2 was used in order to calculate mass fraction of metals in e-waste sample in unit of mg/kg (Ueberschaar and Rotter, 2014).

Recovery potentials of base, precious and rare earth metals from PCBs of mobile phones and from motherboards of computer were estimated by combining information about metal fractions (g/kg), component percentages (%) and amounts of discarded devices (tons) at the end of this study.

5. RESULTS AND DISCUSSION

5.1. Elemental Characterization of E-waste

Elemental characterization of e-waste was the first step of this study in order to determine the recovery potential of valuable metals from e-waste. Therefore, different e-waste samples were collected from various sources and prepared for elemental analyses. Before experimental studies, an extensive literature review about the content of electronic devices was completed in order to decide on the elements that could be evaluated throughout the study. After that, e-waste samples were digested by using microwave assisted acid digestion method and then concentrations of selected base, precious and rare earth metals in digested samples were detected by performing generated ICP-OES methods. During the study, five different aliquots of each e-waste sample were analysed to determine the concentrations of elements in the samples. The concentration results of five aliquots of each sample and also their mean, standard deviation and relative standard deviation (coefficient of variance) values were presented in **Appendix A.**

E-waste samples analyzed in the scope of this study were categorized as mobile phone samples and computer samples and their elemental characterization results were assessed, respectively.

5.1.1. Mobile Phone Samples

During this study, thirteen (13) different printed circuit boards (PCBs) and two (2) different displays of several mobile phone samples were chemically analyzed in order to determine their metal concentrations. The results of metal concentrations in printed circuit boards and diplays of mobile phone samples are presented and evaluated in this chapter.

5.1.1.1. Printed Circuit Boards. Table 5.1 presents the average concentrations of the detected metals in PCBs of mobile phone samples supplied by Ludre Company (Istanbul, Turkey) and TUHH (Hamburg, Germany) for this study. The results indicated that copper (Cu) was the metal of the highest concentration in printed circuit boards of each mobile phone sample. The concentration values for copper varied from 206 g/kg (in Nokia 3210) to 451.4 g/kg (in Nokia 3410) for all PCB samples. Since copper is one of the most widely used base metals in electronic devices due to its high conductivity, high copper concentration values in PCB samples were expected.

Iron (Fe) was another base metal measured in relatively elevated levels in all PCB samples. It had a wide concentration range changing between 5 g/kg (in Nokia 3310) and 48.4 g/kg (in Nokia 6110). Nickel (Ni) also had high concentration values ranging from 11 g/kg (in Nokia 3210) to 59.3 g/kg (in Nokia 3410). The reason of high nickel concentration in PCB samples might be the use of nickel film under metallic contacts of the keys of mobile phones during manufacturing (Veit et al., 2005; Svoboda and Fujita, 2003). However, tin (Sn) and lead (Pb) are the base metals used in welding of electronic components of PCBs (Zhang and Forssberg, 1999). Their average concentration values in PCB samples were measured from 13 g/kg (in Siemens C5) to 355 g/kg (in Nokia 3310) and from 1.0 g/kg (in General Mobile) to 27.3 g/kg (in Blackberry smartphone), respectively. The concentrations of chromium (Cr) and cobalt (Co) were detected in relatively low levels in all samples used in this work.

Among the precious metals, silver (Ag) and gold (Au) had the highest concentrations in all samples analyzed. While the highest concentration of silver (Ag) was detected to be 8.3 g/kg in Nokia 3210, the highest concentration of gold (Au) was measured to be 2.9 g/kg in NG 870. These result may arise from the wide use of silver and gold against oxidation in PCBs (Veit et al., 2005). Since rare earth metals are not used in the production of PCBs of mobile phones, their concentrations have not been analyzed in the samples during this study.

Table 5.1. Mean concentrations of metals in printed circuit boards (PCBs) of mobile phone samples.

SUPPLIER	**LUDRE (Turkey)**				**TUHH (Germany)**								
Element (g/kg)	**Asus Pegasus**	**General Mobile**	**NG 870**	**Nokia C5**	**Nokia 6110**	**Nokia 3210**	**Nokia 3310**	**Nokia 6210**	**Nokia 3410**	**Siemens C5**	**BB Smart****	**Mix 1**	**Mix 2**
Base Metals													
Cu	324.7	370.4	227.5	378.0	404.0	206.0	287.5	305.2	451.4	313.1	397.7	282.4	409.8
Fe	23.6	20.4	37.2	33.9	48.4	10.0	5.0	14.8	6.4	11.9	46.3	10.1	34.2
Al	8.9	13.2	10.4	11.5	12.9	10.7	11.8	14.9	16.6	16.3	20.1	15.9	19.7
Sn	62.7	34.3	51.8	28.3	26.2	29.6	35.5	29.7	25.3	13.0	33.0	27.1	13.7
Ni	32.3	13.6	23.8	21.0	37.7	11.0	15.8	31.9	59.3	27.0	17.0	15.0	20.1
Zn	28.1	8.2	21.2	2.3	17.8	3.5	7.2	30.2	67.0	5.1	26.9	13.6	18.9
Cr	0.19	0.11	3.9	0.33	0.51	0.13	0.29	0.46	0.17	0.44	0.44	0.14	15.0
Pb	1.6	1.0	7.3	2.6	16.7	16.3	17.9	14.6	23.3	10.0	27.3	15.6	1.9
Co	0.14	0.05	0.27	0.11	0.19	0.11	0.12	0.37	0.23	0.70	0.05	0.30	0.10
Precious Metals													
Ag	2.5	1.7	2.0	2.0	4.7	8.3	5.1	3.7	3.2	3.9	2.6	5.9	1.7
Au	2.4	0.65	2.9	1.4	1.3	1.8	1.6	1.5	0.82	1.1	0.53	1.6	0.17
Pd	0.01	<DL*	0.04	0.26	0.22	0.36	0.40	0.82	0.12	0.47	<DL*	0.39	0.14
Pt	0.032	0.022	0.026	0.028	0.050	0.033	0.019	0.007	0.012	0.015	0.026	0.036	0.026

*<DL: Below detection limit, **Blackberry Smart Phone

Table 5.2. Metal concentration values (wt.%) in PCBs of mobile phones.

Element (wt.%)	Values from this study			Literature values		
	Min	Max	Mean	Kasper et al. (2011)	Yamane et al. (2011)	Konstantinos et al. (2013)
Cu	20.6	45.1	33.5	37.8	34.4	1.71
Fe	0.50	4.84	2.32	4.85	10.57	2.71
Al	0.89	2.01	1.41	0.61	0.26	1.19
Sn	1.30	6.27	3.16	2.55	3.39	0.09
Ni	1.10	5.93	2.50	2.54	2.63	1.88
Zn	0.23	6.70	1.92	1.82	5.92	0.18
Cr	0.01	1.50	0.17	-	-	0.31
Pb	0.10	2.73	1.20	1.23	1.87	0.57
Co	0.01	0.07	0.02	-	-	-
Ag	0.17	0.83	0.36	-	0.21	-
Au	0.02	0.29	0.14	-	-	-
Pd	0.001	0.08	0.03	-	-	-
Pt	0.001	0.005	0.003	-	-	-

Table 5.2 shows the minimum, maximum and mean concentration values in weight percent (wt. %) of the thirteen PCB samples evaluated in this study and also the mean concentration values from various studies for comparison of results. Mean concentrations values of copper (Cu), tin (Sn), nickel (Ni), zinc (Zn) and lead (Pb) determined in this study are very similar to the values from studies of Kasper et al. (2011) and Yamane et al. (2011). However, iron (Fe) and aluminum (Al) showed more similar behavior with mean of concentration values reported in the study of Konstantinos et al (2013). Regarding the precious metals, only silver (Ag) was reported in the study of Yamane et al. (2011) and its mean concentration was slightly lower than that of this study. Elemental concentration differences in these studies can arise from variation of brands, models and production date of mobile phones. In addition, employed methods and used instruments are the other factors that may affect the concentration results in the different studies.

5.1.1.2. Displays. Table 5.3 shows the average concentrations of the detected metals in displays of two different mobile phone samples supplied by TUHH

(Hamburg, Germany). The results indicated that the most abundant metals in displays were silicon (Si), copper (Cu) and aluminum (Al), in descending order. While 21 g/kg Si, 15.0 g/kg Cu and 12.0 g/kg Al were detected in Blackberry display samples, the average concentration values of Si, Cu and Al in Nokia display samples were measured as 16.6, 13.5 and 3.8 g/kg, respectively. The reason of high Si and Al concentrations in samples can be the aluminosilicate glass that is commonly used in the displays of mobile phones, that is composed of a mix of alumina (Al_2O_3) and silica (SiO_2).

Table 5.3. Mean concentrations of metals in displays of mobile phone samples.

Element (g/kg)	Blackberry Display	Nokia Display
Base Metals		
Cu	15.0	13.5
Al	12.0	3.8
Sn	1.2	0.75
Ni	1.4	1.7
Zn	0.30	0.24
Cr	3.7	0.27
Pb	0.26	0.33
Si	20.9	16.6
Precious Metals		
Ag	0.22	0.60
Au	0.013	0.19
Pd	<DL	<DL
Rare Earth Elements		
La	0.20	0.48
Ce	0.13	0.004
Pr	<DL	0.03
Dy	<DL	0.02

*<DL: Below detection limit

Silver (Ag) and gold (Au) were the precious metals observed in display samples in low concentrations. Among the rare earth elements (REEs), while lanthanum (La) and cerium (Ce) were detected in both samples, praseodymium (Pr) and dysprosium (Dy) were measured only in Blackberry display. Cerium (Ce) and lanthanum (La) are commonly used rare earth elements in low quantities to produce colours especially in displays of smartphones. While one of the analyzed display samples was dismantled from an old generation Nokia mobile phone, the other one was the display of a new generation Blackberry smartphone. Therefore, the reason of the concentration differences between two display samples could be the variety of mobile phone models.

5.1.2. Computer Samples

In this study, seven (7) computer motherboards, two (2) PCBs of different computer monitors and one (1) hard drive disk (HDD) were analyzed for their metal concentrations. The results of metal concentrations in computer samples were presented and evaluated in this chapter.

5.1.2.1. Motherboards. Motherboards are the main printed circuit boards (PCBs) of computers and they have different components attached on their surface, such as connectors, sockets, chips and batteries. While the components of three (3) motherboard samples were mostly dismantled before analyses, four (4) of motherboards samples were analyzed with their components. Therefore, motherboard samples analyzed in this study were categorized as motherboads with components and motherboards without components.

Table 5.4 and Table 5.5 present the average concentrations of the detected metals in computer motherboards with components and without components, respectively. The results showed that copper (Cu) had the highest concentration in all motherboard samples. While copper concentration in motherboards with components ranged from 105.7 g/kg (in mixed sample supplied by KATU, Trabzon, Turkey) to 347.1 g/kg (in mixed sample supplied by TUHH), it ranged from 166.7 g/kg (in mixed sample supplied by KATU) to 233.8 g/kg (in MSI supplied by LUDRE) in motherboards samples without components. Since computer motherboards are single layer PCBs, their copper concentrations have been detected at relatively lower values than those of multilayer PCB samples of mobile phones.

Table 5.4. Mean concentrations of metals in motherboards (with components) of computer samples.

SUPPLIER	LUDRE		KATU	TUHH
Element (g/kg)	**Asus A6J**	**Compaq Armada**	**Mixture**	**Mixture**
Base Metals				
Cu	164.0	303.5	105.7	347.1
Fe	42.3	109.8	28.8	107.3
Al	3.9	8.2	50.8	23.8
Sn	27.7	27.5	43.9	30.8
Ni	29.1	8.2	3.9	12.6
Zn	11.8	22.5	12.7	3.2
Cr	0.17	0.11	0.33	0.62
Pb	14.8	6.4	33.8	4.8
Co	1.05	0.05	0.77	0.25
Precious Metals				
Ag	2.3	3.2	0.42	3.4
Au	3.0	1.4	0.38	0.78
Pd	0.15	0.19	<DL	<DL
Pt	0.01	0.04	0.04	0.10
Rare Earth Elements				
La	0.003	<DL	<DL	<DL
Nd	0.86	1.5	0.16	0.77
Ce	<DL	<DL	0.01	<DL
Pr	0.08	0.04	<DL	0.1
Dy	<DL	<DL	<DL	0.45

*<DL: Below detection limit

Iron (Fe), tin (Sn), aluminum (Al), nickel (Ni), lead (Pb) and zinc (Zn) were the other detected base metals in all motherboard samples with high concentration values. However, chromium (Cr) and cobalt (Co) were detected at relatively low concentrations among the base metals.

Table 5.5. Mean concentrations of metals in motherboards (without components) of computer samples.

SUPPLIER	LUDRE		KATU
Element (g/kg)	**Gigabyte**	**MSI**	**Mixture**
Base Metals			
Cu	190.1	233.8	166.7
Fe	32.0	66.2	19.4
Al	12.1	11.6	15.1
Sn	32.2	51.4	43.4
Ni	30.0	27.1	4.9
Zn	36.7	46.2	9.3
Cr	0.08	0.31	1.0
Pb	24.1	25.8	23.2
Co	0.18	1.2	0.17
Precious Metals			
Ag	1.7	1.5	0.7
Au	1.2	3.1	0.17
Pd	<DL	<DL	0.07
Pt	0.04	0.01	0.04
Rare Earth Elements			
La	<DL	<DL	0.02
Nd	0.16	1.3	0.13
Ce	<DL	<DL	<DL
Pr	<DL	<DL	<DL
Dy	0.02	0.01	<DL

*<DL: Below detection limit

In terms of precious metals, silver (Ag) and gold (Au) had relatively high concentrations in motherboard samples, ranging from 3.4 g/kg Ag (in mixed sample supplied by TUHH) to 0.42 g/kg Ag (in mixed sample supplied by KATU) and from 3.1 g/kg Au (in MSI) to 0.17 g/kg Au (in mixed sample supplied by KATU). While platinum (Pt) was determined in low concentrations in all motherboard samples, palladium (Pd) concentrations were measured to be under detection limit in four of the motherboard samples.

Lanthanum (La), neodymium (Nd), cerium (Ce), praseodyium (Pr) and dysprosium (Dy) were the rare earth elements analysed in the motherboard samples. Among these rare earth elements, neodymium (Nd) was the only element that was detected in all samples with relatively elevated levels, ranging from 0.13 g/kg (in mixed sample supplied by KATU) to 1.5 g/kg (in Compaq Armada). Since the neodymium (Nd) magnets are used as components in the motherboards of computers, concentrations of neodymium (Nd) in motherboards samples with components are relatively higher than the motherboard samples without components.

Table 5.6. Concentration values of metals in motherboards of computers from literature and this study.

Element (wt.%)	This study			Literature values		
	Min	Max	Mean	Oguchi et al. (2012a)	Yamane et al. (2011)	Umicore (2011)
Cu	16.7	23.4	19.7	20.0	20.2	-
Fe	1.94	6.62	3.92	1.30	7.33	-
Al	1.16	1.51	1.29	1.80	5.70	-
Sn	3.22	5.14	4.23	1.80	8.83	-
Ni	0.49	3.0	2.07	-	0.43	-
Zn	0.93	4.62	3.07	0.27	4.48	-
Cr	0.01	0.10	0.05	0.03	-	-
Pb	2.32	2.58	2.44	2.30	5.53	-
Co	0.02	0.12	0.05	-	-	-
Ag	0.07	0.17	0.13	-	0.16	0.08
Au	0.02	0.31	0.15	-	-	0.02
Pd	0.007	0.007	0.010	-	-	0.008
Pt	0.001	0.004	0.003	-	-	-

Table 5.6 presents the minimum, maximum and mean concentration values of motherboards samples without components evaluated in this study and also the

mean concentration values of motherboards from various studies in literature. Since the motherboard samples evaluated in the literature were analyzed without their components, three motherboard samples without components analyzed in this study were selected for the comparison. The results showed that the measured copper concentration value was very similar to the concentrations reported in the studies of Oguchi et al. (2012a) and Yamane et al. (2011). However, the mean concentration values of iron (Fe), tin (Sn), zinc (Zn) and lead (Pb) were detected between the concentration values reported by Oguchi et al. (2012a) and Yamane et al. (2011). Although Yamane et al. (2011) and Umicore (2011) have reported the concentrations of certain precious metals in motherboars, still no exact information has been encountered in literature for the concentrations of most of the precious and rare earth metals in motherboards.

5.1.2.2. Printed Circuit Boards of Monitors. Table 5.7 presents the results of metal concentrations detected in printed circuit boards of two different computer monitors. According to the results, the distribution of concentrations of base and precious metals in PCBs of computer monitors were similar to other PCB samples. While copper (Cu) had the highest concentration among the base metals, iron (Fe), tin (Sn) and nickel (Ni) were the other base metals measured in elevated concentrations in PCBs of computer monitors.

The results indicated that silver (Ag) and gold (Au) were the most abundant precious metals in both of the samples due to wide use of them against oxidation in PCBs. While the concentration of platinum (Pt) was detected in relatively low levels, the concentration of palladium (Pd) was under detection limit for both samples. However, in the study of Chancerel and Rotter (2009), the concentrations of Ag, Au and Pd in PCBs of monitors were reported as 1.3 g/kg, 0.49 g/kg and 0.099 g/kg, respectively.

Table 5.7. Mean concentrations of metals in printed circuit boards (PCBs) of monitors of computer samples.

Element (g/kg)	Asus A6J	Compaq Armada
Base Metals		
Cu	249.5	131.8
Fe	25.0	81.9
Al	7.1	9.9
Sn	23.2	49.9
Ni	9.9	29.8
Zn	7.5	21.1
Cr	0.11	0.20
Pb	0.87	5.9
Co	0.03	0.21
Precious Metals		
Ag	0.64	6.7
Au	0.62	2.6
Pd	<DL	<DL
Pt	0.02	0.04

*<DL: Below detection limit

5.1.2.3. Hard Disk Drives. The average results of the metal concentrations in the hard disk drive sample (HDD) supplied by TUHH for this study were presented in Table 5.8. No hard disk drive sample from Turkey were collected and analyzed in this study.

The results indicated that copper (Cu) had the highest concentration in the sample with 290.9 g/kg. In addition, tin (Sn), aluminum (Al), iron (Fe) and lead (Pb) were the most abundant metals, in descending order. Nickel (Ni) and zinc (Zn) were detected at relatively low concentrations. While concentrations of copper (Cu), aluminum (Al), tin (Sn) and zinc (Zn) showed similar behavior with the concentrations reported in the study of Ueberschaar and Rotter (2015), iron (Fe) and nickel (Ni) seemed to have higher concentration values than those of the results by Ueberschaar and Rotter (2015).

Table 5.8. Mean concentrations of metals in hard disk drives (HDDs) of computer samples.

Elements (g/kg)	This study	Ueberschaar and Rotter (2015)
Base Metals		
Cu	290.9	316
Fe	14.7	71
Al	16.9	22
Sn	27.5	24
Ni	9.5	25
Zn	6.3	4
Cr	0.58	-
Pb	11.7	-
Co	0.04	-
Precious Metals		
Ag	1.5	0.34
Au	0.49	0.1
Pd	0.01	0.02
Pt	0.01	-
Rare Earth Elements		
La	0.05	-
Nd	0.62	2
Ce	0.01	5
Pr	<DL	-
Dy	0.03	-

*<DL: Below detection limit

Among the precious metals, silver (Ag) and gold (Au) had relatively high concentrations with 1.5 g/kg and 0.49 g/kg, respectively. Although Nd was detected as the most abundant element with 0.62 g/kg in terms of rare earth elements, it concentration was still lower than that of the concentration of 2 g/kg reported in the study of Ueberschaar (2015). While the concentration of praseodymium (Pr) was observed to be under the detection limit, lanthanum (La), dysprosium (Dy) and cerium (Ce) were detected at very low concentrations.

5.2. Recovery Potential of E-waste

Since e-waste contains a complex mix of various materials such as base, precious and rare earth metals, it is an important secondary raw metal source in the world. E-waste generated globally in a year from mobile phones and computers alone has a potential to contribute to 3% of the world mine supply of gold and silver, 13% of palladium and 15% of cobalt (Schluep et al. 2009). However, while certain base metals such as aluminum, copper and tin are easy to separate from e-waste, actual recycling processes are not efficient to separate most of the precious and rare earth elements. Since currently used recycling methods lead to a 100 % loss of the REE materials, REEs go to non-recoverable material streams (Ueberschaar and Rotter, 2014). Therefore, this study aims to draw attention to the high metal recovery potentials of e-waste and also to the importance of developing effective recycling strategies and methods.

Both the determination of the metal concentrations in single components of e-waste and also the calculation of their recovery potentials are basis of designing effective recycling processes. Therefore, after elemental characterization step was completed, recovery potentials of base, precious and rare earth metals from e-waste were estimated, respectively.

5.2.1. Recovery Potential of Printed Circuit Boards of Mobile Phones

Table 5.9 presents the average metal concentrations and recovery potentials of metals from printed circuit boards of mobile phones. Recovery potentials from PCBs of mobile phones were estimated by using the average metal concentration of thirteen (13) different PCB samples determined in the characterization step.

Copper (Cu) has the highest recovery potential from PCBs of mobile phones with 189.1± 11.6 tons per year and its economic value equals to 0.9 million USD. Tin (Sn) and nickel (Ni) have high recovery potentials and also they are two of the most valuable base metals. Economic values of their recovery are around 0.32 million USD and 0.14 million USD per year, respectively.

Table 5.9. Average metal concentrations and recovery potentials of metals from printed circuit boards of mobile phones.

	Average Concentration (g/kg)	**Recovery Potential (tons/year)**	**Economic Value (million $/year)**
Base Metals			
Cu	335.2 ± 74.0	189.1 ± 11.6	0.89
Fe	23.2 ± 15.2	13.1 ± 2.4	0.001
Al	14.1 ± 3.5	7.9 ± 0.6	0.013
Sn	31.6 ± 13.5	17.8 ± 2.1	0.32
Ni	25.0 ± 13.1	14.1 ± 2.1	0.14
Zn	19.2 ± 17.3	10.9 ± 2.7	0.023
Cr	1.7 ± 4.1	0.96 ± 0.6	0.002
Pb	12.0 ± 8.7	6.8 ± 1.4	0.012
Co	0.21 ± 0.18	0.12 ± 0.03	0.003
Precious Metals			
Ag	3.6 ± 2.0	2.1 ± 0.3	1.4
Au	1.4 ± 0.75	0.77 ± 0.1	32.7
Pd	0.29 ± 0.23	0.17 ± 0.04	3.1
Pt	0.03 ± 0.01	0.014 ± 0.002	0.49

PCBs of discarded mobile phones lead to recovery potentials of 2.1 ± 0.3 tons Ag, 0.77 ± 0.1 tons Au, 0.17 ± 0.04 tons Pd and 0.014 ± 0.006 tons Pt per year in Turkey. The total economic value of the recovery of precious metals from PCBs was estimated to be around 38 million USD per year.

5.2.2. Recovery Potential of Motherboards of Computers

Table 5.10 presents the average metal concentrations of four (4) computer motherboard (with components) samples and also their recovery potentials. Since copper (Cu) is the most abundant metal in motherboard samples as being in PCBs of mobile phone samples, it has the highest recovery potential and economic value among base metals with 1087.4 ± 538.4 tons/year and around 5 million USD/year, respectively. Although iron (Fe) has the second highest recovery potential with 340.5 ± 201.0 tons/year, it has a lower economic value than most of the base metals due to its low price.

Table 5.10. Average metal concentrations and recovery potentials of metals from motherboards of computers.

	Average Concentration (g/kg)	**Recovery Potential (tons/year)**	**Economic Value (million $/year)**
Base Metals			
Cu	230.1 ± 113.9	1087.4 ± 203.5	5.1
Fe	72.1 ± 42.5	340.5 ± 75.9	0.019
Al	21.7 ± 21.2	102.4 ± 37.9	0.17
Sn	32.5 ± 7.8	153.5 ± 13.9	2.7
Ni	13.5 ± 11.0	63.6 ± 19.7	0.62
Zn	12.6 ± 7.9	59.3 ± 14.1	0.13
Cr	0.31 ± 0.23	1.5 ± 0.4	0.003
Pb	15.0 ± 13.3	70.7 ± 23.8	0.13
Co	0.53 ± 0.46	2.5 ± 0.8	0.06
Precious Metals			
Ag	2.3 ± 1.4	11.0 ± 2.4	7.1
Au	1.4 ± 1.2	6.6 ± 2.0	280.4
Pd	0.09 ± 0.10	0.40 ± 0.18	7.4
Pt	0.05 ± 0.04	0.22 ± 0.07	7.7
Rare Earth Elements			
La	0.0008 ± 0.0015	0.004 ± 0.003	0.0
Nd	0.84 ± 0.57	3.9 ± 1.0	0.23
Ce	0.004 ± 0.007	0.018 ± 0.012	0.0
Pr	0.06 ± 0.044	0.26 ± 0.08	0.02
Dy	0.11 ± 0.22	0.53 ± 0.4	0.12

Among the rare earth elements, neodymium (Nd) has the highest recovery potential with 3.9 ± 2.7 tons per year. Recovery potentials of dysprosium (Dy) and praseodymium (Pr) are estimated as 0.53 ± 1.1 and 0.26 ± 0.21 tons/year, respectively. In spite of relatively low recovery potentials of rare earth elements, the total economic value of their recovery was estimated to be around 0.4 million USD per year due to their high market prices.

In terms of precious metals, gold (Au) is the most valuable metal and it has a recovery potential of 6.6 ± 5.4 tons/year, which is equal to around 279 million USD per year. Recovery potentials of Ag, Pd and Pt were calculated as 11.0 ± 6.4, 0.40 ± 0.47, and 0.22 ± 0.18 tons/year, respectively. The total economic value of the recovery of precious metals was estimated as 301 million USD per year.

6. CONCLUSION AND RECOMMENDATIONS

With the rapid development of technology, more electrical and electronic products have been consumed in the last decades all over the world. Along with the high consumption of electronic products, the amount of e-waste has increased sharply. Today, e-waste is one of the fastest growing waste streams of the world with a growth rate of 3-5% per year. Within these e-wastes, there are different metals requiring proper management and recycling techniques to prevent health and environmental problems. However, there is a proportion of precious and rare earth metals present in e-waste that is lost in most of current recycling processes despite its high economic value. Therefore, the aim of this study was to determine the recovery potential of precious and rare earth metals from e-waste and also to draw attention to the importance of recovery of these metals.

Although metals are being used with the similar purposes both in computers and mobile phones, their concentrations vary according to the structure and model of the electronic products. The results of this study indicate that concentrations of base and precious metals in PCBs of mobile phones are higher than those of displays of mobile phones. However, displays of mobile phones contain rare earth elements like lanthanum, cerium, praseodymium and dysprosium. Therefore, while the recovery of precious metals may be the main goal of the recycling process of printed circuit boards from mobile phones, the recovery of REEs should be the focus of the recycling process of displays of mobile phones.

According to the results of the study, motherboards of computers contain various base, precious and rare earth metals in different concentrations. In terms of precious metals, gold (Au) and silver (Ag) show a noteworthy potential in the motherboards of computers. Among rare earth elements, neodymium (Nd) has a potential in the motherboards and therefore has a recycling potential for the future. In addition, it can be indicated that the hard drive disks of computers have relatively high concentrations of gold (Au), silver (Ag) and neodymium (Nd).

Therefore, recovery of these metals may have priority in the recycling process of computers.

Detection and quantification of precious and rare earth metals in the e-waste samples was the most challenging part of this study. An ICP-OES was employed by using different methods in order to determine the concentration of precious and rare earth metals. Due to the relatively low concentrations of these metals, using ICP-MS (Inductively coupled plasma mass spectrometer) can give more precise concentration results because of its lower detection limits.

This study was completed using limited e-waste samples due to the complexity of sample preparation process. E-waste samples were supplied by three different sources prepared in different ways. Therefore, further research should be conducted with more e-waste samples prepared in the same way to get more reliable metal concentration data. However, generated data in this study can be a guide for further studies in terms of metal content of e-waste samples.

REFERENCES

Ahluwalia, S. S., Goyal, D., 2007. Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresource Technology, 98-12, 2243-2257.

Antrekowitsch, H., Potesser, M., Spruzina, W., Prior, F., 2006. Metallurgical Recycling of Electronic Scrap. In The Minerals, Howard, S.M. (Eds.), Metals and Materials Society, Warrendale, PA., USA.

Babu, B.R., Parande, A.K., Basha, C.A., 2007. Electrical and electronic waste: a global environmental problem. Waste Management and Research, 25, 307-318.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-Waste Monitor: Quantities, Flows and Resources. United Nations University, Institute for the Advanced Study of Sustainability–Sustainable Cycles (IAS-SCYCLE). http://i.unu.edu/media/ias.unu.edu.

Barrett, J., Hughes, M. N., Karavaiko, G.I., Spencer, P.A., 1993. Metal extraction by bacterial oxidation of minerals. 1-153, Ellis Harwood limited, England.

Bhat, V., Rao, P., Patil, Y., 2012. Development of an integrated model to recover precious metals from electronic scrap:a novel strategy for e-waste management. Procedia-Social and Behavioral Sciences, 37, 397-406.

Bosecker, K., 1997. Bioleaching: metal solubilization by microorganisms. FEMS Microbiology, 20, 591-604.

Chancerel, P., Rotter, V.S., (2009). Stop Wasting Gold - How a Better Mining of End-of-life Electronic Products Would Save Precious Resources. Proceedings of the R'09 Twin World Congress and World Resources Forum, Davos, Switzerland.

Chung, S.S., Lau, K.Y., Zhang, C., 2011. Generation of and control measures for e-waste in Hong-Kong. Waste Management, 31, 544-554.

Commission of the European Communities, 2003. Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Official Journal European Union, L37**,** 24-38.

Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: A review. Journal of Hazardous Materials,158, 228-256.

Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials, 99, 243-263.

Davis, G., Herat, S., 2008. Electronic waste: the local government perspective in Queensland, Australia. Resources, Conservation and Recycling Journal, 52, 1031-1039.

Drechse, C.H., 2006. Mechanical Processes for Recycling Waste Electric and Electronic Equipment with the Rotor shredder and Rotor Impact Mill. Aufbereitungs Technik, 47.

Duan, X.H., 2011. Preparation of activated carbon from Jatropha Hull with microwave heating: Optimization using response surface methodology. Fuel Processing Technology, 394-400.

Dwivedy, M., Mittal, R.K., 2010. Estimation of future outflows of e-waste in India. Waste Management, 30, 483-491.

ETC/RWM, 2003. European Topic Centre on Resource and Waste Management (Topic Centre of the European Environment Agency) part of the European Environment Information and Observation Network (EIONET).

Eurostat, 2015. Eurostat yearbook. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/CH_11_2015/EN/CH_11_2015-EN.PDF.

Goosey, M., Kellner, R., 2002. A Scoping study end-of-life printed circuit boards. Makati City: Intellect and the Department of Trade and Industry.

Gramatyka, P., Nowosielski, R., Sakiewicz, P., 2007. Recycling of waste electrical and electronic equipment. Journal of Achievements in Materials and Manufacturing.

Gullett, B.K., Linak, W.P., Touati, A., Wasson, S.J., Gatica, S., King, C.J., 2007. Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. Journal of Material Cycles Waste Management, 9, 69-79.

Guo, J., Tang, Y., Xu, X., 2010. Wood Plastic Composite produced by nonmetals from pulverized waste printed circuit boards. Environmental Science and Technology, 44-1, 463-468.

Hageluken, C., 2006. Recycling of electronic scrap at Umicore's integrated metals smelter and refinery. World of Metallurgy, 59-3,152-161.

IIyas, S., Bhatti, H.N., Bhatti, I.A., Sheikh, M.A., Ghauri, M.A., 2010. Bioleaching of metal ions from low grade sulphide ore: Process optimization by using orthogonal experimental array design. African Journal of Biotechnology, 9, 2801-2810.

Kang, H.Y., Schoenung, J.M., 2005. Electronic waste recycling: a review of U.S. infrastructure and technology options. Resources, Conservation and Recycling Journal, 45, 368-400.

Kasper, A.C., Berselli, G.B.T., Freitas, B.D., Tenorio, J.S.A., Bernardes, A.M., Veit, H.M., 2011. Printed wiring boards for mobile phones: characterization and recycling of copper. Waste Management, 31, 2536-2545.

Kaya, I., 2012. Evaluation of outsourcing alternatives under fuzzy environment for waste management. Resources, Conservation and Recycling, 60, 107-118.

Kell, D., 2009. Recycling and Recovery. In Hester, R. E. & Harrison, R. M. (Eds.) Electronic Waste Management, The Royal Society of Chemistry.

Khetriwal, D.S., Kraeuchi, P., Widmer, R., 2009. Producer responsibility for e-waste management: key issues for consideration e learning from the Swiss experience. Journal of Environmental Management, 90, 153-165.

Kohama, H., 2007. Industrial Development in Postwar Japan. Taylor and Francis Group Routledge, 89–90.

Koto, Y., Kano, N., Wang, Y., Sakamoto, N., Imaizumi, H., 2010. Biosorption of Lanthanides from Aqueous Solutions Using Pretreated Buccinum tenuissimum Shell Biomass. Bioinorganic Chemistry and Applications, 804854.

Li, J., Tian, B., Liu, T., Liu, H., Wen, X., Honda, S., 2006. Status quo of e-waste management in mainland China. Journal of Material Cycles Waste Management, 8,13-20.

Li, Y., Duan, Y.P., Huang, F., Yang, J., Xiang, N., Meng, X.Z., Chen, L., 2013. Polybrominated diphenyl ethers in e-waste: level and transfer in a typical e-waste recycling site in Shanghai, Eastern China. Waste Management, 28, 1475–1481.

Meng, X., 2008. Network Design on Reverse Logistics of Electronic Waste Recycling. International Conference on Automation and Logistics, Qingdao, China.

Murugan, R., 2008. Milling and separation of the multi-component printed circuit board materials and the analysis of elutriation based on a single particle model. Powder Technology, 183, 169-176.

Nnorom, I.C., Osibanjo, O., 2008a. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resources, Conservation and Recycling, 52, 843-858.

Nnorom, I.C., Osibanjo, O., 2008b. Electronic waste (e-waste): material flows and management practices in Nigeria. Waste Management, 28, 1472-1479.

Nnorom, I.C., Osibanjo, O., Ogwuegbu, M.O.C., 2011. Global disposal strategies for waste cathode ray tubes. Resources, Conservation and Recycling, 55, 275-290.

OECD, 2011. Extended producer responsibility: a guidance manual for governments.

OEKO (Oeko-Institut – Institute for applied ecology), 2012. Recycling critical raw materials from waste electronic equipment.

Oguchi, M., Sakanakura, H., Terazono, A., 2012a. Toxic metals in WEEE: characterization and substance flow analysis in waste treatment processes. Science of the Total Environment, 463-464, 1124-1132.

Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Management, 31, 714-730.

Ozturk, T., 2015. Generation and management of electrical–electronic waste (e-waste) in Turkey. Journal of Material Cycles Waste Management, 17, 411-421.

Pant, D., Ioshi, D., Upreti, M.K., Kotnala, R.K., 2012. Chemical and biological extraction of metals present in e-waste: a hybrid technology. Waste Management, 32, 979-990.

Puckett, J., Smith, T., 2002. Exporting harm: the high-tech trashing of Asia. The Basel Action Network, Seattle7 Silicon Valley Toxics Coalition.

Rao, Q., Guo, J., Xu, Z., 2007. Application of glass-nonmetals of waste printed circuit boards to produce phenolic moulding compound. Journal of Hazardous Material, 153, 728–734.

REC Turkey, 2011. Atık Elektrikli ve Elektronik Eşyalar Direktif (AEEE) (2002/96/EC) Düzenleyici Etki Analizi. http://rec.org.tr/dyn_files/21/6281-AEEE-Nihai-DEA.pdf.

Republic of Turkey Ministry of Environment and Urbanism, 2012. Waste Electrical and Electronic Equipments Control Regulation. Official journal, 28300.

Republic of Turkey Ministry of Science, Industry and Technology, 2012. National Recycling Strategy Document and the Action Plan 2013-2016.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Science of the Total Environment, 408, 183-191.

Sand, W., Gehrke, T., Jozsa, P., Schippers, A., 2001. Biochemistry of bacterial leaching-direct vs. indirect bioleaching. Hydrometallurgy, 59, 159-175.

Saphores, Jean-Daniel, M., Ogunseitanc, Oladele A., Shapiro, Andrew A., 2012. Willingness to engage in a pro-environmental behavior: an analysis of e-waste recycling based on a national survey of U.S. households. Resources, Conservation and Recycling, 60, 49-63.

Schluep, Mathias, Hagelueken, C., Kuehr, R., Magalini, F., Maurer, C., Meskers, C., Mueller, E., Wang, F., 2009. From E-Waste to Resources. Tokyo: United Nations Environmental Programme & United Nations University.

Shinkuma, T., Huong, N.T.M., 2009. The flow of e-waste material in the Asian region and a reconsideration of international trade policies on e-waste. Environment Impact Assessment, 29, 25–31.

Simate, G. S., Ndlovu, S., 2008. Bacterial leaching of nickel laterites using chemolithotrophic microorganisms: Identifying influential factors using statistical design of experiments. International Journal of Mineral Processing, 88, 31-36.

Sinha, D., 2004. The management of electronic waste: a comparative study on India and Switzerland. University of St. Gallen.

Smita, K., Singh, S.K., Kumar, B., 2013. Rapid microwave digestion procedures for the elemental analysis of alloy and slag samples of smelted ocean bed polymetallic nodules. Journal of Chemistry, 2013, 151395.

Soylak, M., Saracoglu, S., Elci, L., 2004. Investigation of adsorption of metal ions on polystyrene divinyl benzene copolymers by scanning electron microscopy and flame atomic absorption spectrometry. Asian Journal of Chemistry, 16, 1673-1680.

Stutz, M., Burkhard, C., Ertel, J., 2002. Cost elements of recycling and the design of mobile phones in the context of WEEE. Proceedings of Care Innovation, Vienna.

Svoboda, J. Fujita, T., 2003. Recent Developments in Magnetic Methods of Material Separation. Minerals Engineering, 16, 785-792.

Tange, L., Drohmann, D., 2005. Waste electrical and electronic equipment plastics with brominated flame retardants – from legislation to separate treatment - thermal processes. Polymer Degradation and Stability, 88, 35-40.

Tribustch, H., 2001. Direct versus indirect bioleaching. Hydrometallurgy, 59, 175-185.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. Minerals Engineering, 25, 28-37.

Ueberschaar, M., Rotter, V.S., 2014. Enabling the recycling of rare earth elements through product design and trend analyses of hard disk drives. Journal of Material Cycles and Waste Management, 17, 266-281.

Umicore, 2011. Information on the material composition of different WEEE fractions.

Vegliò, F., Beolchini, F., 1997. Removal of metal by biosorption: a review. Hydrometallurgy, 44-3, 301316.

Veit, H.M., Bernardes, A.M., Ferreira, J.Z., Tenório, J.A.S., Malfatti, C.F., 2006. Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy. Journal of Hazardous Materials, 137, 1704-1709.

Volesky, B., 2003. Biosorption process simulation tools. Hydrometallurgy, 71, 1-2, 179190.

Wang, X., Gaustad, G., 2012. Prioritizing material recovery for end-of-life printed circuit boards. Waste Management, 32, 1903-1913.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on e-waste. Environmental Impact Assessment, 25, 436-458.

William, J.H., Williams, P.T., 2007. Separation and recovery of materials from scrap printed boards. Resources, Conservation and Recycling, 51, 691-709.

Xu, X., Yang, H., Chen, A., Zhou, Y., Wu, K., Liu, J., Zhang, Y., Huo, X., 2012. Birth outcomes related to informal e-waste recycling in Guiyu, China. Reproductive Toxicology, 33, 94-98.

Yamane, H.L., Moraes, V.T., Espinosa, D.C.R., Tenorio, J.A.S., 2011. Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers. Waste Management, 31, 2553-2558.

Yazıcı, E.Y., Deveci, H., 2009. E-atıklardan Metallerin Geri Kazanımı (Recovery of Metals from E-wastes). Madencilik, 48 (3), 3-18.

Yazıcı, E.Y., Deveci, H., Alp, I., Akcil, A., Yazıcı, R., 2010. Characterisation of Computer Printed Circuit Boards for Hazardous Properties and Beneficiation Studies. International Mineral Processing Congress, XXV, 6-10, 4009-4015.

Zhang, S., Forssberg, E., 1998. Mechanical recycling of electronics scrap: the current status and prospects. Waste Management and Research, 16, 119-128.

Zhang, S., Forssberg, E., 1999. Intelligent liberation and classification of electronic scrap. Powder Technology, 105, 295-301.

APPENDIX A

The concentrations of five different aliquots of each e-waste sample are denoted by A, B, C, D and E in tables. Standard deviation and relative standard deviation (coefficient of variance) of five different aliquots are presented as SD and RSD, respectively.

Table A.1. Results for the printed circuit board of Asus Pegasus mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	363.2	297.0	264.1	241.8	457.2	324.7	87.1	26.8
Fe	28.3	25.2	17.1	15.4	31.9	23.6	7.1	30.3
Al	9.8	9.6	8.1	8.4	8.8	8.9	0.7	8.3
Sn	58.9	62.8	65.8	53.5	72.6	62.7	7.2	11.5
Ni	32.4	26.6	32.6	37.6	32.3	32.3	3.9	12.2
Zn	41.7	15.5	23.9	25.5	34.0	28.1	10.0	35.7
Cr	0.14	0.22	0.20	0.18	0.24	0.19	0.04	19.9
Pb	2.4	2.4	<DL	3.2	<DL	1.6	1.5	93.4
Co	0.14	0.10	0.18	0.12	0.17	0.14	0.03	22.0
Ag	2.3	2.8	2.1	2.8	2.6	2.5	0.3	11.5
Au	2.4	2.6	2.2	2.5	2.5	2.4	0.2	6.7
Pd	0.023	0.022	<DL	<DL	<DL	0.009	0.012	137.0
Pt	0.038	0.032	0.026	0.022	0.044	0.032	0.009	27.7

* <DL: Below Detection Limit

Table A.2. Results for the printed circuit board of General Mobile DSTQ100 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	388.5	383.2	337.2	381.2	362.1	370.4	21.1	5.7
Fe	24.2	23.8	24.1	25.6	4.5	20.4	9.0	43.8
Al	10.9	13.9	14.0	11.4	15.6	13.2	2.0	14.9
Sn	36.2	36.9	31.8	34.9	31.5	34.3	2.5	7.3
Ni	20.3	14.7	11.2	11.8	9.8	13.6	4.2	30.8
Zn	16.7	5.1	3.5	2.7	13.1	8.2	6.3	76.5
Cr	0.12	0.13	0.12	0.11	0.08	0.11	0.02	19.0
Pb	1.18	1.09	0.73	1.00	0.85	1.0	0.2	18.8
Co	0.09	0.06	0.07	0.04	0.02	0.05	0.03	53.5
Ag	1.81	1.77	1.61	1.82	1.62	1.73	0.10	5.87
Au	0.87	0.64	0.49	1.06	0.18	0.65	0.34	52.5
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.028	0.012	0.018	0.020	0.033	0.022	0.008	36.8

[*] <DL: Below Detection Limit

Table A.3. Results for the printed circuit board of NG 870 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	234.9	170.8	278.8	247.3	205.7	227.5	41.1	18.1
Fe	28.5	19.6	45.6	51.2	41.0	37.2	12.9	34.7
Al	8.8	11.7	12.6	9.8	9.1	10.4	1.7	16.1
Sn	69.0	45.1	48.1	63.5	33.2	51.8	14.5	28.0
Ni	21.9	16.3	23.6	28.8	28.3	23.8	5.1	21.5
Zn	25.4	15.5	24.4	27.1	13.9	21.2	6.1	28.6
Cr	1.8	3.4	2.8	5.2	6.1	3.9	1.7	45.2
Pb	9.5	3.7	6.3	12.5	4.7	7.3	3.6	49.5
Co	0.33	0.30	0.22	0.27	0.26	0.27	0.04	14.6
Ag	2.1	1.7	1.8	2.2	2.3	2.0	0.3	13.2
Au	5.6	2.2	2.4	2.6	2.0	2.9	1.5	51.0
Pd	0.07	<DL	0.06	<DL	0.08	0.04	0.04	90.7
Pt	0.03	0.03	0.02	0.04	0.01	0.026	0.01	52.1

[*] <DL: Below Detection Limit

Table A.4. Results for the printed circuit board of Nokia C5 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	433.2	355.6	386.8	370.8	343.4	378.0	34.9	9.2
Fe	43.8	46.1	12.2	20.0	47.3	33.9	16.5	48.7
Al	12.9	8.9	11.9	10.3	13.4	11.5	1.9	16.2
Sn	22.8	26.1	41.8	24.2	26.6	28.3	7.7	27.2
Ni	26.7	28.1	18.1	19.0	12.9	21.0	6.4	30.3
Zn	2.5	2.8	2.0	1.4	2.7	2.3	0.6	24.9
Cr	0.24	0.17	0.18	0.42	0.61	0.33	0.19	57.4
Pb	1.5	1.4	3.0	3.8	3.1	2.6	1.1	41.1
Co	0.13	0.14	0.08	0.09	0.10	0.11	0.025	23.2
Ag	2.1	1.5	2.1	2.6	1.9	2.0	0.4	19.4
Au	2.7	1.4	1.5	0.9	0.7	1.4	0.8	53.4
Pd	0.54	0.27	0.34	0.16	<DL	0.26	0.20	77.2
Pt	0.028	0.014	0.039	0.034	0.028	0.028	0.010	33.4

* <DL: Below Detection Limit

Table A.5. Results for the printed circuit board of Nokia 6110 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	438.0	401.3	411.5	405.5	363.8	404.0	26.7	6.6
Fe	62.5	62.6	17.4	50.0	49.7	48.4	18.5	38.1
Al	13.6	13.3	13.9	11.7	11.8	12.9	1.1	8.2
Sn	25.7	24.1	31.1	20.8	29.5	26.2	4.1	15.8
Ni	33.2	33.5	31.3	42.1	48.5	37.7	7.3	19.4
Zn	20.4	13.7	15.7	19.4	19.7	17.8	2.9	16.4
Cr	0.22	0.52	0.79	0.51	0.51	0.51	0.20	39.1
Pb	18.0	15.0	17.7	13.9	19.1	16.7	2.2	13.1
Co	0.19	0.19	0.22	0.17	0.18	0.19	0.02	9.5
Ag	3.4	4.9	5.6	5.3	4.1	4.7	0.9	19.8
Au	1.41	0.92	0.87	1.39	1.72	1.26	0.36	28.4
Pd	0.29	0.01	0.39	0.43	0.01	0.22	0.21	94.5
Pt	0.01	0.06	0.03	0.07	0.08	0.05	0.03	56.6

Table A.6. Results for the printed circuit board of Nokia 3210 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	197.3	190.3	203.2	236.3	203.0	206.0	17.7	8.6
Fe	13.7	10.4	10.2	6.1	9.9	10.0	2.7	26.8
Al	10.3	11.1	11.1	10.9	10.0	10.7	0.5	4.7
Sn	28.4	24.3	29.5	32.8	33.2	29.6	3.6	12.2
Ni	10.0	10.2	11.6	13.3	10.0	11.0	1.4	13.1
Zn	6.1	3.5	2.0	3.6	2.5	3.5	1.6	45.0
Cr	0.13	0.14	0.10	0.18	0.12	0.13	0.03	20.8
Pb	15.7	12.5	16.5	18.6	18.2	16.3	2.5	15.1
Co	0.10	0.09	0.09	0.20	0.06	0.11	0.05	48.3
Ag	7.0	9.3	10.5	8.1	6.7	8.3	1.6	19.0
Au	1.6	2.0	1.6	1.9	2.1	1.8	0.2	12.7
Pd	0.51	0.26	0.29	0.54	0.20	0.36	0.15	42.9
Pt	0.032	0.031	0.036	0.039	0.030	0.033	0.004	11.5

Table A.7. Results for the printed circuit board of Nokia 3310 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	293.6	309.6	259.7	265.8	309.0	287.5	23.6	8.2
Fe	4.2	4.1	5.0	4.6	7.3	5.0	1.3	26.0
Al	11.8	12.3	11.7	12.3	10.7	11.8	0.6	5.5
Sn	26.8	31.4	37.4	40.2	41.7	35.5	6.2	17.5
Ni	17.8	15.9	13.9	13.8	17.5	15.8	1.9	11.9
Zn	9.5	7.3	8.8	5.0	5.5	7.2	2.0	27.0
Cr	0.27	0.30	0.28	0.31	0.29	0.29	0.01	5.1
Pb	16.4	14.4	16.8	23.1	18.8	17.9	3.3	18.4
Co	0.12	0.14	0.10	0.09	0.14	0.12	0.02	21.0
Ag	5.9	4.7	5.0	4.5	5.5	5.1	0.6	11.4
Au	1.8	1.4	1.8	1.5	1.3	1.6	0.2	14.2
Pd	0.31	0.42	0.50	0.35	0.40	0.40	0.07	18.3
Pt	0.015	0.018	0.027	0.019	0.018	0.019	0.004	23.2

Table A.8. Results for the printed circuit board of Nokia 6210 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	287.6	301.2	296.8	308.0	332.5	305.2	17.0	5.6
Fe	18.5	15.8	8.6	14.4	16.7	14.8	3.8	25.4
Al	16.8	13.6	15.2	15.7	13.1	14.9	1.5	10.1
Sn	27.9	31.9	31.8	27.6	29.1	29.7	2.1	7.0
Ni	33.5	31.6	28.9	28.5	37.0	31.9	3.5	11.0
Zn	29.6	29.3	32.5	32.1	27.4	30.2	2.1	7.04
Cr	0.48	0.45	0.58	0.41	0.38	0.46	0.07	16.2
Pb	13.7	16.6	15.8	13.1	13.6	14.6	1.5	10.5
Co	0.19	0.48	0.64	0.14	0.43	0.37	0.21	55.44
Ag	4.08	4.32	3.78	3.40	3.10	3.74	0.50	13.26
Au	1.36	1.57	1.62	1.46	1.60	1.52	0.11	7.21
Pd	0.81	1.08	0.48	0.47	1.26	0.82	0.35	42.87
Pt	0.005	0.008	0.010	0.005	0.006	0.007	0.001	30.67

Table A.9. Results for the printed circuit board of Nokia 3410 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	446.3	416.5	479.3	479.0	435.8	451.4	27.5	6.1
Fe	8.2	6.4	5.2	6.6	5.5	6.4	1.2	18.8
Al	18.6	16.6	15.6	14.0	18.2	16.6	1.9	11.3
Sn	20.9	22.3	32.3	18.6	32.2	25.3	6.5	25.9
Ni	65.8	58.6	72.0	51.4	48.7	59.3	9.7	16.4
Zn	65.3	57.8	80.8	65.7	65.3	67.0	8.4	12.6
Cr	0.16	0.18	0.14	0.19	0.20	0.17	0.03	14.6
Pb	22.1	19.8	27.1	17.1	30.4	23.3	5.4	23.3
Co	0.40	0.27	0.20	0.13	0.17	0.23	0.11	45.7
Ag	3.2	4.5	3.1	2.7	2.6	3.2	0.8	23.6
Au	0.53	1.02	1.08	0.80	0.67	0.82	0.23	28.6
Pd	0.09	0.12	0.14	0.12	0.13	0.12	0.02	16.6
Pt	0.016	0.013	0.011	0.010	0.010	0.012	0.003	21.9

Table A.10. Results for the printed circuit board of Siemens C5 mobile phone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	276.1	331.7	366.8	293.9	296.9	313.1	36.1	11.5
Fe	7.2	7.6	13.3	10.9	20.2	11.9	5.3	44.9
Al	15.8	17.3	14.9	17.2	16.1	16.3	1.0	6.4
Sn	13.9	16.7	11.0	12.1	11.4	13.0	2.4	18.1
Ni	23.6	22.1	27.9	27.1	34.3	27.0	4.7	17.5
Zn	3.7	6.4	4.7	6.4	4.2	5.1	1.3	25.0
Cr	0.38	0.35	0.59	0.42	0.48	0.44	0.10	21.5
Pb	10.3	9.6	10.3	10.5	9.2	10.0	0.6	5.6
Co	0.69	0.96	0.46	0.92	0.45	0.70	0.24	34.9
Ag	3.6	4.0	3.2	3.8	4.8	3.9	0.6	15.6
Au	1.25	1.17	1.14	1.05	1.01	1.13	0.10	8.6
Pd	0.45	0.42	0.57	0.43	0.50	0.47	0.06	13.1
Pt	0.018	0.008	0.011	0.038	0.001	0.015	0.014	96.0

Table A.11. Results for the printed circuit board of Blackberry smartphone.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	418.3	418.8	426.5	365.0	360.0	397.7	32.3	8.1
Fe	51.6	49.4	37.4	53.9	39.3	46.3	7.5	16.2
Al	18.4	20.7	21.5	18.0	22.0	20.1	1.8	9.1
Sn	36.4	27.5	27.2	35.8	38.2	33.0	5.2	15.9
Ni	17.2	20.0	11.3	16.5	20.2	17.0	3.6	21.2
Zn	33.5	36.3	13.0	14.6	37.1	26.9	12.0	44.7
Cr	0.46	0.43	0.37	0.49	0.43	0.44	0.04	10.2
Pb	28.8	25.0	21.9	30.9	29.9	27.3	3.8	13.7
Co	0.06	0.04	0.03	0.07	0.05	0.05	0.01	30.1
Ag	2.7	2.8	2.2	2.5	3.1	2.6	0.3	12.9
Au	0.57	0.67	0.31	0.53	0.60	0.53	0.13	25.2
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.028	0.037	0.017	0.027	0.021	0.026	0.008	30.0

* <DL: Below Detection Limit

Table A.12. Results for the mixture of printed circuit boards of various mobile phones (Mixture 1).

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	287.9	298.8	241.4	260.0	324.0	282.4	32.4	11.5
Fe	10.0	7.0	8.4	11.9	13.2	10.1	2.5	24.9
Al	14.3	14.9	19.3	14.4	16.5	15.9	2.1	13.3
Sn	32.1	24.0	34.7	24.4	20.5	27.1	6.0	22.1
Ni	15.5	14.7	13.7	15.9	15.2	15.0	0.9	5.8
Zn	16.8	13.7	15.8	11.8	10.1	13.6	2.8	20.3
Cr	0.12	0.14	0.17	0.13	0.15	0.14	0.02	13.4
Pb	12.2	14.5	18.3	18.3	15.0	15.6	2.6	16.9
Co	0.24	0.25	0.41	0.28	0.32	0.30	0.07	22.8
Ag	5.6	7.0	6.7	5.2	5.2	5.9	0.8	14.3
Au	1.9	1.3	1.5	1.3	1.9	1.6	0.3	17.9
Pd	0.57	0.28	0.51	0.46	0.15	0.39	0.17	43.4
Pt	0.03	0.02	0.05	0.05	0.03	0.036	0.02	49.0

Table A.13. Results for the mixture of printed circuit boards of various mobile phones (Mixture 2).

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	312.4	307.0	418.4	477.4	533.8	409.8	113.0	19.2
Fe	42.4	41.3	21.4	48.5	17.2	34.2	23.1	40.7
Al	23.8	13.8	19.2	15.1	26.5	19.7	5.5	27.9
Sn	13.6	13.2	15.7	12.2	14.0	13.7	1.3	34.9
Ni	27.6	15.8	15.3	28.3	13.5	20.1	7.2	36.1
Zn	16.0	28.5	15.8	16.2	17.9	18.9	5.4	28.7
Cr	27.2	16.5	5.5	9.2	16.8	15.0	8.3	55.6
Pb	2.6	<DL	4.6	0.7	1.5	1.9	1.8	93.9
Co	0.14	0.09	0.09	0.11	0.09	0.10	0.02	21.7
Ag	0.61	0.25	4.32	0.51	2.83	1.70	1.79	105.2
Au	0.09	0.03	0.46	0.12	0.14	0.17	0.17	100.1
Pd	0.12	0.15	0.15	0.15	0.12	0.14	0.02	12.4
Pt	0.027	0.014	0.023	0.046	0.020	0.026	0.012	46.5

* <DL: Below Detection Limit

Table A.14. Results for the printed circuit board of Blackberry smartphone display.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	18.5	17.5	12.5	13.0	13.4	15.0	2.8	18.7
Al	12.5	11.6	10.8	13.3	11.9	12.0	0.9	7.7
Sn	0.8	1.5	1.0	1.2	1.7	1.2	0.4	29.8
Ni	1.09	1.23	1.11	1.03	2.54	1.40	0.64	45.8
Zn	0.29	0.28	0.25	0.37	0.32	0.30	0.05	15.2
Cr	3.34	2.03	3.96	3.50	5.46	3.66	1.24	33.8
Pb	0.22	0.36	0.16	0.29	0.26	0.26	0.08	30.1
Si	21.2	20.9	20.2	21.8	20.3	20.9	0.6	3.1
Ag	0.16	0.30	0.25	0.19	0.21	0.22	0.05	24.6
Au	0.020	0.017	0.000	0.000	0.029	0.013	0.013	97.9
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
La	0.18	0.19	0.19	0.27	0.18	0.20	0.04	18.9
Ce	0.11	0.13	0.13	0.18	0.11	0.13	0.03	22.4
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	<DL	<DL	<DL	<DL	<DL	-	-	-

* <DL: Below Detection Limit

Table A.15. Results for the printed circuit board of Nokia mobile phone display.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	18.3	10.6	14.5	10.2	13.8	13.5	3.3	24.6
Al	4.0	4.0	4.1	3.7	3.5	3.8	0.2	6.2
Sn	0.69	0.67	0.82	0.65	0.93	0.75	0.12	15.9
Ni	1.9	1.7	1.0	2.3	1.6	1.7	0.5	28.0
Zn	0.30	0.22	0.27	0.21	0.22	0.24	0.04	17.2
Cr	0.31	0.27	0.26	0.28	0.23	0.27	0.03	11.2
Pb	0.32	0.27	0.36	0.33	0.37	0.33	0.04	12.6
Si	16.4	17.5	18.0	15.0	16.3	16.6	1.2	6.9
Ag	0.26	0.73	0.64	0.66	0.70	0.60	0.19	32.0
Au	0.24	0.24	0.17	0.14	0.15	0.19	0.05	25.9
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
La	0.59	0.61	0.39	0.40	0.43	0.48	0.11	24.5
Ce	0.004	0.003	0.006	0.003	0.003	0.004	0.001	24.9
Pr	0.028	0.026	0.028	0.022	0.031	0.027	0.003	12.5
Dy	0.017	0.017	0.017	0.016	0.018	0.017	0.001	4.4

* <DL: Below Detection Limit

Table A.16. Results for the motherboard of ASUS A6J computer.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	122.5	154.7	165.4	159.2	218.3	164.0	34.6	21.1
Fe	30.4	46.7	45.5	38.8	50.1	42.3	7.8	18.5
Al	4.2	5.1	3.0	3.7	3.7	3.9	0.8	19.6
Sn	20.9	25.6	39.6	20.2	32.3	27.7	8.2	29.7
Ni	18.6	31.5	32.9	24.5	38.0	29.1	7.6	26.0
Zn	6.1	5.9	13.8	10.6	22.6	11.8	6.9	58.2
Cr	0.14	0.32	0.13	0.11	0.14	0.17	0.08	50.3
Pb	14.0	14.4	18.9	8.6	18.2	14.8	4.1	27.6
Cd	0.03	0.02	0.03	0.04	0.11	0.04	0.04	80.0
Co	0.71	1.16	1.06	1.15	1.18	1.05	0.2	19.0
Ag	2.1	2.2	2.2	2.4	2.6	2.3	0.2	8.4
Au	4.6	2.8	2.3	3.5	1.7	3.0	1.1	36.7
Pd	0.14	0.12	0.18	0.12	0.19	0.15	0.03	20.4
Pt	<DL	0.025	<DL	<DL	0.016	0.008	0.012	142.0
La	0.008	0.001	0.005	0.002	<DL	0.003	0.003	96.9
Nd	0.82	0.73	1.75	0.45	0.57	0.86	0.51	59.7
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	0.07	0.04	0.09	0.04	0.17	0.08	0.05	62.8
Dy	<DL	<DL	<DL	<DL	<DL	-	-	-

[*] <DL: Below Detection Limit

Table A.17. Results for the motherboard of Compaq Armada computer.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	267.6	237.0	194.1	403.9	414.8	303.5	100.2	33.0
Fe	87.1	121.3	203.6	64.6	72.5	109.8	56.8	51.7
Al	9.5	5.9	7.5	11.8	6.5	8.2	2.4	29.4
Sn	15.7	17.3	22.6	21.5	60.6	27.5	18.7	67.9
Ni	13.2	6.6	13.6	4.0	3.7	8.2	4.8	58.8
Zn	11.7	24.4	36.0	10.5	29.8	22.5	11.2	49.7
Cr	0.07	0.16	0.13	0.07	0.11	0.11	0.04	36.6
Pb	5.8	<DL	10.3	8.1	7.9	6.4	3.9	61.1
Cd	<DL	0.015	0.035	0.004	0.006	0.012	0.014	116.4
Co	0.03	0.04	0.09	0.03	0.04	0.05	0.02	53.6
Ag	2.1	3.4	4.7	2.7	2.9	3.2	1.0	30.4
Au	1.78	1.40	1.22	1.25	1.33	1.40	0.23	16.3
Pd	0.24	0.15	0.19	0.20	0.19	0.19	0.03	16.2
Pt	0.039	0.031	0.040	0.043	0.024	0.035	0.008	21.2
La	<DL	<DL	<DL	<DL	<DL	-	-	-
Nd	0.85	1.72	4.37	0.56	0.24	1.55	1.67	107.9
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	0.007	0.030	0.136	<DL	0.001	0.035	0.058	166.3
Dy	<DL	<DL	<DL	<DL	<DL	-	-	-

* <DL: Below Detection Limit

Table A.18. Results for the mixture of various computer motherboards supplied by KATU.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	110.0	97.1	96.2	67.5	157.8	105.7	33.0	31.2
Fe	29.3	28.9	28.0	25.0	33.0	28.8	2.9	9.9
Al	52.1	55.0	49.6	43.8	53.6	50.8	4.4	8.7
Sn	41.9	45.4	42.9	43.5	45.9	43.9	1.7	3.9
Ni	3.6	4.2	3.7	3.4	4.6	3.9	0.5	12.1
Zn	12.0	12.6	12.8	9.2	17.0	12.7	2.8	22.2
Cr	0.33	0.36	0.30	0.32	0.35	0.33	0.02	6.6
Pb	33.3	34.1	33.7	32.9	35.3	33.8	0.9	2.7
Co	0.77	0.77	0.74	0.74	0.82	0.77	0.03	4.4
Ag	0.33	0.78	0.23	0.40	0.36	0.42	0.21	50.1
Au	0.31	0.37	0.25	0.30	0.67	0.38	0.17	44.5
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.01	0.05	0.05	0.02	0.06	0.04	0.02	54.4
La	<DL	<DL	<DL	<DL	<DL	-	-	-
Nd	0.14	0.16	0.14	0.16	0.17	0.16	0.01	8.4
Ce	0.014	0.016	0.012	0.013	0.013	0.014	0.001	9.3
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	<DL	<DL	<DL	<DL	<DL	-	-	-

* <DL: Below Detection Limit

Table A.19. Results for the mixture of motherboards of various computers supplied by TUHH.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	369.0	372.3	296.5	322.5	375.0	347.1	35.6	10.2
Fe	105.6	100.3	105.8	97.5	127.5	107.3	11.8	11.0
Al	20.5	26.4	20.1	24.7	27.1	23.8	3.3	13.9
Sn	30.0	30.7	33.4	30.9	29.0	30.8	1.6	5.3
Ni	12.8	12.3	9.9	13.2	14.8	12.6	1.7	13.9
Zn	3.8	2.1	4.9	2.9	2.5	3.2	1.1	35.1
Cr	0.79	0.63	0.50	0.51	0.68	0.62	0.12	19.9
Pb	5.1	4.1	5.5	4.3	5.1	4.8	0.6	12.5
Co	0.06	0.34	0.28	0.25	0.31	0.25	0.11	44.2
Ag	3.3	3.9	3.5	3.7	2.7	3.4	0.5	13.5
Au	0.61	0.72	0.81	0.83	0.95	0.78	0.13	16.0
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.14	0.08	0.12	0.07	0.09	0.10	0.03	28.7
La	<DL	<DL	<DL	<DL	<DL	-	-	-
Nd	0.81	0.83	0.65	0.75	0.80	0.77	0.07	9.6
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	0.11	0.11	0.06	0.10	0.10	0.10	0.02	23.6
Dy	0.44	0.59	0.37	0.42	0.41	0.45	0.08	18.4

[*] <DL: Below Detection Limit

Table A.20. Results for the motherboard of Gıgabyte computer.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	230.3	180.8	155.0	236.7	147.7	190.1	41.5	21.8
Fe	25.6	25.2	31.7	41.6	36.2	32.0	7.0	21.9
Al	20.0	5.9	5.0	24.5	5.1	12.1	9.4	77.4
Sn	34.7	20.7	33.3	36.4	36.1	32.2	6.6	20.4
Ni	28.4	34.0	26.4	31.9	29.3	30.0	3.0	10.0
Zn	80.4	<DL	24.6	65.1	13.6	36.7	34.4	93.7
Cr	0.08	0.08	0.09	0.09	0.10	0.08	0.007	8.1
Pb	24.5	23.1	20.2	19.8	32.8	24.1	5.3	21.9
Co	0.09	0.22	0.16	0.21	0.20	0.18	0.05	30.1
Ag	1.69	1.68	1.60	1.53	1.77	1.65	0.09	5.6
Au	0.98	1.28	1.43	0.86	1.26	1.16	0.23	20.1
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.037	0.038	0.050	0.051	0.031	0.041	0.009	21.3
La	<DL	<DL	<DL	<DL	<DL	-	-	-
Nd	0.06	0.10	0.09	0.12	0.46	0.16	0.17	102.6
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	0.021	0.015	0.028	0.026	0.023	0.023	0.005	22.5

* <DL: Below Detection Limit

Table A.21. Results for the motherboard of MSI computer.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	234.0	262.7	235.6	221.2	215.6	233.8	18.2	7.8
Fe	64.0	69.9	63.0	67.8	66.4	66.2	2.8	4.2
Al	13.3	8.9	7.4	12.3	15.9	11.6	3.4	29.5
Sn	46.6	32.3	57.9	61.9	58.3	51.4	12.1	23.6
Ni	32.5	28.3	24.4	26.1	24.4	27.1	3.4	12.4
Zn	44.4	51.5	61.7	44.6	28.9	46.2	12.0	25.9
Cr	0.30	0.30	0.28	0.32	0.33	0.31	0.02	6.4
Pb	22.8	24.2	21.8	28.3	31.9	25.8	4.2	16.4
Cd	0.30	0.29	0.44	0.53	0.53	0.42	0.12	28.6
Co	1.71	1.29	0.95	1.10	0.81	1.17	0.35	29.9
Ag	1.5	1.6	1.3	1.2	1.9	1.5	0.3	19.6
Au	3.4	3.2	3.0	3.3	2.6	3.1	0.3	11.0
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	<DL	0.020	<DL	0.012	0.004	0.007	0.009	118.5
La	<DL	<DL	<DL	<DL	<DL	-	-	-
Nd	0.64	1.88	0.96	1.64	1.65	1.35	0.53	38.9
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	0.013	0.014	0.014	0.020	0.014	0.015	0.003	20.6

[*] <DL: Below Detection Limit

Table A.22. Results for the mixture of motherboards of various computers supplied by KATU.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	151.1	156.0	169.9	204.7	151.9	166.7	22.5	13.5
Fe	19.2	18.2	19.3	21.7	18.7	19.4	1.3	6.9
Al	14.7	15.3	15.1	16.2	14.2	15.1	0.8	5.1
Sn	40.4	45.4	43.6	42.6	45.0	43.4	2.0	4.7
Ni	5.1	4.5	5.0	4.9	5.2	4.9	0.3	5.2
Zn	11.1	9.0	8.5	10.0	7.9	9.3	1.3	13.6
Cr	0.98	1.00	1.01	1.04	0.98	1.00	0.02	2.4
Pb	22.8	22.9	23.4	24.8	22.3	23.2	1.0	4.2
Co	0.16	0.17	0.18	0.20	0.16	0.17	0.01	8.6
Ag	0.74	0.61	0.73	0.66	0.74	0.70	0.06	8.8
Au	0.19	0.17	0.14	0.19	0.16	0.17	0.02	12.9
Pd	0.078	0.068	0.073	0.080	0.072	0.074	0.005	6.4
Pt	0.05	0.08	0.02	0.06	0.02	0.044	0.03	59.0
La	0.024	0.019	0.019	0.021	0.023	0.021	0.002	11.3
Nd	0.13	0.13	0.12	0.14	0.14	0.13	0.008	6.35
Ce	<DL	<DL	<DL	<DL	<DL	-	-	-
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	<DL	<DL	<DL	<DL	<DL	-	-	-

* <DL: Below Detection Limit

Table A.23. Results for printed circuit board of Asus A6J computer monitor.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	238.5	239.5	239.2	264.3	266.2	249.5	14.4	5.8
Fe	31.7	28.6	24.5	22.9	17.5	25.0	5.4	21.8
Al	6.9	6.3	7.2	7.1	7.7	7.1	0.5	7.3
Sn	18.1	21.0	33.4	22.8	21.0	23.2	5.9	25.6
Ni	11.1	13.4	8.6	9.1	7.1	9.9	2.4	24.3
Zn	8.3	9.3	7.5	6.8	5.4	7.5	1.5	19.7
Cr	0.095	0.104	0.154	0.097	0.092	0.108	0.026	24.0
Pb	0.78	0.88	0.93	0.82	0.96	0.87	0.07	8.5
Ag	0.83	0.59	0.55	0.71	0.55	0.64	0.12	18.5
Au	0.75	0.46	0.65	0.64	0.59	0.62	0.11	17.2
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.021	0.020	0.023	0.021	0.022	0.021	0.001	5.9

* <DL: Below Detection Limit

Table A.24. Results for printed circuit board of Compaq Armada laptop monitor.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	125.6	128.3	161.1	124.8	119.0	131.8	16.8	12.7
Fe	102.8	66.5	74.2	73.4	92.6	81.9	15.1	18.5
Al	9.1	11.8	10.9	11.4	6.2	9.9	2.3	23.3
Sn	44.9	60.0	60.0	35.2	49.3	49.9	10.5	21.1
Ni	33.7	22.1	26.8	30.6	36.0	29.8	5.5	18.6
Zn	19.5	15.7	20.9	27.5	22.0	21.1	4.3	20.3
Cr	2.7	1.9	1.9	1.9	2.4	2.2	0.4	16.6
Pb	4.2	9.1	2.6	11.7	1.8	5.9	4.3	73.3
Ag	6.4	7.4	7.4	6.5	5.8	6.7	0.7	10.3
Au	3.7	2.1	2.3	3.2	1.8	2.6	0.8	30.6
Pd	<DL	<DL	<DL	<DL	<DL	-	-	-
Pt	0.042	0.042	0.050	0.034	0.037	0.041	0.006	15.0

* <DL: Below Detection Limit

Table A.25. Results for the mixture of various hard drive disks supplied by TUHH.

Element	A (g/kg)	B (g/kg)	C (g/kg)	D (g/kg)	E (g/kg)	Mean (g/kg)	SD (g/kg)	RSD (%)
Cu	308.3	314.3	293.0	250.0	288.8	290.9	25.1	8.6
Fe	11.3	12.1	16.0	15.3	18.8	14.7	3.1	20.9
Al	18.4	17.4	16.9	14.1	17.9	16.9	1.7	10.1
Sn	32.1	22.3	27.2	28.1	27.9	27.5	3.5	12.7
Ni	8.8	10.2	9.5	8.2	10.7	9.5	1.0	10.7
Zn	5.3	5.8	6.6	7.6	6.1	6.3	0.9	14.2
Cr	0.61	0.51	0.56	0.58	0.66	0.58	0.06	9.9
Pb	15.0	11.0	10.0	13.6	9.0	11.7	2.5	21.4
Co	0.032	0.064	0.035	0.036	0.044	0.042	0.013	31.3
Ag	1.3	1.6	1.8	1.6	1.5	1.5	0.2	11.0
Au	0.52	0.65	0.52	0.30	0.47	0.49	0.13	25.73
Pd	0.011	0.018	0.020	<DL	<DL	0.010	0.009	97.7
Pt	0.013	0.012	0.012	0.012	0.015	0.013	0.001	7.9
La	0.003	0.055	0.033	0.092	0.075	0.052	0.035	68.0
Nd	0.64	0.56	0.63	0.61	0.66	0.62	0.04	5.9
Ce	0.010	0.009	0.014	0.004	0.010	0.009	0.004	41.2
Pr	<DL	<DL	<DL	<DL	<DL	-	-	-
Dy	0.030	0.020	0.021	0.028	0.035	0.027	0.006	24.1

* <DL: Below Detection Limit

APPENDIX B

Table B.1. Market prices of metals analyzed in the study.

	Price[a] (US$/kg)
Base Metals	
Cu	4.71
Fe	0.055
Al	1.64
Sn	17.73
Ni	9.74
Zn	2.12
Cr	1.94
Pb	1.82
Co	25
Precious Metals	
Ag	643
Au	42490
Pd	18486
Pt	34883
Rare Earth Elements	
La	7
Nd	60
Ce	7
Pr	85
Dy	230

[a] London Metal Exchange, January 2016