Waste Management xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Review

Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – A review

Ata Akcil [a,*], Ceren Erust [a], Chandra Sekhar Gahan [a,b], Mehmet Ozgun [a], Merve Sahin [a], Aysenur Tuncuk [a]

[a] Mineral-Metal Recovery and Recycling (MMR&R) Research Group, Mineral Processing Div., Dept. of Mining Eng., Suleyman Demirel University, TR32260 Isparta, Turkey
[b] Department of Microbiology, School of Life Sciences, Central University of Rajasthan, Bandar Sindri-305817, NH-8, Kishangarh Tehsil, Ajmer district, Rajasthan, India

ARTICLE INFO

Article history:
Received 17 November 2014
Accepted 15 January 2015
Available online xxxx

Keywords:
E-waste
Cyanide
Metal
Thiosulphate
Thiourea
Precious

ABSTRACT

Waste generated by the electrical and electronic devices is huge concern worldwide. With decreasing life cycle of most electronic devices and unavailability of the suitable recycling technologies it is expected to have huge electronic and electrical wastes to be generated in the coming years. The environmental threats caused by the disposal and incineration of electronic waste starting from the atmosphere to the aquatic and terrestrial living system have raised high alerts and concerns on the gases produced (dioxins, furans, polybrominated organic pollutants, and polycyclic aromatic hydrocarbons) by thermal treatments and can cause serious health problems if the flue gas cleaning systems are not developed and implemented. Apart from that there can be also dissolution of heavy metals released to the ground water from the landfill sites. As all these electronic and electrical waste do posses richness in the metal values it would be worth recovering the metal content and protect the environmental from the pollution. Cyanide leaching has been a successful technology worldwide for the recovery of precious metals (especially Au and Ag) from ores/concentrates/waste materials. Nevertheless, cyanide is always preferred over others because of its potential to deliver high recovery with a cheaper cost. Cyanidation process also increases the additional work of effluent treatment prior to disposal. Several non-cyanide leaching processes have been developed considering toxic nature and handling problems of cyanide with non-toxic lixiviants such as thiourea, thiosulphate, aqua regia and iodine. Therefore, several recycling technologies have been developed using cyanide or non-cyanide leaching methods to recover precious and valuable metals.

1. Introduction

In the fast developing world today, technological advancements in electrical and electronic equipments (television, computers, printer, telephone, modem, fax machines, copy machines, LED/LCD monitors, laptops, printed circuit boards, medical equipments, etc.) have a lesser life span compared to olden days due to rapid increase in demand of advanced products. Short life span of the electrical and electronic equipment (EEE) has generated huge tonnage of waste Electrical and Electronic Equipments (WEEE) called "E-waste". The reasons for decreasing life span of electrical and electronic devices are as follows:

- Incoming of highly advanced and technically skilled devices/equipments with cheaper price and more features.
- Rapid growth in life style of human beings with modern facilities having user friendly electrical and electronic equipments.
- Stiff competition amongst individuals to use and small enterprises and industries to produce and sell best products made on advanced technologies.

The average annual growth of the E-waste market was predicted to be 8.8% (2004–2009) resulting with scrapped computers outnumbering the production rate (BCC, 2005; Kang and Schoenung, 2005). Fifteen countries amongst all the EU countries categorised dumped/unused refrigerator, personal computers (PC), television (TV), copy machine and small home appliances E-waste with a resultant increase in waste generation from 3.3 to 4.3 kg/person (Wildmer et al., 2005). Studies conducted on the generation of E-waste predicted 19.1 kg/year/person in 27 EU countries by 2012 with total of 10.5 million tons of E-waste by 2014 (Huisman, 2010). Increasing concern over environmental issues in the global scenario in the recent years has mobilised researchers, scientists and industries together with government

* Corresponding author. Tel.: +90 246 2111321; fax: +90 246 2370859.
E-mail address: ataakcil@sdu.edu.tr (A. Akcil).

http://dx.doi.org/10.1016/j.wasman.2015.01.017
0956-053X/© 2015 Elsevier Ltd. All rights reserved.

authorities to execute several recycling strategies for metal recovery from E-waste. The primary reason for development of recycling strategies on E-waste is due to the stricter policies and regulations imposed on the industries and landfill zones. Moreover the 2002/96/EC regulation proposes obligatory recovery of metal values from E-wastes. In accordance to EU regulations, Turkish Ministry of Environment and Forestry has also prepared the "Regulation of Controlling Waste of Electric and Electronic Equipments (WEEE)" (No. 2830) with stringent policies and regulations on recycling/reusing of E-wastes in 2012 as follows:

- Municipalities are obliged to collect and store E-wastes separately from conventional wastes.
- The manufacturers must take the responsibility of recycling their discarded products in their production centre/separate recycling centre/outsource to licensed recycling centres.
- The manufacturers must carry out their own research or outsource research projects to develop better recycling technologies for E-wastes (Regulation of Controlling Waste Electric Electronic Equipments, 2012).

Kiddee et al. (2013a,b) presented an overview of toxic substances present in E-waste, their potential environmental and human health impacts together with management strategies currently being used in certain countries. Several tools including Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Multi Criteria Analysis (MCA) and Extended Producer Responsibility (EPR) have been developed to manage E-wastes especially in developed countries. Recycling E-wastes is predicted to be the appropriate method of E-waste management, developing environment friendly, technically feasible and economically appropriate methods of recycling. However this could be an important source of metal recovery from secondary resources at the time when primary metal resources are depleting. Furthermore, steps should also be taken to educate the consumers/users of the electrical and electronic products regarding E-waste collection centres to increase the collection rate to recover higher content of metal values prior to its disposal in landfills. E-waste is well known to contain several environmentally hazardous organics such as fire retardants (Cl^-/Br^-, etc.) and several inorganic elements (He et al., 2006). Advancement in the technological throughput with innovative approaches accounting to the rapid growth in science and technology and market demand for better qualitative products with cheaper costs has increased the consumption of electrical-electronic equipments. This has resulted with generation of 20–50 million tons E-wastes annually worldwide with 35% increase per year (Schwarzer et al., 2008). Table 1 shows the equipments/devices included in the E-waste category together with the amount of waste generated in UK. The table also states that the home/household appliances contribute highest amongst all the E-wastes.

Table 1
The tonnage and amount of basic e-wastes by the year 2000 (ICER, 2000).

Equipment	Units (Millions)	Weight (tonnes)	% of Total
Large household appliances	10	392	43
Small household appliances	15	30	3
IT equipment	22	357	39
Telecoms	7	8	1
Radio, TV and audio	12	72	8
Lamps	77	12	1
Medical	No data		
Monitoring and control	8	8	1
Toys	8	8	1
Electronic electrical tools	6	28	3
Automatic dispensers	No data		
Total	165	915	100

WEEE contains a variety of hazardous inorganic substances such as Hg and Pb, which may cause some environmental problems when it is not properly managed (Xu et al., 2009, 2010; Li and Lu, 2010). Secondary metal resources such as WEEE contain base metal such as Cu, in particular and precious metals Au, Ag, Pt and Pd comparable to the metal content in ores and concentrates (Havlik et al., 2011; Tuncuk et al., 2012; Birloaga et al., 2013). Therefore, recycling of WEEE is of prime importance from both environmental and economic benefit (Wildmer et al., 2005; Robinson, 2009; Yazici and Deveci, 2013).

The period between 1994 and 2003 observed generation of huge E-waste due to discarding of ~500 million personal computers, which contained 2.8 million tons of plastic, 0.7 million tons of lead (Pb), 1339 tons of cadmium (Cd), 848 tons of chromium (Cr) and 282 tons of mercury (Hg) (Puckett et al., 2002). High content of base metal (Fe, Cu, Al, Pb and Ni) and precious metal (Ag, Au, Pt and Pd) present in E-waste results makes it a potential source of secondary resources for metal recovery (Table 2). E-waste such as DVD players, printed circuit boards, computers and electronic scrap has maximum content of base metals whilst the electronic devices such as personal computers and mobile phone cards contained highest level of precious metal. The metal content of Cu and Au in primary metal resources like ores/concentrate was 0.5–1% and 1–10 g/ton respectively, whilst in case of secondary metal resources such as E-waste it was 20% and 250 g/ton respectively. This justifies that the metal content in secondary metal resources would be worth recovering if feasible technologies can developed with environmental friendly methods (USGS, 2001; Goosey and Kellner, 2003; Cui and Zhang, 2008).

The weight percentage of metals obtained from PCB's is shown in Table 3 with highest copper content amongst all other metals.

The metal content in E-wastes varies with the source and type of the E-waste. A typical computer circuit board contains ~20% Cu and ~250 g/ton Au, whilst mobile phone contains 13% Cu and 350 g/ton Au (Hagelüken, 2006). It is very important to note that the E-wastes contain 13–26 times higher Cu content and 35–50 times more Au content compared to ores/concentrates (Zhang and Forssberg, 1998; Cui and Zhang, 2008). As the precious metal content in Waste PCB's is higher than the ores/concentrates it would be worth to recycle waste for economical and environmental advantage. The metal contents in circuit board (Table 4) describe its economic value, for which the recovery of metal values from E-waste could be preferred in future (Yu et al., 2009).

The content of precious metals in telephone, calculators and printed circuit boards is about 70% whilst about 40% in TV boards and DVD players (Cui and Zhang, 2008). Various economical and environmental advantages of the metal recovery from E-wastes are as follows (Zhang and Forssberg, 1998):

- Conservation of primary metal resources.
- Decrease in the amount of solid waste generated.
- Recovery of non-metal material (plastic, etc.).
- Recovery of Ferrous metals, Non-ferrous metals and precious metals.
- Energy savings at a greater than the primary metal resources.
- Prevention of environmental pollution caused by heavy metals, solvent based flame retardant, plastics and toxic gas released the from E-waste.

The metal recovery from E-wastes and the amount of energy savings is shown in Table 5, where highest energy savings ratio is obtained from aluminium recovery process.

Precious metal content in the E-wastes plays a crucial role in choosing and developing metal recovery methods. Hagelüken classified E-wastes as high, medium and low grade based on its gold content (Hagelüken, 2006). In general high grade primary metal