Waste Management xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Comprehensive characterization of printed circuit boards of various end-of-life electrical and electronic equipment for beneficiation investigation

Anshu Priya, Subrata Hait *

Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihta, Bihar, India

A R T I C L E I N F O

Article history:
Received 29 June 2017
Revised 5 February 2018
Accepted 7 February 2018
Available online xxxx

Keywords:
End-of-life electrical and electronic equipment
Printed circuit board
Comprehensive characterization
Elemental content
Beneficiation

A B S T R A C T

Comprehensive characterization of printed circuit board (PCB) of end-of-life electrical and electronic equipment (EEE) is obligatory for prospective profitable beneficiation. In this study, beneficiation oriented comprehensive characterization of two brands of PCBs each of 16 end-of-life EEE was conducted in terms of their physicochemical characteristics with special emphasis on the content of 16 general elements, 2 precious metals and 15 rare earth elements (REEs). General elements and their highest weight percent composition found in different PCBs of the EEEs were Cu (23% in laptop), Al (6% in computer), Pb (15% in DVD player) and Ba (7% in TV). The high abundant of precious metals such as Au (316 g/ton) and Ag (636 g/ton) in mobile phone and laptop, respectively coupled with rapid obsolescence age makes waste PCBs of information technology and telecommunication equipment the most potent resource reservoir. Additionally, most of the waste PCBs were observed to contain REEs in considerable quantity with Sc up to 31 g/ton and Ce up to 13 g/ton being the major constituents. Comprehensive characterization of waste PCBs therefore will systematically help towards better understanding of e-waste recycling processes for beneficiation purpose and sustainable resource circulation and conservation.

1. Introduction

The consistent advancements in electrical and electronic equipment (EEE) with advent of smart features, designs and technology during the last few decades have led to rapid obsolescence of many electronic items, leading to build up of waste electrical and electronic equipment (WEEE) or electronic waste (e-waste). E-waste encompasses a large variety of electrically powered products including large and small domestic devices which are discarded by the owner as waste without the intention of reuse (Ongondo et al., 2011). EEE are classified based on their type and utility. According to the WEEE Directive (Directive, 2012/19/EU) (WEEE Directive, 2012), EEE are classified into various categories such as information technology and telecommunication equipment, large household, small household, consumer, lighting equipment and others. Another way of classification of EEE is into white, brown and grey goods (Nnorom and Osibanjo, 2008). Large household equipment such as refrigerator, washing machine, air conditioner, etc. which are mostly painted with white enamel are called white goods. Brown goods are relatively light consumer as well as information technology and telecommunication equipment like television, computer, mobile phone, radio, etc. Grey goods are the branded EEE that are sold outside the authorized territory by the unauthorized dealers at a price lower than the manufacturing territory. E-waste is considered as one of the fastest growing waste streams. The global e-waste generation is predicted to increase from 41.8 Mt in 2014 at a growth rate of 4–5% per annum reaching 49.8 Mt by 2018 (Baldé et al., 2015). Country-wise e-waste generation linking to their per capita purchasing power has been reviewed in detail elsewhere (Priya and Hait, 2017a).

EEE are made of a multitude of components among which printed circuit board (PCB) is the core part (Ongondo et al., 2011). PCB, employed in virtually all EEE, is used to mechanically support and electrically connect microelectronic components such as semiconductor chips, capacitors, etc. using conductive pathways and trace signal etched from copper sheets laminated onto a non-conductive substrate (Li et al., 2004). PCBs have complex and heterogeneous matrix. The principal support matrix of PCBs includes substrates such as ceramic materials, Teflon, epoxy laminates, fibreglass and flame-retardant (FR) materials onto which metals are embedded (Hall and Williams, 2007). PCBs comprise of about 28% metallic and 72% non-metallic constituents (Zhou and Qiu, 2010). It has been reported that PCBs contain significantly higher content of metals including base, toxic as well as precious

* Corresponding author at: Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Bihta, Patna 801 106, Bihar, India.

E-mail address: shait@iitp.ac.in (S. Hait).

https://doi.org/10.1016/j.wasman.2018.02.014
0956-053X/

metals as compared to the natural deposit of respective metals (Cui and Zhang, 2008; Kaya, 2016). However, the actual composition of PCBs varies depending upon their specific type, class, product and brand. With the technological advancements, PCBs are exhibiting variability in their elemental composition over the years. In the context, PCBs have become an important target for metals recycling from the viewpoints of waste management, resource conservation and pollution control.

Given the quantum of e-waste generated, complexity of PCBs and tremendous metals content; the physical and chemical characterization of waste PCBs is obligatory for prioritization of metals to be recycled as well as the target end-of-life EEE. Though PCBs are recognized as valuable secondary metals reservoir in end-of-life EEE, the precise information related to their physical and chemical characteristics is sparse in the existing literature (Bandyopadhyay, 2008; Deveci et al., 2010; Hall and Williams, 2007; Hagelüken, 2006; Hagelüken and Art (2006); Holgersson et al., 2017; Kang and Schoenung, 2005; Maragkos et al., 2013; Oguchi et al., 2011; Priya and Hait, 2017b; Theo, 1998; Yamane et al., 2011; Yazıcı et al., 2010). Till date, very scarce and scattered information on comprehensive characterization of PCBs of different end-of-life EEE in terms of their weight percentage, moisture, volatile matter content, pH and elemental content exist (Bandyopadhyay, 2008; Deveci et al., 2010; Hall and Williams, 2007; Hagelüken, 2006; Hagelüken and Art (2006); Holgersson et al., 2017; Kang and Schoenung, 2005; Maragkos et al., 2013; Oguchi et al., 2011; Priya and Hait, 2017b; Theo, 1998; Yamane et al., 2011; Yazıcı et al., 2010). Further quantification of PCBs of various end-of-life EEE for rare earth elements (REEs) content and related beneficiation investigation have also not been conducted extensively which is leading to sheer waste of resources.

Thus, the study aims at recycling-oriented comprehensive characterization of waste PCBs from WEEE categories viz., information technology and telecommunication equipment; large household and consumer equipment and lighting equipment encompassing two brands each of 16 end-of-life EEE. The WEEE considered in the study include computer, laptop, mobile phone, calculator, modem, refrigerator, washing machine (WM), air conditioner (AC), inverter, television (TV), radio, DVD player, TV remote control, stereo amplifier, compact fluorescent lamp (CFL) and rechargeable lamp. In this study, waste PCBs were characterized (in terms of their physical characteristics and chemical composition) with special emphasis on the 16 general elements, 2 precious metals and 15 REEs scoping towards prospective profitable beneficiation investigation for prioritization of recovery of elements.

2. Materials and methods

2.1. PCBs from end-of-life EEE

A total of sixteen end-of-life EEE under WEEE categories such as information technology and telecommunication equipment, large household equipment, consumer equipment and lighting equipment were selected. Two different brands, referred herein as Brand I and Brand II, of each of the end-of-life EEE were chosen for the purpose. The end-of-life EEE considered in the study includes computer, laptop, mobile phone, calculator, modem, refrigerator, WM, AC, inverter, TV, radio, DVD player, TV remote control, stereo amplifier, CFL and rechargeable lamp. Details of the end-of-life EEE used in the study and their average obsolesce age as collated from the literature are presented in Table 1. The end-of-life EEE were disassembled manually at the local repair shops and scrapyards to separate the PCBs from other components. The PCBs of respective brands of each of the end-of-life EEE were collected in triplicate from the local repair shops and scrap dealers in Patna, Bihar, India. Fig. 1 presents typical PCB of various end-of-life EEE considered. In order to estimate the weight percentage share that PCB holds in the whole equipment, information pertaining to the total weight of each of the end-of-life EEE was obtained from the repair shops and scrap dealers while manually dismantling the PCBs from the equipment. The summary of the procedural steps followed for characterization of PCBs of end-of-life EEE is schematically shown in Fig. 2.

2.2. Sample preparation

For the purpose of sample preparation, mounted electrical components, viz. capacitors, resistors, batteries etc. were removed from the PCBs by means of tools such as hammer, screw driver and pliers. The PCBs were cleaned by air spray, wiped with acetone and dried to remove dust particles and other possible contaminants. Pliers and stainless steel scissors were also used to cut the PCBs into pieces of dimensions approximately 2 cm × 2 cm for initial size reduction. CFL PCBs were not subjected to initial size reduction due to their smaller sizes. For each of the end-of-life EEE, the pieces of the batch of waste PCBs of respective brands were then subjected to mechanical comminution collectively using the cutting mill (SM200, Retsch GmbH, Germany) for further size reduction to the size range of <0.038 mm to >1 mm and subsequently

Table 1
Details of end-of-life EEE investigated and their average obsolescence age.

S. No.	Category as per WEEE Directive (2012)	Group (Nnorom and Osibanjo, 2008)	EEE	Average obsolescence age		Number of brands of EEE	Number of PCBs for each brand
				Years	Reference		
1	Information technology and telecommunication equipment	Brown goods	Computer	3–5	Kang and Schoenung (2005), Liu et al. (2006)	2	3
			Laptop	2.5–4	Yang and Williams (2009)	2	3
			Mobile phone	2–3	Robinson (2009)	2	3
			Calculator	6	DIT (2014)	2	3
			Modem	6	DIT (2014)	2	3
2	Large household equipment	White goods	Refrigerator	9	Liu et al. (2006)	2	3
			WM	9	Liu et al. (2006)	2	3
			AC	10	Liu,et al. (2006)	2	3
			Inverter	20–30	Bower et al. (2006)	2	3
3	Consumer equipment	Brown goods	TV	8	Liu,et al. (2006)	2	3
			Radio	9.5	Oguchi et al. (2008)	2	3
			DVD player	7.2	Oguchi et al. (2008)	2	3
			TV remote control	10	DIT (2014)	2	3
			Stereo Amplifier	14	Oguchi et al. (2008)	2	3
4	Lighting equipment	Brown goods	CFL	1	Lim et al. (2013)	2	3
			Rechargeable lamp	0.25	Ogundiran et al. (2017)	2	3

Please cite this article in press as: Anshu Priya, , Hait, S. Comprehensive characterization of printed circuit boards of various end-of-life electrical and electronic equipment for beneficiation investigation. Waste Management (2018), https://doi.org/10.1016/j.wasman.2018.02.014